Environmental Impact of Household Biogas Plants in India: Local and Global Perspective

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ABSTRACT

In this study, the environmental impacts of biogas technology in India were studied when biogas as a cooking fuel substitutes biofuels (fuelwood, dung and crop residues) and fossil fuels (kerosene and LPG). Over three million household biogas plants (2-6 m^3) have been set up in rural India till the end of year 2000. In addition to local environmental impact an attempt was made to evaluate global environmental impact of this kind of small-scale renewable energy technology implemented in such large-scale as in India. As the global point of view the greenhouse implications of biogas as cooking fuel were studied compared to other fuels. Three things were studied representing local environmental impacts when biogas technology is used instead of the direct burning of biofuels: 1) Impacts on biomass, 2) impacts on soil quality and 3) impacts on indoor air quality. As the base of the calculation the emissions per useful energy (going into pot) measured by previous studies were used. The annual production of one average household biogas plant (2 m^3) in India was estimated to be 372 m^3 of biogas, which contains 4.3 GJ of useful energy. The production of all small-scale biogas plants in India (at functionality status of 81 %) could replace annually 3.8 Mt of fuelwood or 48.7 Mt of dung. The CO emissions of biogas as cooking fuel were esimated to be 120 times smaller than fuelwood and 260 times smaller than dung and TSP emissions 8 times smaller than fuelwood and 13 times smaller than dung. The annual reduction of GHGs of 3.03 million biogas plants as CO_2 equivalent was estimated to be 4.4 Tg and at amount of 12 million plant 21.5 Tg when biogas replaces solid biofuels. CO_2, CO, CH_4 and N_2O were included in the estimation of the greenhouse implications of biogas compared to direct burning of solid biofuels or using of fossil fuels. To get the whole picture of the greenhouse implication of biogas technology e.g. the methane leakages of reactors should be noticed.

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TIIVISTELMÄ

Tässä työssä tutkittiin Intian pienimuotoisen biokaasuteknologian ympäristövaikutuksia biokaasun korvatessa kotitalouksien ruuanvalmistuksessa kiinteitä biopolttoaineita (polttopuu, karjanlanta ja viljankorjuujäte) ja fossiilisia polttoaineita (kerosiini ja nestekaasu). Vuoden 2000 loppuun mennessä oli Intian maaseudulle rakennettu yli kolme miljoonaa pienimuotoista biokaasulaitosta (2-6 m^3). Paikallisten ympäristövaikutusten lisäksi tutkittiin tällaisen pienimuotoisen, mutta laajamittaisesti toteutetun uusiutuvan energian teknologian globaaleja ympäristövaikutuksia. Globaalia näkökulmaa edustivat biokaasun ilmastovaikutukset verrattuna muihin em. polttoaineisiin. Biokaasuteknologian paikallisista ympäristövaikutuksista tutkittiin kolmea seikkaa: 1) Vaikutuksia biomassavaroihin, 2) viljelysmaan laatuun ja 3) sisäilman laatuun. Näitä tutkittiin vertaamalla biokaasun ja kiinteiden biopolttoaineiden poltosta syntyneitä hiukkas- ja hiilimonoksidipäästöjä. Laskelmien pohjana käytettiin ko. polttoaineille aikaisemmissa tutkimuksissa mitattuja päästöarvoja suhteessa käyttökelpoisen energian määrään. Keskimääräisen intialaisen biokaasulaitoksen vuosituotoksi laskettiin 372 m^3 biokaasua, jonka sisältämä käyttökelpoisen energian määrä on 4,3 GJ. Intian pienimuotoisten biokaasulaitosten (81 % toimivia) tuottama ruuanvalmistuksessa käyttökelpoinen energia korvaa 3,8 Mt polttopuuta tai 48,7 Mt karjanlantaa. Biokaasun hiilimonoksidipäästöjen laskettiin olevan 120 kertaa pienemmät kuin polttopuun ja 260 kertaa pienemmät kuin lannan suorassa poltossa ja kokonaishiukkaspäästöt 8 kertaa pienemmät kuin polttopuun ja 13 kertaa pienemmät kuin lannan. Biokaasuohjelman globaalin ilmastovaikutuksen osalta huomioitiin neljän kaasun (CO_2, CO, CH_4 ja N_2O) vaikutus. Hiilidioksidiekvivalentin vähennyksen laskettiin olevan 4,4 Tg ja tavoitellulla tasolla (12 milj. laitosta) 21,5 Tg vuodessa, kun biokaasu korvaa biopolttoaineet siinä suhteessa kuin ne ovat Intiassa ko. käytössä. Tässä laskelmassa mukana ovat vain poltettaessa syntyneet päästöt. Biokaasuteknologian ilmastovaikutusta kokonaisuudessaan arvioitaessa olisi huomioitava myös muut biokaasuteknologian päästövaikutukset, mm. reaktoreiden mahdolliset metaanivuodot.

TERMS AND ABBREVIATIONS

AFPRO	Action for Food Production
ARI	Acute respiratory infection
BOD	Biological oxygen demand
CBP	Community biogas plant
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary disease
CPCB	Central Pollution Control Boards
DALYs	Disability-adjusted life-years
GDP	Gross domestic product
GHG	Greenhouse gas
GoI	Government of India
GWC	Global warming commitment
GWP	Global warming potential
HC	Hydrocarbons
IBP	Institutional biogas plant
ICAR	Indian Council for Agricultural Research
Kgce	Kilograms of coal equivalent
MCF	Methane-conversion factor
MNES	Ministry of Non-Conventional Energy Sources
MoEF	Ministry of Environment and Forests
MPN	Most probable number
Mt	Megaton
Mtoe	Megatonnes of oil equivalent
NBP	Night-soil (human excrement) based biogas plant
NCE	Nominal combustion efficiency
NGO	Non-governmental organisation
NO_x	Nitrogen monoxide and dioxide
NBD	National Burden of Disease
NPBD	National Project on Biogas Development
NPK	Nitrogen, phosphorus and potassium
PAHs	Polyaromatic hydrocarbons
PIC	Product of incomplete combustion
PM_{10}	Particles less than 10 micrometers in diameter
$PM_{2.5}$	Particles less than 2.5 micrometers in diameter
PV	Solar photovoltaic
Rs.	Rupees, Indian currency (1 euro = 52 Rs. 12/2003)
RSP	Respirable suspended particulate
RPM	Respirable Particulate Matter
SO_2	Sulphur dioxide
SOM	Stabilized organic material
SPM	Suspended particulate matter
TB	Tuberculosis
TERI	The Energy and Research Institute Previously: Tata Energy Research Institute
TSP	Total suspended particulates
WHO	World Health Organization
YLLs	Years of lost life

CONTENTS

1 INTRODUCTION

In the rural areas of developing countries, where about 40 % of all people live, the household stove accounts for more than half of human energy use. In many of the poorest countries, 80 % or more of all national fuel combustion occurs under cooking pots. In the early 1990s, nearly half the households in the world, mainly in rural areas and urban slums of developing countries, rely on unprocessed solid fuels (biomass or coal) for cooking and heating (Smith 1993). These materials are typically burnt in simple stoves with very incomplete combustion. Consequently, women and children are exposed to high levels of indoor air pollution every day (Bruce et al. 2000).

Solid household fuels account for 10-15 % of global energy use but do not often figure prominently in discussion to reduce the greenhouse gas (GHG) contributions of human fuel use. The GHG emissions from household use of biomass (wood, crop residues and animal dung) are often ignored in such discussions because it is assumed that as long as biomass fuel cycles rely on renewable harvesting they are GHG neutral. Indeed, essentially all dung and crop residues and a large portion of the wood is harvested on sustainable basis globally (however in many developing countries a large portion of wood harvested is not on sustainable basis) and thus the carbon is recycled within a short period. However, simple stoves using solid fuels do not convert all fuel carbon into carbon dioxide (CO_2), which is then taken up by vegetation during the next growing season. Because of poor combustion conditions significant portion of the fuel carbon convert into products of incomplete combustion (PICs), which in general have greater impacts on climate than CO_2 (Smith et al. 2000a).

Small-scale biogas technology is one of the most potential alternatives for rural household cooking purposes. Others are improved cooking stoves, solar cookers and fossil fuels: kerosene and LPG. Small-scale biogas technology is widespread countrywide in rural India and it has many impacts at the user and community levels. When it is realised in large-scale program it may have environmental impact in global level. The Ministry of Non-Conventional Energy Sources (MNES), Government of India, launched the National Project on Biogas Development (NPBD) in 1982 (although the first biogas plants were built allready in beginning of 1970s), and until the end of year 2000, more than 3 million household biogas plants have been built in rural areas in India (MNES 2001, 25).

In this study the household biogas technology in rural areas of India is approached particularly in the aspect of environmental and health impact. The main objective of this study is to estimate the climate change implication of biogas as a substitute for biomass (wood, dung and crop residues) combustion and fossil fuel use in rural India. The estimation is made by defining the Global Warming Commitment (GWC) for the overall impact of GHG emissions of different fuels and stoves and by comparing it to impact of using biogas at present status and realised potential. The secondary objective is to make a survey of local environmental and health-related problems of biomass combustion in cookstoves and to compare it with using of biogas.

2 STATE OF INDIA´S ENVIRONMENT

In this chapter the biggest environmental problems India are facing at the moment are introduced. The meaning of the chapter is to give an overview of the state of India´s environment as well as to put the matters discussed in this study in proportion with other environmental problems in India.

The rapidly growing population, with increased economic development, has burdened India's infrastructure, and country's environment. Deforestation, soil erosion, water pollution and land degradation continue to get worse. Rapid industrialization and urbanization in India's cities are also serious concerns (EIA 2001).

Key current environmental issues in India are the following (Countrywatch 2001):

- Deforestation
- Soil erosion
- Overgrazing
- Desertification
- Threats to biodiversity, in particular specific forms of wildlife such as the Bengali Tiger
- Threats to the marine ecosystems, including the destruction of coral reefs
- Air pollution from industrial effluents and vehicle emissions
- Water pollution from raw sewage and runoff of agricultural pesticides
- Non-potable water throughout the country
- Over-population and concomitant strain on natural resources
- Energy related environmental problems, such as chemical and oil pollution

2.1 Population and Poverty

The population of India has growth from 238 million in 1901 to 914 million in 1994 and over 1 billion in 2000. Most of it occurred following 1950. In particular, 150 million persons were born between 1981 and 1991 alone (Registrar General 1991) (Figure 1). The population growth can be caused by a decrease in the death rate, with no fall in birth rates in the period 1951 to 1971 (Figure 2). This is typical with many developing countries, which have access to western medical technology, which reduces death from contagious and other diseases, without the economic and social development that reduces the demand for large families (Reidhead et al. 1996).

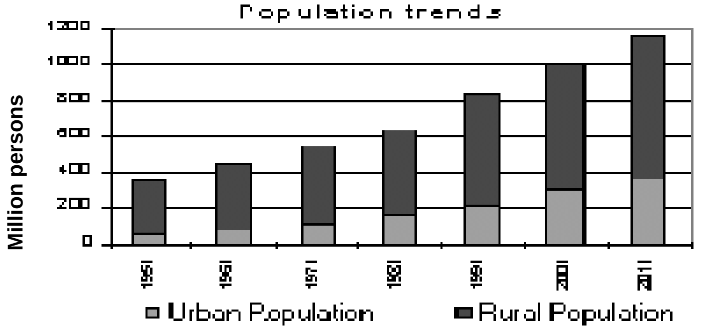


Figure 1. Population trends of India (Registrar general 1991).

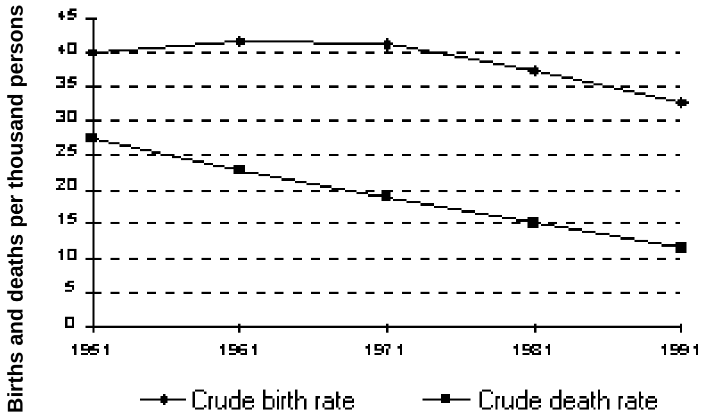


Figure 2. Trends in birth and death rates (Registrar general 1991).

However, during the last decade India's population has dropped slightly in its annual rate of increase, from 2.2 percent in 1984 to 1.9 percent in 1993 (Registrar General 1995, 26). During the 10-year period from 1984 to 1994, total fertility fell from 4.5 children to 3.5, a decline of 0.1 each year (Registrar General 1995, 26). This improvement has been indicated to be consequence of two things. The first is the Government of India's dedication to birth control and family planning from the 1950s. One of the achievements of this program was the rise of contraceptives from 10 percent of married women, to more than 40 percent in 1990 (Srinivasan 1993, Lappe et al. 1989).

The second reason for the decrease in fertility is that the level of female education has increased and influences their understanding of the social costs of additional children and raises the minimum age at marriage. The primary school enrolment for girls has increased from 5.4 percent in 1950-51, to 40.4 in 1990-91 (Figure 3). The last four decades female literacy has grown at the rate of ten percentage per decade, i.e., from 10 percent of the population in 1951, to 39 in 1991. Although the gains in both schooling and literacy are significant, females are characterized by distinctly lower rates in both of these categories, as well as higher dropout rates. The reason for this is the lower value traditionally placed on women, and their role as donor in the dowry system (Reidhead et al. 1996).

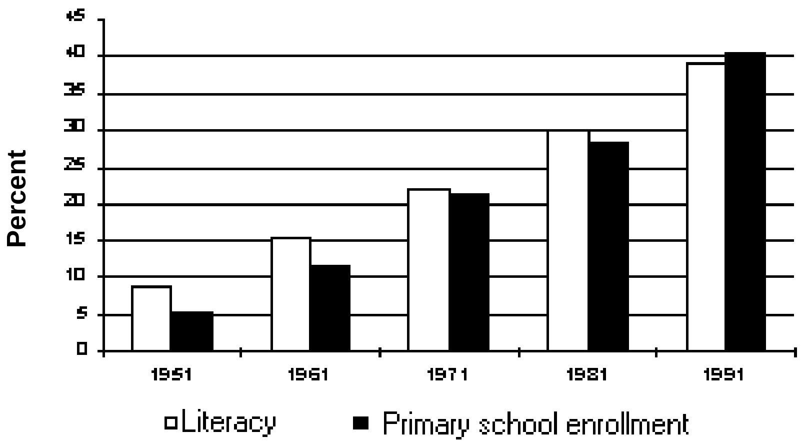


Figure 3. Female education and literacy (MHRD 1995).

Inadequate nutrition has been a persistent problem for India. It often comes along when the agricultural and economic engines of a region are not able to keep up with food demand, and the agricultural production of the country is not being adequately distributed (Reidhead et al. 1996). The calorie requirement for India, based on lifestyle and climatic factors, is 2150 kcal/day (UNDP 1995). The result of several intervention programs has been a gradual increase in caloric intake from 2197 in 1984 to 2395 in 1992 (MHFW 1992).

The total food grain production in India has increased from 51 million metric tonnes to a production of 185 million metric tonnes in four decades, a gain of 263 percent. This corresponds to a growth in per capita grain production from 142 kg in 1951 to 214 kg in 1991. These indicators of national nutrition fail to describe the distribution of food. Studies by the United Nations Development Programme and the World Bank show that the general view for India, in terms of percentage below the poverty line, has only slightly improved. The World Bank (1990) estimated that in 1984, 317 million Indians fell below the poverty line (42 percent of the total population), while the UNDP (1995) estimated that 350 million fell below that level in 1992 (40 percent of the population).

Because of the continuous increase in population, it will be necessary to develop further the agricultural production (Reidhead et al 1996). The demand for food grains is 240-245 Mt in 2000 and 400 Mt in 2035. Even with additions of farmland through wasteland reclamation, productivity will have to double to 2700 kg/ha to be able to meet the demand (Bali 1994).

The second reason for concern because of the population explosion is the increase in consumption. Even the sheer increase in per capita consumption rate will translate to a massive increase in the burden on India degrading the environment, e.g. in the form of damage to soil and drinking water supplies (Reidhead et al 1996). Consumption patterns have also been changing with urbanisation and increasing incomes. Of the final consumption expenditure in the domestic market, about 64 % was spent on food in 1970, which declined to roughly 50 % in 1997. A larger share of expenses in the comsumption is used to clothing and footwear, fuel and power, and transport and communication (TERI 1998a).

Continued economic growth has translated to a more than doubling in per capita net national product between 1950 and 1990 (Figure 4). According to Reidhead et al. (1996) “this means that the average person may be demanding more natural resources, generating more pollution, and discarding more waste. And since economic theory states that as income increases, people spend a smaller portion of their income on food, and more on other types of goods (like automobiles and appliances), there may be a worsening in the form of environmental damage affected”.

Figure 4. Per capita net national product (Economic Survey 1995).

Industrial development has played a remarkable role in economic growth in India, although often at the expense of environment. Industrial output grew fourfold between 1963 and 1991 while toxic releases grew sixfold. The industrial development has been realized by use of high-polluting energy source like coal, which comprised 52% of total primary energy consumption in 1999. A report from Ministry of Finance Government of India estimates that the annual cost of environmental degradation in India in the past few years is about 4.5% of gross domestic product (GDP) (EIA 2001, TERI 2002).

2.2 Air pollution

Air pollution has become a major concern in India in recent years. The reason for this is that the Indian urban population in the biggest cities are exposed to some of the highest pollutant levels in the world. New studies around on the health effects of air pollution have also increased confidence in estimates of the risks posed by air pollution exposures (Smith 2000). The major sources of air pollution are transport, power plants, industry and biomass-based cooking (TERI 1998a).

Annual average levels of total suspended particulate mater (SPM) are at least three times the WHO standard in six of India´s largest cities (TERI 2002). The capital, New Delhi is one of the top ten most polluted cities in the world. Surveys indicate that in New Delhi the incidence of respiratory diseases due to air pollution is about 12 times the national average. In Mumbay, where there are higher levels of sulphur dioxide, there has been an increased prevalence of breathing difficulties, coughs, and colds. Mortality data between 1971 and 1979 indicates a link between air pollution in Mumbay and a higher rate of death from respiratory and cardiac conditions and cancer (WRI 1994).

The major pollutants are particulate matter, sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), photochemical oxidants (e.g. ozone), metals (e.g. lead), and other gases and vapours (TERI 1998a). Annual concentrations reported at urban monitors in India for particles less than 10 microns in diameter (PM_{10}), range 90-600 $\mu g/m^3$, with a population mean of about 200 $\mu g/m^3$ (Smith 2000).

The industrial centers have spread throughout the urban areas without corresponding pollution control mechanisms (EIA 2001). However, the Central Pollution Control Board has launched the National Ambient Air Quality Monitoring Programme in 1984 with 28 stations in 7 cities. Along with the program, 290 stations have been established; spread over 92 cities and towns (TERI 1998a).

Since independence 1947, the total emissions from motorized transport in India increased 68-fold (TERI 1998a). Between 1970 and 1990, the number of vehicles has increased 11.5 times, from about 1.9 million to more than 21 million. Over the period of past two decades vehicular pollution has increased eightfold (EIA 2001). Of the total 40 million vehicles registered in 1998, 82 percent are personal modes of transport, with the share of two-wheelers and cars at 69 percent and 12 percent respectively. A third of vehicles are concentrated in the 23 metropolitan cities. Although 2-wheelers are generally more fuel-efficient than passenger cars, they often discharge bigger emissions of carbon monoxide, sulphur dioxide and nitrogen oxide (MST 1993, TERI 2002).

Supreme Court issued directions for control of vehicular pollution in Delhi commercial vehicles. These initiatives have largely been directed by way of not allowing old and polluting vehicles to operate on city roads or requiring them to be retrofitted to use cleaner alternative fuels, like compressed natural gas (CNG) (TERI 2002).

Thermal power constitutes about 72% of the total installed power generation capacity. Since India´s independence 1947, the amount of thermal power capacity has grown from about one gigawatt (GW), to over 72 GW. Thermal power stations account for about 71 % of power generation capacity. Since Indian coal is of poor quality (35%-40% of which is ash), it emits large quantities of particulate matter, and also makes the operation of electrostatic precipitators more difficult (TERI 2002).

Pollution from industries has quadrupled ovaer the past two decades. The total emissions of particulate matter from iron and steel, cement, sugar, fertilizer, paper and paperboard, copper, and aluminium industries increased 15-fold. A few industrial sub-sectors are responsible for an excessive share of pollution in India. Petroleum refineries, textiles, pulp and paper, and industrial chemicals produce 27% of the industrial output but contribute 87% of sulphur emissions and 70% of nitrogen emissions. Besides, iron, steel and non-metallic mineral products, account for about 16% of the industrial output but emit 55% of the total quantities of particulate matter (TERI 1998a).

Between 1964 and 1994, the number of registered industries in India has increased sevenfold, to over 100,000 industries, with large growth in the production of steel, aluminium, and chemical fertilizers (Ministry of Industry 1994). Many of these continue to emit large quantities of air pollutants, although there has been a movement in these industries to adopt pollution control measures (Reidhead et al. 1996). Urban areas have taken action to improve their ambient quality by relocating some of the more polluting industries from high density, highly polluted areas, to lower density areas. For example, Delhi, which has experienced a massive growth in small-scale, has been directed by the Supreme Court to relocate its 114 highly polluting stone crushers to outside the city boundaries (WWF 1995).

Biofuels such as wood, crop residues, and dung cakes are the primary source of energy for the majority of people. These fuels, when cooking with inefficient ovens, generate large quantities of particulate matter, most often indoors. Combined with poor ventilation, the impacts of air pollution due to these fuels are particularly serious (TERI 1998a). In both rural areas and in urban slum neighbourhoods, individuals cook daily in small, enclosed areas, and often use some form of biomass. These fuels burn ineffectively, and emit many types of toxic gases like carbon monoxide, formaldehyde and polycyclic aromatic hydrocarbons (PAHs). These pollutants, when inhaled in close quarters, can cause serious health problems. Indoor air pollution presents a growing concern because of the large number of population inhabiting rural and urban slums (Reidhead et al. 1996).

2.3 Water resources and pollution

Inadequate access to clean drinking water and sanitation facilities are perhaps the most significant environmental problems and threats to public health in both rural and urban India. 42.9 percent of urban India and 3.5 percent of rural India had sanitation facilities in 1993 (Reidhead et al. 1996). Of the urban population, 84.9 percent had access to clean drinking water in 1993 as compared to 69 percent in 1985. Of the rural population the figures fell from 82 percent in 1985 to 78.4 percent in 1993 (WRI 1995).

Major sources of water pollution in India are untreatedly released city sewage, industrial waste and wastewater from agriculture. The sewage released from cities increased from an estimated 5 billion litres a day in 1947 to around 30 billion litres a day in 1997. Facilities to treat sewage are inadequate and vy estimation only 10% sewage is treated. Input-intensive agriculture is one increasing source of water pollution. Excessive use of fertilizers has increased the level of nitrates in shallow groundwater sources. Intensive agriculture has contributed to high levels of such pesticides as DDT in the groundwater in some areas (TERI 1998a).

It is estimated that 1.5 million pre-school children in India die every year from diarrhoea. Cholera, dysentery and gastroenteritis are responsible for 60% of the total urban deaths (Sivaramakrishnan 1993). In 1990, there were almost ten million cases of acute diarrhoeal diseases, 1.8 million of malaria, and 3700 of cholera (MHFW 1992).

Most Indian rivers fall short of Central Pollution Control Boards (CPCB) standards, due to excessive pollution by untreated sewage, and domestic and industrial wastewaters. As per the data generated by CPCB from its 270 monitoring stations across all 28 major Indian rivers, mean biological oxygen demand (BOD) values have shown a marginal increase over 1979-1991, remaining in excess of the standard value of 3 mg/l. The minimum and maximum coliform values have go through 30-fold and 100 000-fold increases over the same time, indicating severe pollution. Of all the 28 Indian rivers studied, only two have the most probable number (MPN) coliform levels below the acceptable standard of 5000 MPN/100 ml. According to the BOD and MPN values, Sabarmati and Ganges are the most polluted rivers of India (Reidhead et al. 1996).

2.4 Forest Resources

India's recorded forest area was in 1999 68.9 million hectares (Mha) and covers 23% of the geographical area. Roughly half of this (37.7 Mha) comprise dense forests (crown density more than 40%), about a third (25.5 Mha) comprise open forest (crown density between 10% and 40%) and 7% of this (5.2 Mha) scrubland (crown density less than 10 %) and mangroves (0.5 Mha) (Figure 5) (TERI 2002). The per capita availability of forestland is 0.08 ha, one of the lowest in the world, against a world average of 0.64 ha (MoEF 1999).

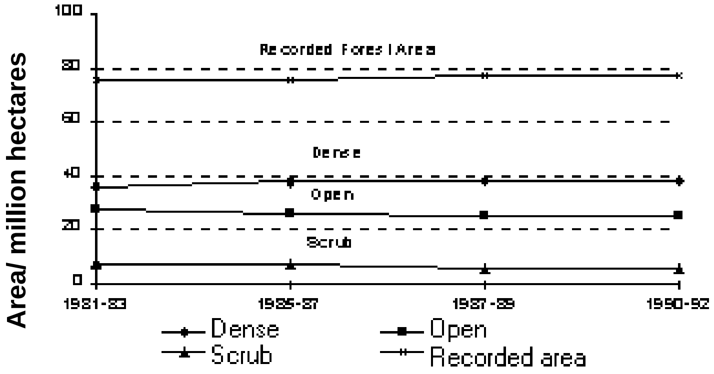


Figure 5. Forest cover by density, 1981-1992 (Forest Survey of India, various years).

The annual rate of deforestration was 1.3 Mha in the 1970s, 0.339 Mha in the 1980s and about 0.13 Mha during 1990-95. Between 1987 and 1999 the area of dense forest increased, while the area of open forest and scrubland decreased. The total forest area decreased during same time about 3 Mha (TERI 2002).

The population and industrial growth have led to increases in the demand for roundwood. Roundwood is defined simply as wood in the rough, and includes trees felled for any purpose. The majority of roundwood production is for use as fuelwood and charcoal, mostly harvested by villagers and to some degree urban squatters (Reidhead et al. 1996). Between 1970 and 1993, there has been a 160 percent increase in fuelwood and charcoal production (Figure 6). 270 million tonnes of fuelwood, 280 million tonnes of fodder and over 12 million tonnes of timber are removed from forests annually (MoEF 1999). The fuelwood consumption was estimated at 260 million m^3 in 1997 as against the sustainable supply of 52.6 million m^3. The growing stock of the forests was 4740 million m^3 with an annual increment of 88 million m^3. An average volume of one ha of forest is 120 m3 and an incremental annual growth of 1.36 m^3 (TERI 1998a).

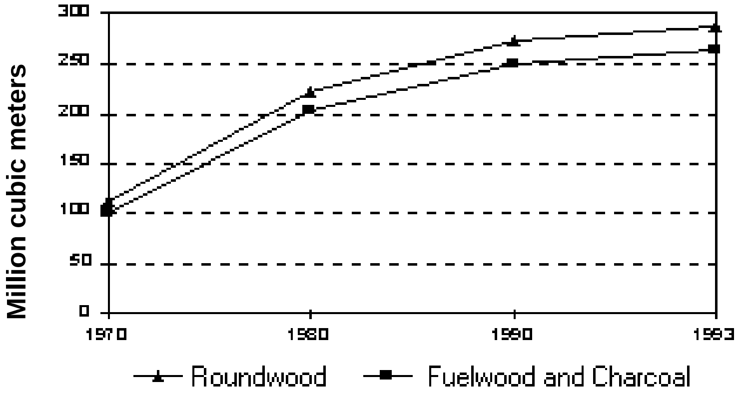


Figure 6. Growth in roundwood and fuelwood production (Forest Survey of India 1995).

A further concern related to the use of forest resources is that of biodiversity and extinction of species. India is home to several thousand animal species, including over 390 mammal, 2546 fish and over 1232 bird species. Over 300 animal species are threatened (MoEF 1999). The destruction of habitat is the primary reason for this problem, and future damages to ecosystems including replacing rich old-growth forest with monospecific plantations will accelerate negative impacts (Reidhead et al. 1996).

2.5 Soil degradation

Roughly 264 Mha of India's total geographical area (329 Mha) is available for agriculture, forestry, and related purposes. The net sown area has increased from 119 Mha in 1950 to 140 Mha in 1970, and has remained at that level since. Soil degradation is the decline in the productive capacity of soil. Four major types of soil degradation are erosion, salinity, waterlogging, and depletion of nurtients.

The reason for soil degradation can be direct or indirect. Deforestation, shifting cultivation, and unsuitable farming practices are direct causes. Indirect causes include population pressure, economic growth, and poverty. Deforestation has been cited as a cause of soil degradation in 98% of the area affected by wind erosion and has also contributed to salinization (TERI 1998a). Inadequate land cover is the reasons for both water erosion and wind erosion, whether it is caused by deforestation, monocropping, overgrazing, or by farming on marginal and hill areas. Shortened fallow periods cause additional problem; chemical deterioration in the form of nutrient loss and leaching (Reidhead et al. 1996).

Only 37 percent of land area can be said to be free from degradation (Reidhead et al. 1996). Erosion by water and wind is the most common cause of soil degradation in India. It accounts for 89 % of the area affected by soil degradation, and the share continues to increase (Table 1).

Table 1. Classification of Indian soil degradation (Sehgal et al. 1994).

		Area (Mha)	Percent (%)
Water erosion			
	loss of top soil	132.5	40.3
	terrain deformation	16.4	5.0
Wind erosion			
	loss of topsoil	6.2	4.1
	terrain deformation/overblown	4.6	1.9
Chemical deterioration			
	loss of nutrients	10.1	3.1
Physical deterioration			
	waterlogging	11.6	3.5
Land not fit for Agriculture		18.2	5.5
Soils with little or no degradation		90.5	27.5
Soils under natural condition		32.2	9.8
Total		328.7	100.0

Between 1977 and 1997, the eroded land area almost doubled in India. About 64% of the eroded soil comes from a few severely eroded sites and soil types. Nearly 30% is washed down to the sea and 10% ends up in reservoirs. About 14 million tonnes of major nutrients as nitrogen, phosphorus, and potassium are lost. About 6 Mha of land area was waterlogged in 1976 and the area increased to 11.6 Mha in 1994. More than 10 Mha is affected by salinity of alkalinity. The economic loss due to soil degradation was 89-232 billion rupees annually, which represents 11%-26% of agricultural output (TERI 1998a).

2.6 Greenhouse gas emissions

Total CO_2 equivalent emissions were little over 1 million Gg in 1990 in India. The emissions represent approximately 3% of global CO_2 equivalent emissions. The energy sector contributed 55% of the national emissions. This sector include for instance emissions from transport of fuels, coal mining, and fugitive emissions from oil and natural gas. GHG emissions from traditional burning of biomass fuels were also included except CO_2 emissions, which are uptaken by vegetation. Agriculture was the second largest source of GHGs.. Enteric fermentation in domestic animals, manure management and rice cultivation cause methane emissions, and with burning of agricultural residues constituted 34% of national GHG emissions. Industrial processes, mainly the cement industry, represented 2.4% of CO_2 equivalent emissions. Methane emissions also came from waste management, particularly industrial waste water management, contributing 0.3% of the national GHG emissions. The net CO_2 uptake and emissions from the land-use change and forestry sector were almost equal in this sector (Table 2) (ADB-GEF-UNDP 1998).

Table 2. India's national greenhouse gases (GHGs) inventory for 1990 (Gg) (ADB-GEF-UNDP 1998).

Greenhouse gas sources and sinks	*CO_2 emissions*	*CO_2 removals*	*Methane*	*Nitrous oxide*	*Oxides of nitrogen*	*Carbon monoxide*	*CO_2 equivalent (methane + nitrous oxide)*[a]
Energy							
Fuel combustion	508600						
Energy and transformation industries	-	-	-	-	2684[c]	3 493	508600
Biomass burning	300460[b]	-	1579	11	400	11472	36569
Fugitive emissions from fuels							
Solid fuels		-	330	-	-	-	6930
Oil and natural gas	-	-	626	-	-	-	13146
Total emissions from energy sector							
(fuel combustion + fugitive)	508600	-	2535	11	3084	14965	565245
Industrial processes	24200	-	-	1	-	-	24510
Agriculture							
Enteric fermentation	-	-	7563	-	-	-	158823
Manure management	-	-	905	-	-	-	19005
Rice cultivation	-	-	4070		-	-	85470
Agricultural soils	-	-		240	-	-	74400
Prescribed burning of savannas	-	-			-	-	-
Field burning of agricultural residues	-	-	116	3	109	3038	3366
Total emissions from agricultural sources	-	-	12654	243	109	3038	341064
Land-use change and forestry							
Change in forests and other woody							
biomass stock	-	-6171	-	-	-	-	-6171
Forests and grassland conversion	52385	-	-	-	-	-	52385
Abandonment of managed lands	-	-44729	-	-	-	-	-44729
Total emissions from land-use change							
and forestry sector	52066	-50900	-	-	-	-	1485
Waste							
Solid waste disposal on land	-	-	334	-	-	-	7014
Domestic and commercial waste water	-	-	49	-	-	-	1029
Industrial waste water	-	-	2905	-	-	-	61005
Other waste	-	-	-	-	-	-	-
Total emissions from waste	-	-	3288	-	-	-	69048
Total national emissions and removals	**585185**	**-50900**	**18477**	**255**	**3193**	**18003**	**1001352**

[a] CO_2 equivalents are based on the GWP (global warming potential) of 21 for methane and 310 for nitrogen oxide. Nitrous oxide and carbon monoxide are not included since GWPs have not been developed for these gases. Bunker fuel emissions are not included in the national total.

[b] CO_2 emissions from biomass burning are not included in the national totals.

[c] Nitrogen oxides and carbon monoxide emissions are computed for the transport sector.

2.7 Environmental policy

The Government of India has a comprehensive policy to address the environment and was the first country to insert an amendment into its constitution allowing for the state to intervene and to protect public health, forests and wildlife. There was a limitation on the amendment specifying that it "shall not be enforceable by any court" (EIA 2001). In fact, first environmental legislation dealing with water pollution was the Indian Penal Code in 1860, even though, it dealed only with public springs and reservoirs used for the purpose of drinking. Water quality was considered legally as an environmental issue in Water (Prevention and Control of Pollution) Act in 1974 (Reidhead et al. 1996).

Environment Protection Act of 1986 represented more effective environmental legislation. According to the Act, the Ministry of Environment and Forests (MoEF) has overall responsibility for administering and enforcing environmental laws and policies. The MoEF established the importance of integrating environmental strategies into any development plan for the country. The reduction of industrial pollution has been one of the MoEF's main focuses (EIA 2001). These legislations empowered the Central Pollution Control Board (CPCB) to maintain ambient water standards, to get information regarding effluent emissions, to shut down polluting activities, and to prevent new discharges (Reidhead et al. 1996).

The air quality regulation was created under the Air Prevention and Control of Pollution Act of 1981 as well as the Environmental Protection Act of 1986. As with water quality standards, MoEF is responsible for maintenance of air quality. These acts empower the agencies to set and uphold Minimal National Standards (MINARS) for effluents from industries and National Ambient Air Quality Standards (NAAQS). The Ministry is also responsible for the National Ambient Air Quality Monitoring (NAAQM) network, with 290 monitoring stations in 92 cities across India (Reidhead et al. 1996).

The need to increase the use of renewable energy sources for sustainable energy development was recognised in the country in the early 70's (MNES 2003). The deforestation due to use of fuelwood as domestic fuel in rural areas was seen as a problem and use of fuelwood was claimed to exceed the natural production (Moulik 1982). Other reason was when the fossil fuel dependency was noticed to be a problem during the energy crisis (Gustavsson 2000). The renewable energy politics were first under the Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology. In 1982, a separate Department of Non-Conventional Energy Sources (DNES) was created in the Ministry of Energy. In 1992, DNES was upgraded and it started functioning as a separate Ministry of Non-Conventional Energy Sources (MNES) (MNES 2003).

3 ENERGY SCENARIO OF INDIA

3.1 Overview of energy sector

Overall, 60% of energy needs in India are met by commercial energy sources, while the remaining 40% are comprised of non-commercial fuels and renewable fuels (Figure 7). Behind China, India is the second largest commercial energy consumer in Non-OECD East Asia, comprising 19% of the region's total primary energy consumption (EIA 2001). The total energy consumption in India was 202 Mt of oil equivalent (MTOE) in 2000/2001. This represents a growth of 5.5 % a year over the period 1990-1999. Coal dominates the energy mix in India, contributing 70% of the total primary energy production (TERI 2001b, 15).

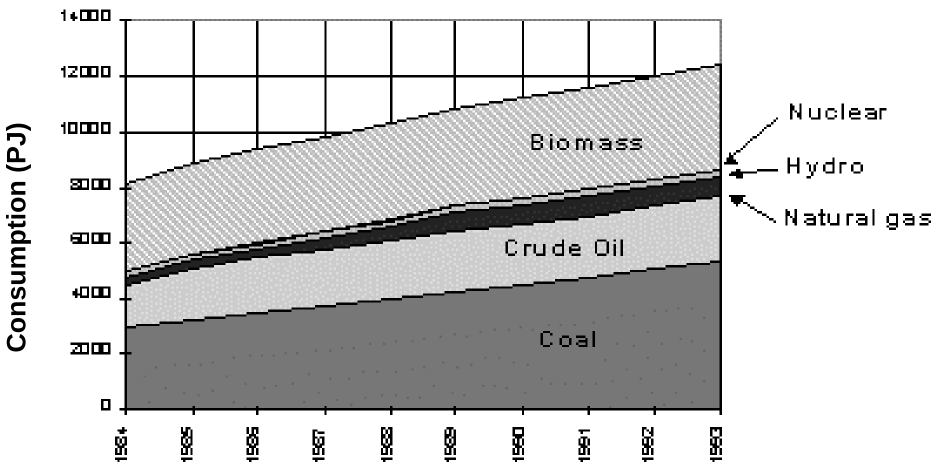


Figure 7. Primary energy consumption (PJ), 1984-1993 (TERI 1996).

Industrial sector is the largest consumer of energy, consuming about half of the total commercial energy in 2000. Coal and lignite meet over half of industrial commercial energy requirements. The transport sector is the next biggest consumer at 22% of total commercial energy consumption (TERI 2001b, 15).

India’s power sector draws upon coal and petroleum products as well as the country’s resources of uranium, wind energy, and hydropower. The total installed capacity of power in India in 2000 was almost 100 000 MW, comprising of 71% thermal, 25% hydro, 3% nuclear, and 1% wind. Despite growth in power generation over the years, India continues to face power shortages and the quality of power continues to be poor (TERI 2001b, 107).

The fuel composition of commercial energy consumption varies significantly from sector to sector (Table 3). Coal continues to meet over 70% of industry’s energy needs, but petroleum products and power are replacing coal in small quantities. In agriculture, draught animal power continues to be used in various farming activities. In transportation, the use of coal is virtually nil following the substitution of steam traction with electric traction. Consequently, the use of power has gone up. The consumption of petroleum products has increased following a sevenfold increase in registered motor vehicles between 1981 and 1997 (MoST 1999). In addition to commercial fuels – coal, oil, natural gas, and power – India consumes large quantities of traditional fuels (TERI 2001b, 287).

Table 3. Sectoral energy consumption (%) by fuel in India (1999/2000) (TERI 2001b, 15).

Sector	Coal	Petroleum products	Natural gas	Power	Total
Agriculture	0	9.5	1.3	89.2	100
Industry	73.1	13.6	2.4	10.9	100
Transport	0	98.5	0	1.5	100
Residential	0	71.3	1.1	27.6	100
Others	0	60.9	33.9	5.2	100

3.2 Commercial energy

On a per capita basis commercial energy consumption in India is low compared to that in many other countries, being less than four percent that of USA and is just one-fourth that of the world average (TERI 2001b, 13). Even so, the country is grappling with issues of energy security, growing imports, and sustainability of balance of payments. India continues to be a net importer of energy: almost 22% of the total energy supply in 1997/98 was imported in the form of coking coal, crude oil, and petroleum products. Self-sufficiency in petroleum products declined from 60% in 1985/86 to 34% in 1997/98 (TERI 2000a, 18).

With 243.3 million metric tons of carbon released from the consumption and flaring of fossil fuels in 1999, India ranked fifth in the world behind the United States, China, Russia and Japan. India's contribution to world carbon emissions is expected to increase in coming years, with an estimated average annual growth rate between 1996 and 2020 of 3.2% in the EIA International Energy Outlook 2001 reference case (compared to 3.9% in China and 1.3% in the United States). India's reliance on low-quality coal with a high carbon content is the primary impetus for this expected increase (EIA 2001).

The consumption of commercial fuels is steadily rising throughout the Indian economy, with coal continuing to be the most prominent energy source. Even so, the country is grappling with issues of energy security, growing imports, and sustainability of balance of payments. India continues to be a net importer of energy: almost 22% of the total energy supply in 1997/98 was imported in the form of coking coal, crude oil, and petroleum products. Self-sufficiency in petroleum products declined from 60% in 1985/86 to 34% in 1997/97 (TERI 2001b).

The demand for energy in India has been growing rapidly and India continues to be a net importer of energy. India imported 39.81 million tonnes of oil and 17.38 million tonnes (net imports) of petroleum products in 1998/99. India is also expected to import natural gas to meet its growing gas requirements. Projections of crude imports indicate that import dependence, which is 66% at present, will rise to 80% by 2010.
On the supply side too several developments have been worrisome. With reserves declining in other parts of the world, the Gulf region is likely to emerge with a much larger share of global oil supplies than in the past (TERI 2001b, 14).

While a large part of the household sector continues to depend on traditional fuels for cooking, this is not documented formally. There appears to be some substitution of petroleum products by power in the household sector. This could be the result of more extensive electrification whereby kerosene gets replaced by electricity for lighting (TERI 2001b, 288).

3.3 Renewable energy

As on end of the year 2000, the total installed capacity of power based on the renewable sources has reached 3000 MW, representing nearly 3 per cent of the total grid capacity of power generated from all sources. The nearly twofold increase in a span of one year has been realized compared to 1600 MW of power based on the renewables on end of the year 1999. Almost all the areas, namely solar, wind, biomass, urban and industrial waste and small hydro, have contributed to this achievement. However, considering that the potential of renewables in the country is estimated at 100 000 MW, the utilisation thereof so far is only marginal. The potential and achievements of various renewable sources of energy are given in Table 4
(MNES 2001, 21).

Table 4. The potential and achievements of various renewable sources of energy (MNES 2001, 21).

	Potential	Situation on 31.12.2000
Biogas plants	12 000 000	3 030 000
Improved chulhas	120 000 000	32 890 000
Wind	45 000 MW	1267 MW
Small hydro	15 000 MW	1341 MW
Biomass power/ Co-generation	19 500 MW	273 MW
Biomass gasifiers		35 MW
Solar PV	20 MW/ km^2	47 MW
Waste-to-energy	1700 MWe	15.15 MWe
Solar Water Heating	140 000 000 m^2	550 000 m^2

A draft renewable energy policy by MNES sets the medium term goals for achievement by 2012. These include coverage of 30 million households with improved chulha, installation of an additional 3 million family size biogas plants, deployment of five million solar lanterns and two million solar home lighting systems, provision of electricity to 25 % of the 18 000 unelectrified villages, and deployment of solar water heating systems in one million homes. The draft includes a 10% share for renewables in the new power capacity by 2012 (MNES 2001, 20).

Hydroelectric power and wind energy are two of India's primary answers to the needed increase in electricity generation. With approximately 150 000 MW of hydropower potential, India has begun to focus on large-scale hydroelectric plants to meet its future energy needs. The government is planning to introduce subsidies to support hydro-plant development, with 12 projects already approved for completion by 2002. In 1992, India´s installed capacity of small-scale hydroelectric plants was 93 MW. By 1999, there was a combined capacity for all plants of 155 MW, with work in progress to bring that total to 230 MW (EIA 2001). In many cases local inhabitants and non-governmental organizations (NGO) have strongly resisted projects of building large-scale hydroelectric plants. The problems of environmental and social problems could hardly be avoided with large-scale systems.

Under the solar photovoltaic power programme, 21 grid interactive PV power projects of aggregate capacity of 1615 kW_e have been installed so far. Besides these, stand-alone small, PV power plants and individual systems deployed so far has reached 65 MW_e, including 18 MW_e capacity products exported. The solar photovoltaic programme has also resulted in significant technological developments and widespread field demonstration and utilisation of SPV technology for various applications. During the year up to end of 2000, as many as 40 978 solar lanterns, 20 437 solar home lighting systems and 1848 street lighting systems have been deployed. The number of SPV water-pumping systems installed on the end of year 2000 was 3575 and a total of 670 windmills have been installed so far. Most of the systems installed during the year were of 1,8 kW array capacity and owned by individual farmers (MNES 2001, 4-9).

With a rapidly increasing population, the demand for electricity generation and vehicular usage also is going to rise. Electricity is the key to economic development and India's current shortages of electricity have hampered industrial growth. Government initiatives aim to reduce the incentive to firms to provide this electricity using older, more inefficient coal-fired plants, as well as reduce the subsidies on low-quality coal. For example, fiscal incentives, in the form of customs waivers and soft loans, encourage the installation of pollution abatement equipment. Market mechanisms such as user charges, deposit refund systems, marketable permits and taxes for implementing pollution measures also are being contemplated (EIA 2001).

3.4 Traditional energy

The term "traditional fuels" is used to refer to biomass fuels used mainly for domestic energy, including wood, charcoal, agricultural residues and animal waste. "Fuelwood" refers to wood that is used directly for fuel whereas the term, "wood fuels" covers fuelwood and charcoal. Traditional fuels are the dominant source of energy in the developing world. It is estimated that they account for about 20-35% of the total energy consumption in the developing countries (Table **5**). In many countries - Burkina Faso, Ethiopia, Malawi, Tanzania and Uganda, to mention the proportion can be as high as over 90% (TERI 2001c).

Table 5. Traditional fuel consumption in the world, 1973 to 1993 (WRI 1996).

Region	Traditional energy as % of total consumption		Percentage change since 1973
	1993	1973	
World	6	6	47
Africa	35	43	76
Europe	1	1	-14
North and Central America	2	1	106
South America	21	30	26
Asia	9	15	47
Oceania	4	6	16
China	6	11	54
India	23	41	58

India is the second largest consumer of biofuels in Asia and uses the most animal waste (in absolute terms). The consumption of biofuels – fuelwood, crop residue and animal waste, were estimated to be 4385, 1493 and 1376 PJ, respectively (Streets & Waldhoff 1999). Identifying district average biofuel use based on respective agro-climatic mean values for the Integrated Rural Energy Planning (IREP) estimates (Table 6).

There is some variation in biofuel consumption in different climatic districts. Fuelwood consumption is high in states that have considerable forest cover. Consumption of dung cakes is high in states like Uttar Pradesh (4.95 kg per household per day) and Rajasthan (3.41 kg per household per day) that have little biomass cover (TERI 2002, 287).

Around 40 % of the energy needs of Indian households continue to be met by traditional energy forms. In urban centres, it is estimated that one in three households uses traditional fuels. Traditional fuels use is most prevalent among the lower income categories. Particularly in higher income classes, there is a decline in consumption of biofuels which is accompanied by growth in consumption of LPG, kerosene, and electricity by about 9%, 3%, and 11 % a year, respectively (TERI 2002, 287).

Traditional fuels constitute the primary source of energy for cooking in over 90% of rural households across income classes. These fuels are also used for water heating and space heating. Draught animal power continues to be used in farming and for transportation in villages and in small towns. Traditional fuels are often classified as ‘non-commercial’ sources because they are mostly gathered or collected from the neighbourhood. While this is true in rural areas, urban poor who use these fuels pay heavily for fuelwood and the price varies significantly across regions, being particularly high in large cities (TERI 2001b, 287-9).

Table 6. Regional consumption of biofuels in India in 1990 (Streets & Waldhoff 1999).

Biofuel energy consumption									
Region	Pop. (million)	Fuelwood		Crop residue		Animal waste		Total	
		Kgce*/cap	Total PJ	kgce/cap	Total PJ	kgce/cap	Total PJ	kgce/cap	Total PJ
Andhra Pradesh	66.8	209.1	409.3	143.6	280.9	62.5	122.2	415.2	812.5
West Bengal-Sikkim	59.2	199.2	345.7	89.2	154.9	66.1	114.7	354.5	615.2
Bihar	86.9	222.4	566.4	44.4	113.0	40.9	104.2	307.7	783.7
Bombay	8.8	6.2	1.6	5.0	1.3	2.1	0.5	13.3	3.4
Calcutta	9.3	14.9	4.0	5.0	1.3	4.8	1.3	24.6	6.7
Delhi	9.4	16.0	4.4	8.6	2.4	13.9	3.8	38.5	10.6
Eastern Himalayas	32.0	328.9	308.7	57.2	53.7	27.1	25.4	413.2	387.8
Gujarat	41.5	132.5	161.3	38.3	46.7	24.5	29.9	195.3	237.8
Haryana	16.4	65.8	31.6	46.8	22.5	69.5	33.4	182.1	87.5
Kamataka-Goa	46.3	146.6	199.0	89.3	121.2	24.8	33.6	260.7	353.8
Kerala	29.2	155.2	132.9	17.6	15.1	18.0	15.4	190.9	163.5
Madras	4.3	9.9	1.3	5.0	0.6	3.2	0.4	18.2	2.3
Maharashtra	70.6	174.8	361.6	56.3	116.6	18.1	37.5	249.2	515.6
Madhya Pradesh	66.5	287.9	561.2	43.6	85.0	40.8	79.5	372.2	725.7
Orissa	31.7	456.5	423.9	118.7	110.2	58.9	54.7	634.0	588.8
Punjab- Chandigarh	20.9	61.0	37.3	44.8	27.5	63.2	38.7	169,0	103.5
Rajasthan	44.2	133.5	172.9	32.2	41.7	77.2	100.0	243.0	314.6
Tamil Nadu	52.5	207.1	318.7	137.4	211.3	62.8	96.7	407.3	626.7
Uttar Pradesh	139.7	74.0	303.3	20.2	82.7	116.1	475.4	210.3	861.3
Western Himal.	12.9	105.0	39.7	11.6	4.4	23.6	8.9	140.2	53.1
Whole country	949.2	176.2	4384.8	60.0	1493.0	55.3	1376.3	291.5	7254.1

*Quantities of biofuel consumed per capita (cap) are expressed in units of kilograms of coal equivalent (kgce). 1 kgce=29.308X10^6 J.

4 RURAL ENERGY SECTOR

The rural population of India, which currently constitutes 70% of the total population, is expected to exceed 900 million by 2010 if it follows the current rate of growth. Primarily engaged in agriculture, the rural population depends heavily on biomass for their energy needs. Every addition to the population brings with it a corresponding increase in the energy consumption, thus increasing the stress on the environment (Malhotra et al. 2000, 7).

The domestic sector accounts for nearly 75% of the energy consumption. Within this sector, cooking is the largest energy consuming end use accounting for almost 90% of household energy, followed by lighting and heating (Malhotra et al. 2000, 7). Biomass fuels provide 85-90% of the domestic energy and 75% of all rural energy (Natarajan 1985).

Other sectors that consume significant quantities of biomass energy in the rural areas are small industries and commercial establishments (hotels, restaurants, shops, etc.). However, reliable statistics on the extent of consumption is not available. Available evidence suggests a high level of fuelwood consumption. One estimate puts the annual fuelwood consumption in these sectors at 10 million tonnes (TERI 1996a).

Land preparation, harvesting, and irrigation activities consume most of the energy used in agriculture. Fertilizer (nitrogen, phosphorus and potassium (NPK)) consumption has increased from 0.5 Mt in 1963/64 to 18.1 Mt in 1999/2000, but is still one of the lowest per ha (75 kg/ha) in the world. The consumption of pesticides decreased from 75 000 tonnes in 1990/91 to 49 160 tonnes in 1998/99. Although farm mechanization has increased with time, the increase in yield levels does not reflect the proper use of energy (TERI 2002, 198-200).

Dependence of traditional fuels has several ecological and social consequences: the danger of excessive pressure on forest resources, contribution to greenhouse gas emissions by burning of biomass in inefficient traditional cookstoves; reduction in soil nutrient level when agricultural residues and animal dung are used as energy sources instead of fertilizers and the health impacts of carrying large head-loads of wood over long distances and the burning of biomass in inefficient and poorly vented appliances (TERI 2002, 288).

4.1 Domestic sector

TERI (2000b) reports that in rural India, 90% of the primary energy use is biomass, of which wood account for 56%, crop residues for 16%, and dung cakes 21%. The rest of energy use divide between biogas (1.6%), kerosene (1.3%), LPG (1.3%) and coal (1.4%) (Figure 8).

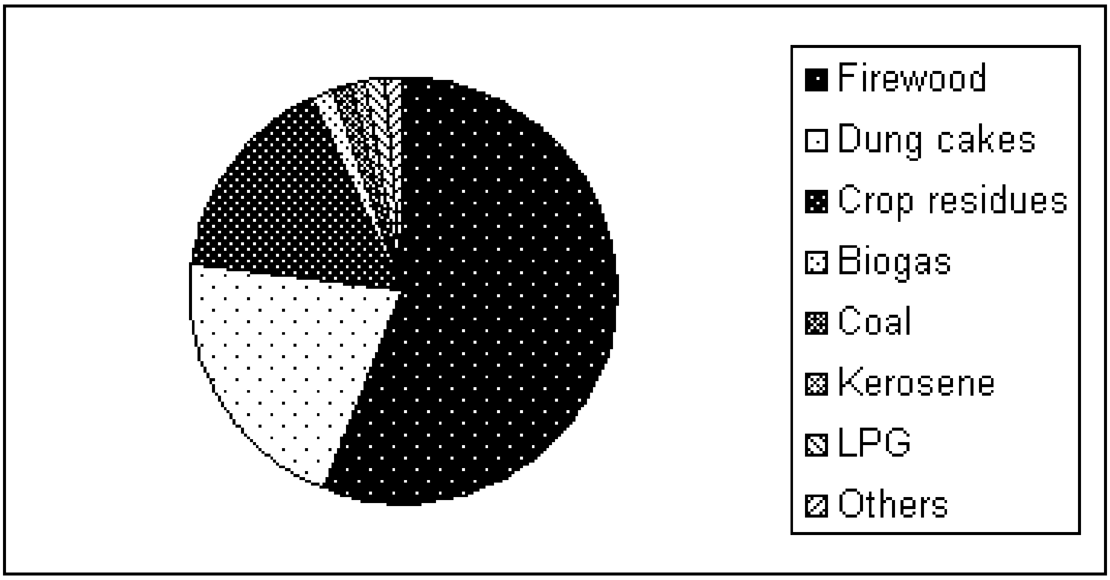


Figure 8. Energy use in the rural domestic sector in India (TERI 2002).

In the rural areas, the shift to commercial fuels has been marginal. For instance, only one per cent of the households in the rural areas have moved from firewood and chips as a source of cooking since 1987/88. While the dependence of rural households on dung cake, coke, and coal has fallen and that on kerosene and gas has risen, the percentage of households (77-79%) dependent on firewood and chips has remained constant (GoI 1997b).

The rural electrification program, which is the largest rural energy program, claims to have electrified more than 85% of the 580 000 villages in the country. But, only 37% of the rural households have electricity connections compared to 83% of urban households (GoI 1997b). On the other hand, during 1983/84 to 1993/94, the use of electricity for lighting has risen by 22% in rural areas as against an increase of 19% in urban areas (GoI 1997b).

The disparity that exists in the energy use between the rural and urban households is quite big. The rural urban disparity exists in the type of fuels and cooking devices used and in the quantity of energy use (TERI 2002, 290). As against 27% of the urban households, only 1.3% of the rural households use LPG for cooking (CMIE 1996a). A similar disparity exists in the case of kerosene, which is promoted predominantly as a subsidized fuel for the poor. According to 1991 census, while 24% urban households use kerosene as a cooking fuel, only 1.3% rural households use kerosene for cooking (CMIE 1996b). While the monthly per capita consumption of firewood and chips has increased in rural areas, it has declined in urban areas between 1987/88 and 1993/94 (Malhotra et al. 2000).

Petroleum products like LPG and kerosene form less than two per cent of the total energy consumption in the rural areas. Hence the large imports of petroleum products only marginally benefit the rural population that constitutes nearly 70% of the population in the country (Figure 9) (TERI 2002, 289).

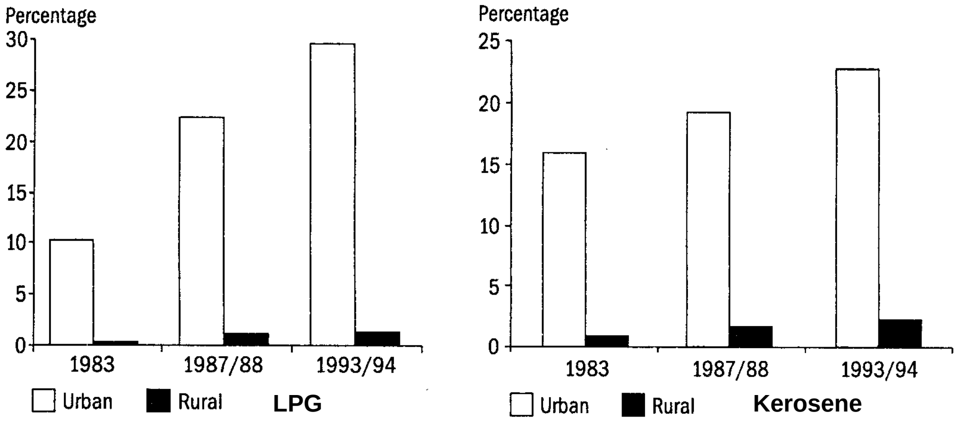


Figure 9. Households using LPG and kerosene for cooking (NSSO 1997).

Kerosene is mainly used for lighting. Around 62 % of the rural households use kerosene primarily for lighting. Less than two per cent of the rural households in India used kerosene as the primary cooking fuel. The total kerosene consumption in India during 2000/01 estimated at around 10.5 million tonnes out of which about 60% was for the rural areas (TERI 2002, 293).

Since 1985, the consumption of LPG has grown from over 100 million tonnes in 1985 to over 6000 million tonnes in 1999. The number of LPG customers served was in 2000 43.6 million. However, the rural penetration during this period is just over one per cent of the total households (MoPNG 2000). Large portion of the over 100% increase in the estimated consumption is going to be in the rural areas. This is due to the fact that with the increasing non-availability of traditional fuels, and LPG being a convenient and safe cooking fuel, the government of India has decided to commence marketing of LPG in the rural areas. People are not shifting to LPG as fuelwood is cheap and easily available and there is fear that LPG is a dangerous fuel (TERI 2002, 292-293).

Biomass use continues to increase. The monthly per capita consumption of firewood increased from 16 to 17 kg over the period 1987/88 to 1993/94. As Figure 10 shows, the use of firewood in the form of logs has tripled in 15 years (Natarajan 1997). The energy consumption in households in rural areas is determined by the availability of biomass resources, peoples´ access to these resources, their competing uses, and availability of commercial energy sources (Figure 11) (Malhotra et al. 2000).

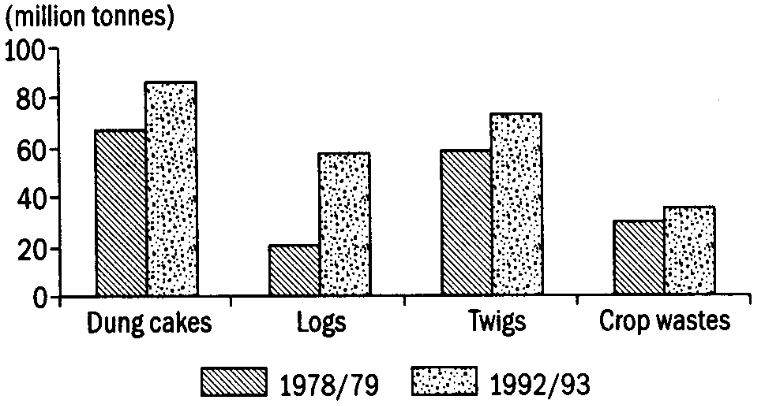


Figure 10. Biofuel consumption in rural households (Natarajan 1997).

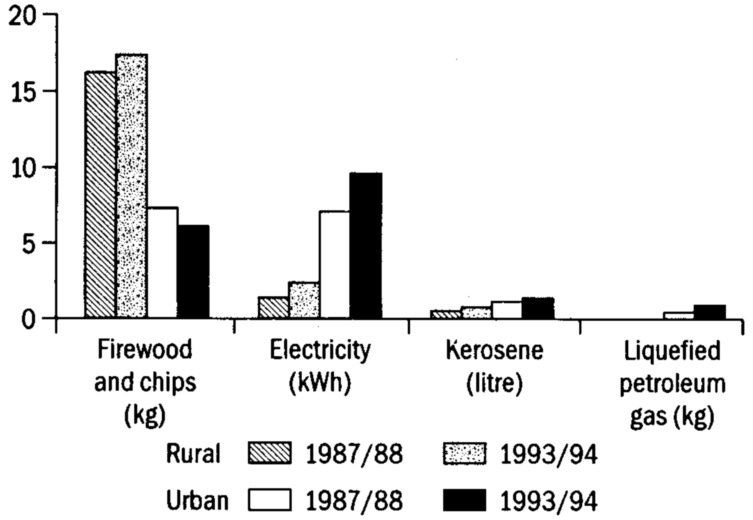


Figure 11. Monthly per capita commercial energy consumption (NSSO 1998).

The demand projections indicate that in 1997 the rural domestic sector alone will have a requirement of 270 Mt of fuelwood while the demand for dung and crop residues will be in the order of 117 Mt and 108 Mt, respectively (TERI 1993). Other factors that do not strictly fall within the energy system, but play a crucial role in determining people's choices regarding fuels, include income levels, purchasing power, and accessibility to urban centres (Malhotra et al. 2000). On the other hand, the supply figures available from different sources show that there is considerable mismatch between the availability and consumption. This is particularly through in the case of fuelwood, whose annual availability from the forests and private lands is put at 58 Mt, just one-third of the most conservative estimate of consumption (TERI 1994a). The production of crop residues (non-fodder) is estimated at 66 Mt. The dung available in the country for fuel purposes is around 100 Mt (Ramana & Joshi 1994).

Most households in the higher monthly per capita expenditure (MPCE) class level use less of firewood and chips as their primary energy source for cooking. However, the percentage of households in all MPCE levels in the rural areas using dung cakes, as the primary source of energy for cooking, remains constant as domestic cattle is maintained by these households (Gol 1997b). In 1978 one-third of the households was purchasing firewood logs, while in 1992 just about one-sixth was doing so (Figure 12) (Agarwal 1995).

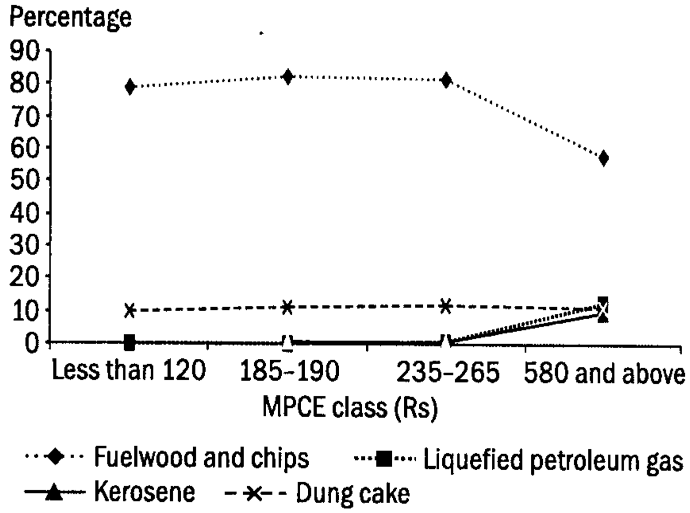


Figure 12. Rural households using primary fuel for cooking across income classes (NSSO 1997).

Among rural households the use of fuelwood and chips declines and the use of kerosene and LPG increases with increase in incomes. However, the transition across income classes is not significant, with the result that even in the highest income category, over 70% of rural households are depended on fuelwood or dung cake for cooking (TERI 2002, 292).

Of the total requirement of 200 Mt, 102 Mt is expected to be met from forest areas and 98 Mt from farm forestry. It is estimated that about 18 Mt is available as fuelwood annually on a sustainable basis from the forests. This means that the remaining requirement of 84 Mt is to be met by excessive removal from forest areas, putting severe stress on Indian forest resources (GoI 1997a).

The over-dependence on traditional fuels in rural energy sector has led to several ecological and health problems. Loss of green cover and burning of biomass in traditional cookstoves significantly contribute to greenhouse gas emissions. In India, it is estimated that of the 68.3 Mt of carbon released annually due to biomass burning, of which fuelwood accounts for 82.3% (TERI 1996, Kaul 1993).

4.2 Agriculture sector

Agriculture is the largest sector of the Indian economy employing 68% of the total workforce. The contribution of agriculture and allied sectors to the total GDP has declined from 59% in 1950/51 to 27% in 1999/2000. The average annual growth rate of agriculture and allied sectors was 3.9% during 1980-91 and 3.6% during the post-reform period of 1992-2000 (TERI 2002, 197).

In the last 10 years, the net area sown has remained constant at around 142 Mha. The area under food grains accounts for 65% of the total gross cropped area and that under oilseed and other commercial crops 13% and 8%, respectively. Nearly two-thirds of the area under food grain crops is under rice and wheat. India has reached a plateau as far as the area under agriculture is concerned (TERI 2002, 198).

In the agriculture sector, animate energy (human and draught power) accounts for more than one-third of the total energy consumed. The share of electricity in the farm sector was 28.7% in 1992/93; in 1950/51, this had been 3.9% (TERI 1998a). This sharp rise can be attributed to the increase in the number of electric pump sets, used for irrigation, from 1.6 million to a whopping 10.3 million between 1970/71 and 1993/94. Diesel, used in pump sets and tractors that assist in tilling and harvesting, is the other major inanimate energy input. From 1970/71 to 1993/94, the number of diesel pump sets more than tripled from 1.5 to 4.9 million. Diesel consumption by agriculture is 10% of the total diesel consumption (TERI 1998a). Energy consumption in the agriculture sector is given in Figure 13.

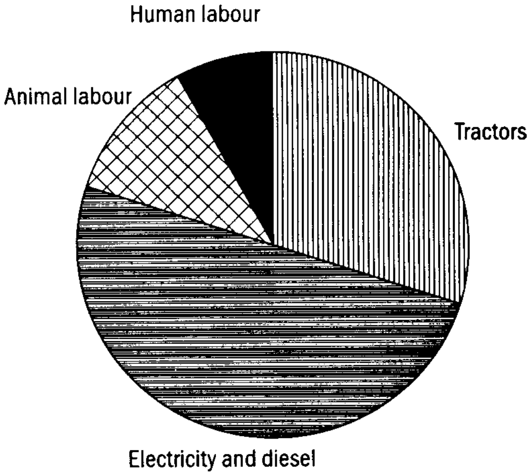


Figure 13. Energy consumption in agriculture sector, 1995/96 (TERI 1998a).

Three activities, namely land preparation, harvesting and irrigation, consume most of the energy used in agriculture. While harvesting and land preparation consume most of the diesel, electricity is largely used for irrigation purposes. Enhanced use of high-yielding seeds, synthetic fertilizers, irrigation, agro-chemicals, and agricultural machines have rendered modern agriculture highly energy-intensive. Consequently, the quantities of diesel and electricity used have increased over time, but their relative shares in total energy consumption have remained constant. The share of human labour and animal power in the total energy consumption for agriculture has decreased from 93% in 1950/51 to 20% in 1995/96, indicating progress in farm mechanization (Figure 14) (TERI 2002, 199).

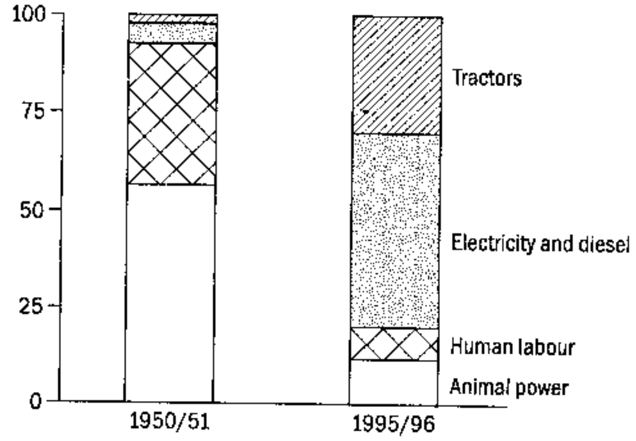


Figure 14. Changes in relative share of different sources of energy in agriculture over time (TERI 2002, 199).

Food production increased from 50 million tonnes in 1950 to 191 million tonnes in 1994, though the area under cultivation remained more of less constant. This meant that more was produced from each ha, which, in turn, required greater quantities of fertilizers, water, and pesticides. In several regions the crops remove more nutrients than are added, which makes the soil progressively poorer (TERI 1998a).

The amount of India's land area dedicated to food grain cropping has grown steadily, from 99.3 Mha in 1950, to 127.5 Mha in 1991 (Ministry of Agriculture 1995). In the last 10 years, the net area sown has remained constant at around 142 Mha. The area under foodgrains accounts for 65% of the total gross cropped area and that under oilseed and other commercial crops 13% and 8%, respectively. Nearly two-thirds of the area under foodgrain crops is under rice and wheat (TERI 2002, 198)

However, in the face of limited land availability and growing land degradation problems, meeting the food requirements of an ever-increasing population will necessitate the consumption of fertilizer for crop production to increase to 22 Mt in 2000 (Ministry of Agriculture 1995). Between 1970 and 2000, Indian consumption of nitrogen, phosphorus, and potassium fertilizer has grown at 9.5 percent annually, making India the third largest consumer in the world. The consumption of NPK has increased from 0.5 MT in 1963/64 to 18.1 MT in 1999/2000 and is now 75 kg/ha, which is one of the lowest in the world (TERI 2002, 199).

The use of agricultural residues and animal dung as energy sources instead of fertilizers reduces the soil nutrient level. It has been estimated that out of the total nitrogen content of dung production of 1.35 Mt annually, 0.4 Mt is lost annually through the burning of dung as fuel (Ravindranath and Hall 1995). The trends of the past two decades indicate that bovine (cattle and buffalo) population in India has reached a stagnant position, which suggests that the total dung production from bovines has stabilized in the range of 240-260 Mt (dry weight) per annum (TERI 1991).

India has increased its consumption of pesticides from 8620 tonnes in 1960/61 to 75 000 tonnes in 1990/91. The largest percentage of this figure is made up by insecticides, which comprise about two thirds of the total. It is believed that there is some potential for future gains in pesticide efficacy, as a portion of rural farmers are suspected to practice inappropriate application of the chemicals due to improper information, etc. (Ministry of Agriculture 1995). Although the consumption of pesticides per hectar in India (300 g) is lower than that of for example the US (1 kg) and Japan (10-12 kg), several pesticide-induced pest outbreaks have been reported from various parts of the country (TERI 2002, 198).

The area of agricultural land under irrigation has continued its growth, from 22.6 Mha in 1950/51 to 94.7 Mha in 1999/2000. Out of 94.7 Mha, 35.3 Mha is accounted for by major and medium irrigation projects and 59.4 Mha by minor irrigation projects. The land under irrigation continues to increase and the ultimate irrigation potential has been reassessed to be 139.9 Mha (TERI 2002, 198-200). The majority of this increase has come from increases in water extracted from groundwater supplies. This is significant because in many ways, groundwater supplies can be considered a non-renewable resource. Finally, the demand for water for irrigation is expected to increase markedly over the next few decades, in line with population growth. Estimates for 1990 place the demand for irrigation water at 46 million hectare meters, and project a growth to over 85 million hecrate meters by 2025 (Shah 1987).

5 BIOMASS COMBUSTION IN COOKSTOVES

5.1 Overview

Biomass energy accounts for about 15% of the world's primary energy consumption and about 38% of the primary energy consumption in developing countries. Furthermore, biomass often accounts for more than 90% of the total rural energy supplies in developing countries. The combustion of biomass causes emission of a number of greenhouse and other gases and substances. If no significant changes occur in end-use biomass energy technologies, emission would be expected to be proportional to the total biomass energy use in the future (Bhattacharya et al. 2000). Indian and international air quality standards in Table 7.

Table 7. Air quality standards in India (consentration in ambient air (µg/m^3)) (CPCB 1994, WHO 1999, Ilmatieteen laitos 2003).

	India			WHO	EU/ Finland
Pollutant and Time-weighted average	Industrial Area	Residential, rural, and other areas	Sensitive area		
SO_2					
1 year	80	60	15	50	20
24 hours	120	80	30	125	125
1 h					350
10 minutes				500	
NOx					
1 year	80	60	15		30
24 hours	120	80	30		
NO_2					
1 year				40	40
24 hours				200	
1 hour					200
SPM					
1 year	360	140	70		
24 hours	500	200	100		
RPM (PM10)					
1 year	120	60	50		40
24 hours	150	100	75		50
CO (mg/m^3)					
8 hours	5	2	1	10	10
1 hour	10	4	2	30	

The burning of biomass in inefficient and poorly vented appliances is a serious health hazard for women and children (Smith 1993). In a study conducted by TERI in the Garhwal Himalaya, the measured mean daily exposure of women (due to cooking) to TSP (total suspended particulate) was found to be as high as 17 mg h/m^3 (Saksena et al. 1992). In the Delhi slums, which represent similar indoor environment in terms of the device and the fuel used, it was found that the exposure of infants (0-12 months) to RSP (respirable suspended particulate) was 5 to 77 times more than the WHO standards for PM_{10} (particulate matter less than 10 ppm) (TERI 1996).

5.2 Emissions from biomass combustion in cookstoves

When combustion of biomass fuels is complete, the only products released are carbon dioxide (CO_2) and water (H_2O) (however some nitrous oxides (NO_X) and sulphur oxide (SO_2) could be released, even if combustion is complete), which are not harmful for health, whereas incomplete combustion releases health-damaging pollutants, like particles, carbon monoxide, sulphur oxides, formaldehyde, and polycyclic organic matter, including carcinogens such as benzo(a)pyrene (De Koning et al. 1985) and GHGs such as CO_2, N_2O, methane (CH_4) and NMVOC (Smith et al. 2000b).

As pointed out by Smith et al. (2000b), the products of incomplete combustion (PICS) have three major adverse effects - energy loss, impact on human health and impact on the environment; they estimated that the use of biomass fuels contributes 1-5% of all CH_4 emissions, 6-14% of all CO emissions, 8-24% of all total non-methane organic compounds (TNMOC) emissions and thus 1-3% of all human induced global warming (Smith et al. 2000b).

Bhattacharya et al. (2000) estimated total emissions of biomass use in some Asian countries. Among these countries considered, China accounts for a major share of the emissions from biomass energy use, followed by India. Table 8 shows the emissions from biomass and fossil fuel combustion in some Asian countries.

Table 8. Emissions from biomass and fossil fuel combustion (kt) in some Asian countries (Bhattacharya et al. 2000).

Country	Base year	Emission from biomass combustion						CO_2 emitted from fossil fuel (EIA 2001)	% of CO_2 emitted from biomass[a]
		CO_2	CO	CH_4	TSP	SO_x	NO_x		
China	1993	568332	31013	2376	3895	1111	1066	2660600	17.6
India	1991	324315	9941	1797	2794	863	802	637820	33.7
Nepal	1993	17729	894	109	219	24	21	1210	93.6
Pakistan	1991	66909	2761	364	725	162	115	64210	51.0
Philippines	1995	29562	1406	132	350	44	36	50160	37.1
Sri Lanka	1993	12817	740	89	103	9	16	5290	70.8
Vietnam	1991	40253	1890	230	314	32	51	16670	70.7

[a] % of CO_2 emitted from biomass to total CO_2 emitted from biomass and fossil fuels.

Narang et al. (1999) estimated the quantities of biomass used for energy in India by end use technologies in 1991 as shown in Table 9. Use of fuelwood, agricultural residues, animal wastes and charcoal for energy amount to 1804, 1015, 1186 and 72 PJ, respectively (Narang et al. 1999). Table 9 shows also the total emission of the selected gases/pollutants generated from biomass use estimated by Bhattacharya et al. (2000). According to the study about 324 Mt of carbon dioxide, 10 Mt of carbon monoxide, 1.8 Mt of methane, 2.8 Mt of total suspended particles, 0.9 Mt of sulphur oxides, and 0.8 Mt of nitrogen oxides are released in the atmosphere annually from biomass use in India.

Table 9. Emission generated from biomass use in India in 1991 (Bhattacharya et al. 2000).

Type of fuel	Application	Quantity used (kt)	Emission (kt)					
		(Narang et al. 1999)	CO_2	CO	CH_4	TSP	SO_X	NO_X
Fuel wood	Dom. heating	0	0	0	0	0	0	0
	Dom. TCS	119500	139012	4650	913	532	72	84
	Dom. ICS	5000	5753	209	53	12	3	6
	Commercial	3500	4071	136	27	16	2	2
	Ind. (heating)	8250	11780	35	55	49	5	33
	Ind. (boiler)	1750	2431	40	18	20	1	6
	Sub total	138000	163047	5070	1066	629	83	131
Agri-residues	Dom.TCS	36860	43282	860	97	88	116	45
	Dom. ICS	1540	1633	148	4	14	5	5
	Commercial	10000	11742	233	26	24	31	12
	Ind. (rice husk)	0	0	0	0	0	0	0
	Ind. (bagasse)	35670	27397	48	86	1034	136	35
	Sub total	84070	84054	1290	214	1161	288	97
Animal waste	Dom. TCS	-	78900	62104	3340	474	982	473
	Dom. ICS	3100	2481	109	17	17	19	16
	Biogas use	14600	6950	0	0.2	0	0	0
	Sub total	96600	71535	3448	491	1000	492	569
Charcoal	Domestic	950	2296	54	11	2	0.3	2
	Commercial	1400	3383	80	15	3	0.5	3
	Industrial	0	0	0	0	0	0	0
	Sub total	2350	5679	133	26	5	1	5
	Total	-	324315	9941	1797	2794	863	802

TCS: traditional cookstoves, ICS: improved cookstoves

A traditional mudstove is the most common cookstove in rural India (Figure 15) (Smith et al. 2000b). 3-stone, which is usual in other developing countries is mostly used by nomads and street dwellers in India. There has been a national programme on improved chulhas (cookstoves) and nearly 33 million improved cookstoves have been launched through the program. The potential is estimated to be 120 million (MNES 2000, 13).

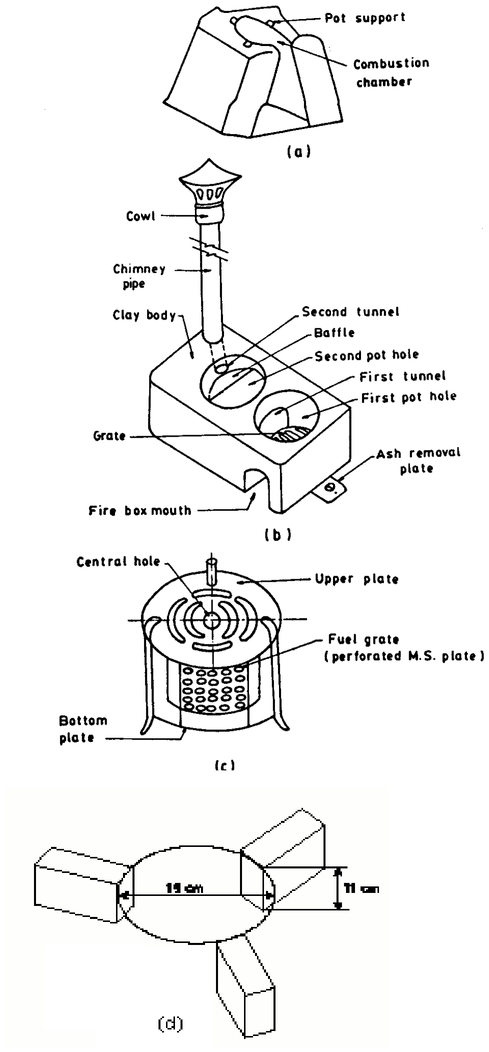


Figure 15. Some biomass cookstoves: (a) traditional cookstove, (b) improved mud cookstove and (c) portable metal cookstove d) 3-stone (Kandpal and Maheshwari 1995, Smith et al. 2000b).

5.2.1 Total suspended particles from biomass combustion

The national air quality standards from the Central Pollution Control Board, (CPCB) India on respirable particulate matter for 24-hours in rural residential areas is 100 µg/m^3.

Raiyani et al. (1993) discussed the indoor concentration of total suspended particles (TSP) during cooking hours across the houses belonging to a low socio-economic group in eastern Ahmedabad, India. He concludes that houses using wood, cattle dung and char coal emit large amounts of TSP. Particulate matter inside houses using LPG and kerosene are due to the outside environment rather than indoor sources. The study also revealed that 50-80% of TSP emissions from biomass cooking stoves were in a respirable fraction of < 2 µm size with the dominancy of 1.1-0.65 µm fraction in the smoke of biomass fuels. It is also considerable that in a respirable fraction, cattledung emits the largest amount of particles, and that coal emits distinctly larger amount than wood (Figure 16) (Raiyani et al 1993).

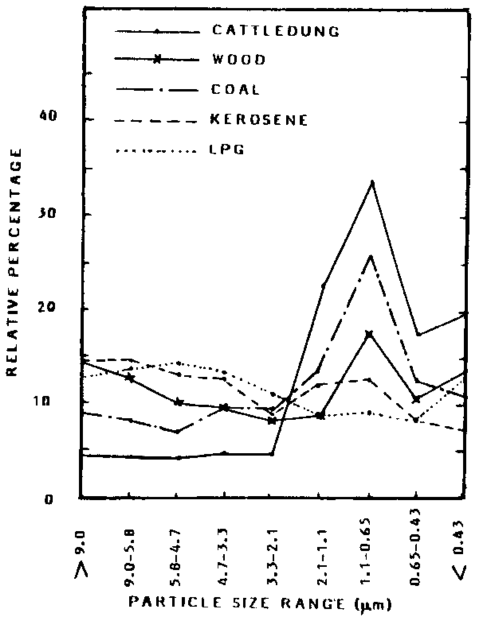


Figure 16. Relative percentage of particles of different sizes in total suspended particulates (TSP) in the houses using different types of cooking fuels (Rayiani et al.1993).

Ramakrishna et al. (1990) tried to establish quantitative estimates of several environmental and cultural characteristics like stove type, kitchen location, and fuel on the TSP exposures. Though the variable location of kitchen was found to be a statistically significant variable, the difference between exposure level using traditional and improved stoves did not prove to be significant. In addition to the factors mentioned above there are several others, which have been identified to explain the large and significant difference in concentration of Respirable Particulate Matter (RPM) between living area and kitchen while cooking activity is going on - ventilation, chimney type, kitchen volume, outdoor concentrations and so on (Smith 1987).

Saksena et al. (1992) measured daily integrated exposure to TSP by personal and stationary sampling of air in six microenvironments in rural and hilly region in the Garhwal Himalaya and comparing the time budget survey (Figure 17) and the daily exposure (Table 10) of various groups of the population.

Table 10. Mean daily exposure to TSP (mg h/m3) (Saksena et al. 1992).

	Adult women	Children	Youths	Adult men
Winter	47	25	19	17
Summer	27	13	7.7	5.8

Saksena et al. (1992) found in the study that adult women got biggest daily exposure in kitchen while cooking and that it is the most important anthropogenic source of TSP (Figure 18). They also found that the daily exposure to TSP proved that adult women (over 19 years) and children (0 - 5 years) are at the highest risk.

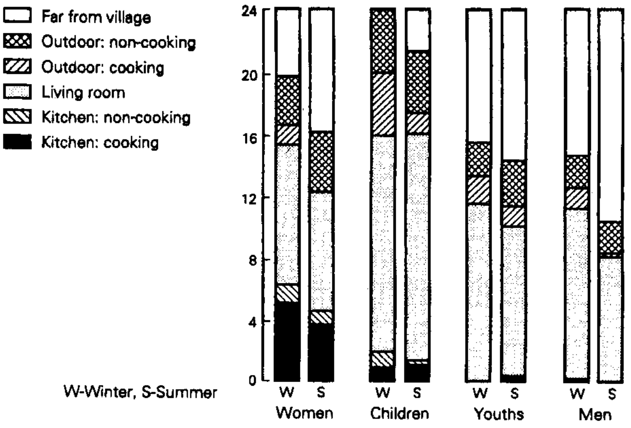


Figure 17. Mean time spent in a day in the six microenvironments (h) (Saksena et al. 1992).

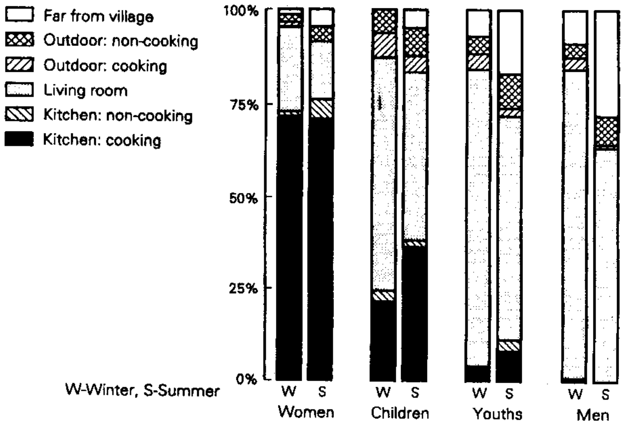


Figure 18. Mean percentage contribution of different microenvironment to the daily exposure to TSP (%) (Saksena et al. 1992).

Parikh et al. (2001) examined the links between indoor pollution and the types of kitchen and fuels. They found that the values of PM_{10} from burning biofuels ranged 500-2000 $\mu g/m^3$ during a two-hour cooking period. The range depended on the type of kitchen and the fuel used. Secondly, the exposure was not limited to the cooks alone. The rest of the family, like senior citizens, children and adult males, in the vicinity are also exposed through a passive cooking effect. Respirable particulate matter (RPM) was the highest during cooking time. Personal exposures RPM while cooking ranged from around 70 $\mu g/m^3$ for houses using clean fuel to around 2000 $\mu g/m^3$ in houses using biofuels. The average RPM in the ambient air was 78.2 $\mu g/m^3$. It was also found in the study that the concentration of RPM at various locations during cooking with biofuels depended on the type of kitchen. Agricultural waste (Tamil Nadu does not appear to have the practice of cooking with animal dung) resulted in the highest personal exposure (Parikh et al. 2001).

The mean exposure to the chief cook when cooking is done inside the house without a partition using traditional stoves comes to 1312 µg/m^3. If the cooking is done with traditional stoves in the open air or with efficient stoves in separate kitchen inside house the exposures are reduced by 1.5 times. The mean concentrations are high (1187 µg/m^3) when cooking is done inside the house without a partition using traditional stoves. The people who are in the vicinity are also vulnerable. 24-hour exposures of individuals based on a time activity pattern, which were in the range of 201±48 µg/m^3 for cooks using biofuels and 53±15 µg/m^3 for cleaner fuel users (Table 11). Biogas was not included in this study but according to emission measurements by Smith et al. (2000b) TSP emissions of biogas clearly smaller than biofuels and even kerosene and LPG. The study also indicate that the exposure to biofuels is more a problem of the poor to middle class income group rather than the extreme poor because the extreme poor generally cook in the open air, cook fewer meals and eat fewer number of dishes (Parikh et al 2001).

Table 11. Mean personal exposures of TSP of cooks at different kitchen locations and fuel types (µg/m3) (Parikh et al. 2001).

	Biofuels			Fossil fuels	
	Firewood	Woodchips	Ag. waste	Kerosene	LPG
Personal exposure µg/m^3					
Indoor kitchen with no partition	1498	1201	2048	76	101
Separate kitchen inside the house	1506	1702	1354	143	80
Separate kitchen outside the house	1341	511	804		
Outdoor cooking	894	824	744	468	

Aggregate levels of individual polycyclic aromatic hydrocarbons (PAHs) in TSP were found in the range of 107-359 and 49-409 ng/m^3, respectively, in the houses using cattle dung and wood; comparatively much lower in the houses using coal (7-31 ng/m^3), kerosene (12-59 ng/m^3) and LPG (6-32 ng/m^3) and mean levels of benzo(a)pyrene in these respective houses were 289, 409, 24, 59 and 17 ng/m^3. Compared to the houses using LPG, the levels of PAHs in the houses using cattle dung, wood, coal and kerosene were higher by factors of 16-40, 10-25, 2-4 and 1-4, respectively (Raiyani et al. 1992).

PAH contents in TSP were the highest in wood smoke followed by cattle dung, kerosene, coal smoke, and were the lowest in the TSP collected from the LPG-using houses. The lower PAH content in smoke particulates of cattle dung as compared to those of wood may be due to cattle dung burning at a lower temperature compared to wood (Prakash and Murray 1972), and due to this there may be a high generation of carbon soot particles during combustion of cattle dung, which would be a factor for a low PAH/TSP ratio (Raiyani et al. 1992).

Study by Kandpal et al. (1994) showed that concentration of HCHO in the indoor environment was 145 µg/m^3 for fuelwood, 98-142 µg/m^3 for dung-cake and 126-164 µg/m^3 for agriresidues after one hour of biomass combustion.

5.2.2 Greenhouse gas emissions from biomass combustion

The products of biomass combustion play significant roles in global atmospheric chemistry and thus in the potential for global warming from an enhanced greenhouse gas effect (Seiler and Crutzen 1980). As shown in Table 12, for example, three reviews estimate the contributions of biomass combustion to global anthropogenic emissions to be as high as one-half for some of the major greenhouse gases (Smith et al 1993).

Table 12. Estimates of global greenhouse gas emissions from biomass burning (Tg/a) (Andreae 1991).

	Biomass	Total	% Biomass[1]	% Biomass[2]	% Biomass[3]
CO_2	3500	8700	40	25-45	
CO	350	1100	32	15-50	
CH_4	38	380	10[4]	3-10	8
N_2O	0.1-0.3	12-14	--	0.8-2	0.4-2
TNMOC*	24	100	24		
CH_3Cl	0.5	2.3	22		

*Total non-methane organic compounds (including, but not limited to NMHC)

[1] Levine, 1990.

[2] Crutzen and Andreae 1990.

[3] IPCC 1990.

[4] Cicerone and Oremland 1988.

It is estimated that biomass combustion contributes as much as 20-50 percent of global GHG emissions. Though the major fraction of the emissions is from large-scale open combustion associated with permanent deforestation, savanna fires and crop residues, combustion in small-scale devices such as cookstoves and space-heating stoves also releases a significant amount of GHGs. A more accurate estimation of emissions from biomass combustion would require better estimates of GHG emission factors from different types of biomass combustion as well as estimates of the amounts burned (Smith et al. 1998). Crutzen and Andreae (1990) estimated the contribution of biomass combustion to the global carbon cycle. Their four categories represent large-scale open combustion including outdoor fires associated with swidden agriculture, permanent deforestation, savanna fires and crop residues.

Much crop residue, however, is also burned in small-scale closed or semi-enclosed conditions inside cooking and heating stoves (perhaps 800 million people rely on such cookfuels according to Barnard 1985). As shown, Meyers and Leach (1989) estimated crop residues used in stoves to be approximately 350 million tonnes. In addition, most firewood in the developing world is burned in semi-enclosed conditions or made into charcoal for use in such conditions. Thus, the developing country biomass fuel flow (crop residues, fuelwood, and wood for charcoal) represents a significant fraction of total global carbon emissions from all biomass combustion, which is more than one-fifth and perhaps approaching one-half (based on data in Table 13).

Table 13. Total carbon released by biomass combustion.

	Tg (carbon)/Year
Open burning[1]	
Swidden agriculture	500-1000
Permanent deforestation	200-700
Savanna fires	300-1600
Crop residues	150-450
Enclosed burning in developing countries[2]	
Crop residues*	350
Firewood	540
Wood for charcoal	70
Wood in developed countries[3]	80
Total biomass	2100-4700
Total fossil fuels	5700

* Includes animal dung used as fuel,[1] Crutzen and Andreae 1990, [2] Meyers and Leach 1989, [3] Andreae 1991

Among the use of wood, crop residues and dung, traditional mud stove is most commonly used as 86.6, 94.8 and 58.8%, respectively. The relative use patterns of biomass stoves and fuels are shown in Table 14, based on national fuel use surveys. Root fuels today are found only in the northwest and do not make up a significant percentage of the national totals (Smith 2000b).

Table 14. Amount (%) of biofuels used in India in different stove designs (Smith et al. 2000b).

Stove	Wood	Crop residues	Dung	Description
Traditional mud	86.8%	94.8%	58.8%	Simple u-shaped block of mud – most common biomass stove in India
Improved metal	0.4%	0.5%	0%	Portable 3-legged circular device with no flue
Improved vented mud	2.9%	4.2%	4.7%	Most popular improved stove with flue (chimney)
Improved vented ceramic	0.3%	0.5%	0.5%	Ceramic combustion chamber with flue
3-stone	9.6%	0%	0%	Simplest stove design- often used by nomads and street dwellers
Hara	0%	0%	36%	Hollowed out mud-lined pit often used for long-term simmering of milk
Total national consumption – Mt	200.5	61.8	53.5	Early 1990s

A pilot study conducted in Manila indicated that the emission factors for CH_4, CO, and NMOC from the combustion of wood and charcoal in cookstoves are high. In the case of wood combustion, the analysis also revealed that the global warming commitment (GWC) of the non-CO_2 GHGs, CO, CH_4, and TNMOC might in some circumstances exceed that from CO_2 itself. In addition, the study seemed to indicate that in some instances substitution of biomass by fossil fuels, such as kerosene and gas, could be considered as means to lower GWC, even when the biomass fuel is harvested renewably (Smith et al. 1993).

However, in these speculations, e.g. the emissions from refineries and transportation, and fugitive emissions of fossil fuels are not taken into account. The locality and availability in crisis of biofuels should also be noticed when compared to fossil fuels. Rather than switch to fossil fuels due to their lower GHG emissions, the focus should be in development of stove designs.

Manila pilot study showed that solid biomass fuels are typically burned with substantial production of PIC. In addition, biomass stoves usually have substantially lower thermal efficiencies than those using liquid and gaseous fuel. As a result, the total CO_2 and PIC emissions per unit delivered energy are considerably greater in the biomass stoves. In general, the ranking follows what has been called the "energy ladder" from lower to higher quality fuels, i.e., emissions decrease and efficiencies increase in the following order: dung>crop residues >wood >kerosene>gas. There are variations, however, depending on specific stove designs (Smith et al. 1993).

Table 15 shows the fuels roughly ranked by average nominal combustion efficiency (NCE), which is defined as the airborne fraction of fuel carbon released as CO_2. Some individual fuel/stove combinations had NCEs of less than 80%, meaning that over one-fifth of the fuel carbon was diverted into PIC (Smith et al. 1998).

Table 15. Efficiencies and emissions for major fuels used in Indian household stoves (emissions: grams pollutant per MJ delivered energy) (Smith et al. 1998).

Fuel	Nominal Combust Efficiency %	Overall Efficiency %	Carbon Dioxide	Carbon Monoxide	Methane	Total Non-Methane Organics	Nitrous Oxide
Biogas	99.4	57.4	144	0.19	0.101	0.060	0.0017
LPG	97.7	53.6	126	0.61	0.002	0.189	0.0018
Kerosene	96.5	49.5	138	1.90	0.033	0.795	0.0008
Wood	90.1	22.8	305	11.4	1.47	3.13	0.018
Root	92.9	18.9	530	13.5	2.34	3.35	0.006
Crop Residues	85.3	14.6	565	36.1	4.13	8.99	0.028
Char fuels	84.8	14.0	710	64.0	2.37	5.60	0.018
Dung	86.6	10.1	876	38.9	7.30	21.8	0.022

Notes:
Overall efficiency = combustion efficiency x heat transfer efficiency = percentage of chemical heat in fuel that enters the pot.
Nominal combustion efficiency = a rough estimate of combustion efficiency = the fraction of airborne carbon emissions that are released as carbon dioxide.

Incomplete combustion represents lost energy and heat, increasing the amount of fuel required to cook a meal or heat a home and thereby increasing total emissions. In fact, Smith states that the results of his pilot study in Manila indicate that "...the loss of energy represented by the PIC from biomass-fired cookstoves is roughly 1 % of total human energy use and could approach 10% for some countries" (Smith et al. 1993).

Because of the inefficiency of combustion and the high GWP of the resulting products, these emissions are even more important when global warming potentials are examined. As an additional consideration, the large quantities of CO and NMVOC released will perturb the atmospheric chemistry, especially as it relates to the formation of tropospheric ozone. If biofuels cannot be phased out in the short term, then it will be important to improve the combustion efficiencies of domestic stoves and cookers, which will reduce the formation of PIC species, and to harvest biofuels sustainably (Streets & Waldhoff 1999).

From measurements made by Smith et al. (1998) it seems that CH_4 emissions from small-scale biomass combustion in India may be about 3.2 Gt. It is thought that Indian biomass stoves represent about 27% of the global total. Thus, if the distribution of stove types globally is similar to India's, it could be expected that biomass stoves produce globally about 12 Gt of CH_4 annually, which is equivalent to about 12% of the estimated global emissions from all harvesting and combustion of fossil fuels.

If GWC only from CO_2, CH_4, and N_2O is considered several of the dung and crop residue stoves have GWCs comparable to kerosene and LPG. In the case of renewably harvested fuels GWC, however, 15 of the biomass stoves are comparable to or lower than the fossil-fuel stoves (Figure 19). However, fossil fuels will have GHG releases also at the oil well, refinery, and transport stages of the fuel cycle (Smith et al. 2000a).

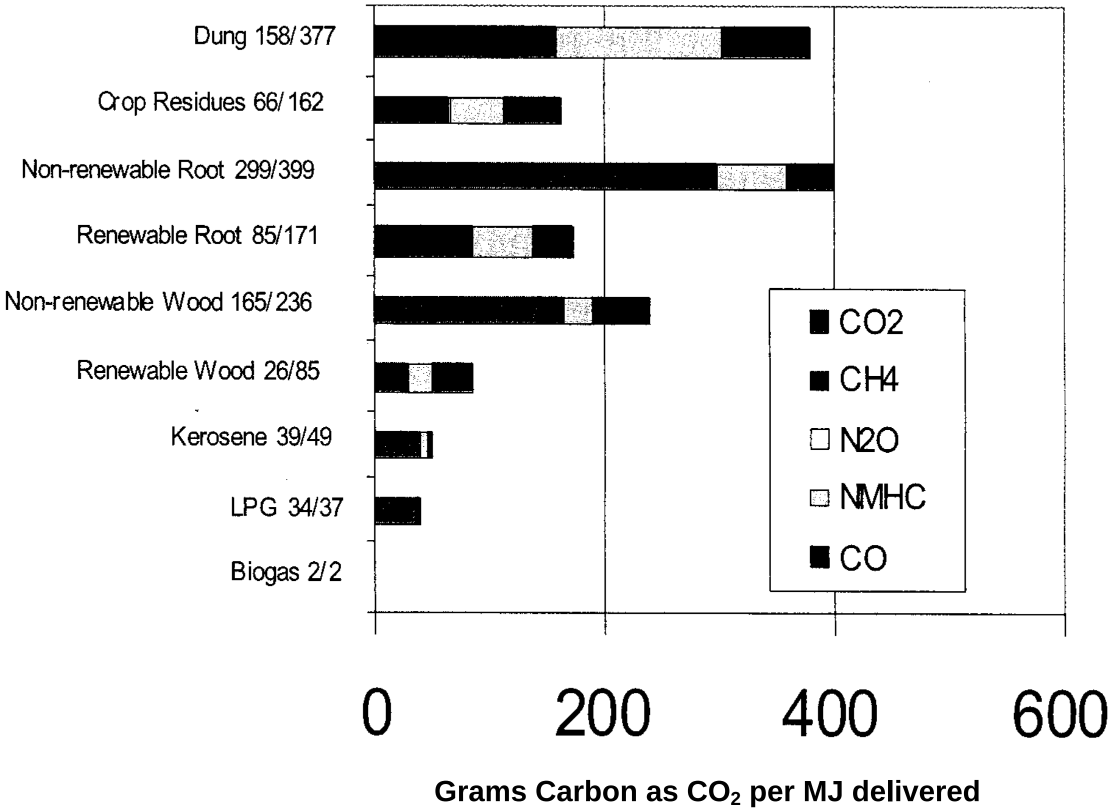


Figure 19. GWCs for household fuels in India (CO_2, CH_4, N_2O)/ CO_2, CH_4, N_2O, NMHC, CO) (Smith 2000a).

In a study by Smith et al. (2000a) biogas was found by far the best of all, with only some 10% of LPG GWC and more than a factor of 200 less than the most GWC-intensive solid biomass fuel-stove combinations. There is a large reduction in GWC represented by biogas compared to direct burning of dung, from which it is made. The remarkable performance of biogas is due to its double advantage of being a gas when burned and renewable when harvested and indicates a huge potential for processed biomass fuels to reduce the GWC of cooking (Figure 20). However biogas will lose some of its apparent lead because of CH_4 leaks from the digester and pipelines.

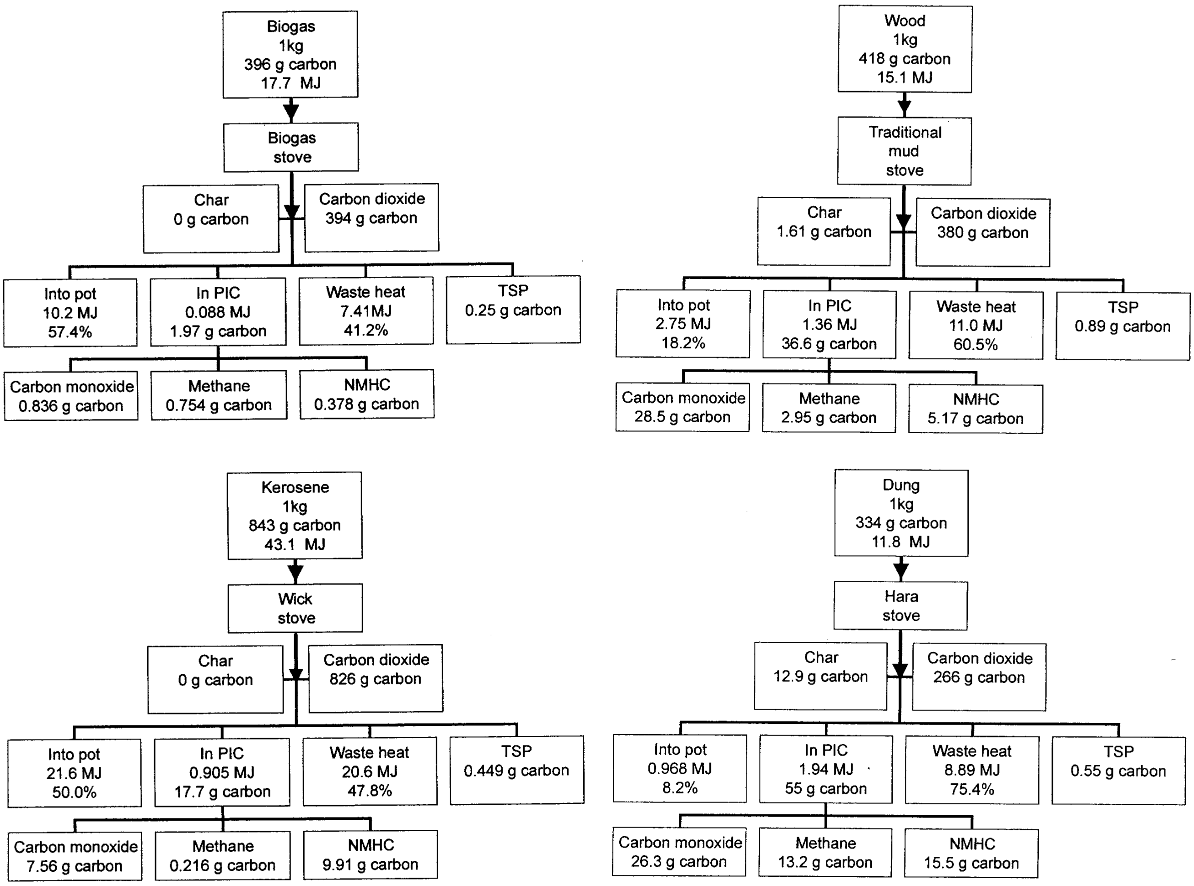


Figure 20. Energy and carbon flows in typical Indian cookstoves (biogas stove, kerosene wick stove, traditional mud stove with wood, hara with dung) (Smith et al. 2000a).

Basically, three conclusions was drawn from the study by Smith et al. (2000a):

- Even if renewably harvested, many biomass fuel cycles are not GHG neutral because of their substantial production of PIC.
- To be GHG neutral, not only must biomass fuel cycles be based on renewable harvesting, they must have close to 100% combustion efficiency, which most do not in their current configurations in India.
- In the processed form of biogas, however, biomass seems to offer the opportunity of providing a renewable source of household energy with extremely low GWC.

5.3 Health impacts of biomass combustion

Many of the substances in biomass smoke can damage human health. The most important are particles, carbon monoxide, sulphur oxides (principally from coal), formaldehyde, and polycyclic organic matter, including carcinogens such as benzo(a)pyrene. PM_{10} and particularly particles less than 2.5 microns in diameter ($PM_{2.5}$) can penetrate deeply into the lungs and appear to have the greatest potential for damaging health (Bruce et al. 2000).

The majority of households in developing countries burn biomass fuels in open fireplaces, consisting of such simple arrangements as three rocks, a U-shaped hole in a block of clay, a pit in the ground or in poorly functioning earth or metal stoves. Combustion is very incomplete in most of these stoves, resulting in substantial emissions, which, in the presence of poor ventilation, produce very high levels of indoor pollution. Indoor concentrations levels of particles usually exceed guideline levels (e.g. USEPA) by a large margin: 24-hour mean PM_{10} levels are typically in the range 300-3000 $\mu g/m^3$ and may reach 30 000 $\mu g/m^3$ or more during periods of cooking (Bruce et al. 2000).

Available data show a distribution of indoor PM_{10} 24-h concentrations measured in Indian solid-fuel-using households ranging to well over 2000 $\mu g/m^3$. The distribution of village means overlap with the higher end of Indian urban concentrations but extends considerably higher. During the cooking period itself, of course, much higher levels are reached indoors. In addition, high household emissions from solid-fuel use result in elevated "neighbourhood" pollution in densely populated communities (Smith 2000).

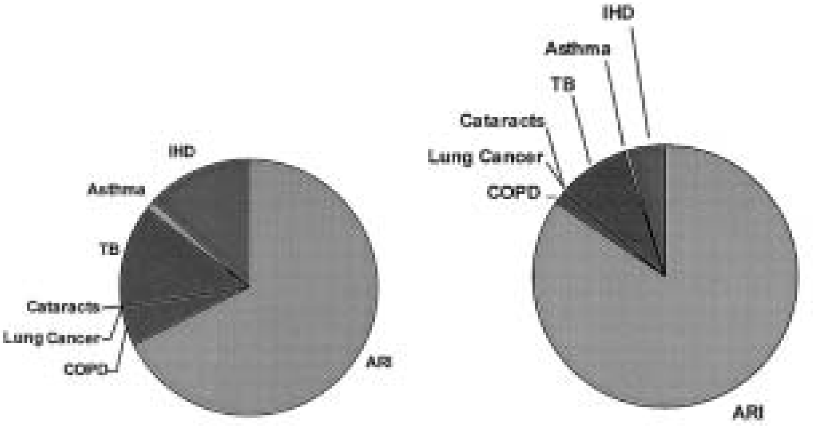
In contrast to simple concentration, exposure is a function not only of the pollution level but also of the number of people involved and frequency and duration of their contact with the pollution - the number of person-hours of exposure. Few other activities involve as many person-hours as cooking does, because it is done in essentially every household every day in most of the world. The combination of high pollution levels in places with many person-hours is a prescription for large total population exposures. Indeed, indoor exposures to the combustion products of unprocessed solid fuels have been estimated to produce the majority of non-smoking human exposures to particulates and probably to a range of other pollutants as well (Smith 1987). With its large, poor, urban and rural populations still using simple solid fuels, the Indian population bears a significant fraction of this exposure (WHO 1997).

The 1991 National Census included for the first time a question about the primary household fuel used and reflected that about 95% of the rural population still relied primarily on biomass fuels (dung, crop residues, and wood). A small fraction uses coal, which means about 97% of households relied principally on these unprocessed solid fuels. Nationwide, some 81% of all households relied on these fuels; 3% used coal and 78% used biomass. An independent probability-weighted national survey of 89 000 households in 1992 derived very similar results (National Family Health Survey 1995).

There were approximately 152 million households in India in 1991-1992. Of these 16% (24 million) did not use solid fuels, 5% (7.6 million) had improved cookstove, and 25% household-equivalents (38 million) cooked outdoors. This leaves about 82 million households at full risk for indoor pollution. Thus, about 460 million people were at risk (Smith 2000).

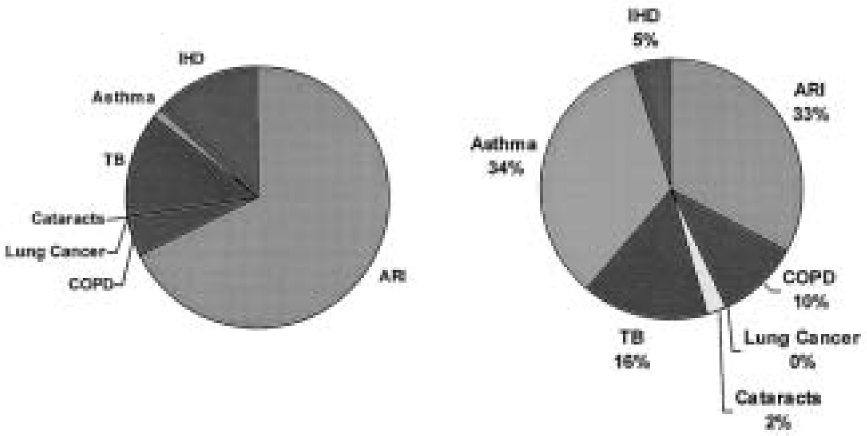
The United States Environmental Protection Agency´s standards for 24-hour average PM10 and PM2.5 concentrations are 150 µg/m^3 and 65 µg/m^3 respectively. The mean 24-hour levels of carbon monoxide in homes using biomass fuels in developing countries are in the range 2-50 ppm; during cooking, values of 10-500 ppm have been reported. The United States Environmental Protection Agency's (USEPA) 8-hour average carbon monoxide standard is 9 ppm or 10 mg/m^3 (USEPA 1997).

In Figure 21 there is an estimation of annual health burden from indoor air pollution in India. The term years of lost life (YLLs) measures the years of lost life through premature mortality. The term disability-adjusted life-years (DALYs) measures both mortality and morbidity; morbidity is measured by evaluating the total number of years lived with a disabling condition, and premature mortality is measured by evaluating the total years of healthy life lost through premature death (Hollinghurst et al. 1999).



A. Deaths
400-550 thousand

B. Lost life years (YLLs)
11-15 million



C. DALYs
12-17 million

D. Sickdays
1.6 -2.0 billion

Figure 21. Estimated distribution of the annual health burden from indoor air pollution in India in terms of deaths (A), years of lost life (YLLs) (B), disability-adjusted life-years (DALYs) (C), and sickdays (D) (Smith 2000).

The range of mortality from indoor air pollution estimates from only those specific diseases for which there are a number of studies in range from 310 000-470 000 in India. These are at the lower end of those where general mortality was estimated to be 360 000-1 800 000. This is what might be expected in that the bottom-up estimates were not made of all specific diseases and age groups thought to be associated with air pollution because of lack of appropriate risk information. A best estimate of 400 000-550 000 premature deaths annually in India from indoor air pollution exposures to children under five and adult women (Figure **21**). This is the range between the low and high estimates from the strong evidence class plus the low estimates from the other evidence classes. No estimate is included for adverse pregnancy outcomes (Smith 2000).

The burden of indoor air pollution is on a risk factor basis just after poor water/sanitation/hygiene and poor food at the household level, which are the largest two risk factors in India in the early 1990s. As shown in Figure 22, it apparently substantially exceeded other major risk factors, such as work-related diseases (occupation), high blood pressure (hypertension), alcohol, unsafe sex (e.g. venereal diseases), and tobacco. The burdens of the latter two, however, are steadily increasing in India, unlike indoor air pollution. The largest risk factors of the individual diseases are listed on the lower part of the figure (Smith 2000).

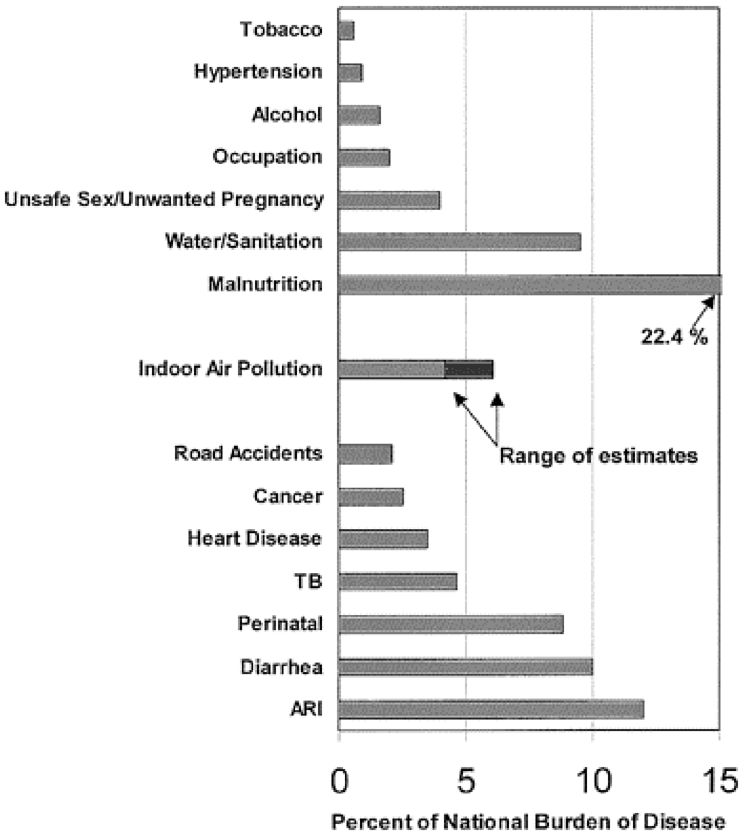


Figure 22. Estimated burden of disease (DALYs) in India for selected major risk factors and diseases compared with that from indoor air pollution (Smith 2000).

Assuming a similar mix of morbidity and mortality, the total burden from air pollution in India would be 5.9-9.2% of the total natinal burden of disease (NBD), nearly rivaling poor water/sanitation/hygiene, although still well below malnutrition.

On that basis, the total world health impact on women and children would be roughly three times larger than the Indian estimates (Smith 2000). Table 16 summarizes the possible mechanisms by which the most important pollutants in biomass and coal smoke may cause cataract and the other health effects.

Table 16. Mechanisms by which some key pollutants in smoke from domestic sources may increase the risk of respiratory and other health problems (Bruce et al. 2000).

Pollutant	**Mechanism**	**Potential health effects**
Particles (small particles less than 10 microns, and particularly less than 2.5 microns aerodynamic diameter)	Acute: bronchial irritation, inflammation and increased reactivity. Reduced mucociliary clearance Reduced macrophage response and reduced local immunity Fibrotic reaction	Wheezing, exacerbation of asthma Respiratory infections Chronic bronchitis and chronic obstructive pulmonary disease Exacerbation of chronic obstructive pulmonary disease
Carbon monoxide	Binding with haemoglobin to produce carboxy haemoglobin, which reduces oxygen delivery to key organs and the developing fetus	Low birth weight (fetal carboxy-haemoglobin 2-10% or higher) Increase in perinatal deaths
Polycyclic aromatic hydrocarbons e.g. benzo(a)lpyrene	Carcinogenic	Lung cancer Cancer of mouth, nasopharynx and larynx
Nitrogen dioxide	Acute exposure increases bronchial reactivity Longer term exposure increases susceptibility to bacterial and viral lung infections	Wheezing and exacerbation of asthma Respiratory infections Reduced lung function in children
Sulphur dioxide	Acute exposure increases bronchial reactivity Longer term: difficult to dissociate from effects of particles	Wheezing and exacerbation of asthma Exacerbation of chronic obstructive pulmonary disease, cardiovascular disease
Biomass smoke condensates including polycyclic aromatics and metal ions	Absorption of toxins into lens, leading to oxidative changes	Cataract
Formaldehyde	Reduces the ability of cells to take up neutral red and to exclude trypan blue while inducing squamous dirrerentiation of human bronchial epithelial cells	Irritation of the eyes, nose and throat, concentration-dependent discomfort, lachrymation, sneezing, coughing, nausea, dyspnoea

The use of biomass fuels has yet one more social and health dimension and it is head-loading. Due to increasing shortages, women are being forced to spend more time and walk longer distances to collect fuelwood. The burden of carrying large head loads of wood over long distances is known to cause ailments such as muscular pains, backache, and pregnancy-related problems (Agarwal 1991). As fuelwood becomes scarcer for both rural and urban poor, head loading serves as a regular source of livelihood for a large number of rural poor. This increases the tendency to exploit biomass resources. Estimate shows that 2 to 3 million people are engaged in head loading as a regular profession, supplying fuelwood to urban markets (CSE 1985).

Attributable risks are calculated in reference to the demographic conditions and patterns of each disease in India. Sufficient evidence is available to estimate risks most confidently for acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), and lung cancer. Estimates for tuberculosis (TB), asthma, and blindness are of intermediate confidence (Smith 2000).

5.3.1 Acute respiratory infections

One of the major diseases thought to be associated with indoor air quality is ARI, a class that includes infections from a wide range of viruses and bacteria, but with similar symptoms and risk factors. In every country, young children contract these diseases at similar rates, but in India and other poor countries, they often proceed to severe stages, including pneumonia and death. It is generally acute lower respiratory infections (ALRI) that impose the highest burden and greatest risk of mortality (Smith 2000).

ARI appear in children under 5 years. Acute lower respiratory infections are the single most important cause of mortality in children aged less than 5 years, accounting for around 2 million deaths annually in this age group in the world. Various studies in developing countries have reported on the association between exposure to indoor air pollution and acute lower respiratory infections (Bruce et al. 2000).

5.3.2 Chronic obstructive pulmonary disease in women

In developed countries, smoking is responsible for over 80% of cases of chronic bronchids, i.e. inflammation of the lining of the bronchial tubes, and for most cases of emphysema (overinflation of the air sacs in the lungs) and chronic obstructive pulmonary disease (progressive and incompletely reversible airflow obstruction). However, these diseases occur in regions where smoking is infrequent (Bruce et al. 2000).

Today in developed countries, nearly all cases of COPD are attributable to tobacco smoking. Undoubtedly, smoking is also a significant factor in COPD incidence among men in least developed countries (LDC). In India, even though relatively few rural women smoked during the past decades, COPD in rural women today is not uncommon (Smith 2000).

5.3.3 Lung cancer in women

Lung cancer in women is a well-demonstrated outcome of cooking with open coal stoves in China (Smith and Liu 1994) but there is little evidence connecting lung cancer to biomass fuel. Biomass smoke, however, contains a wide-range of chemicals that are known or suspected human carcinogens, and it contains particles in the small sizes known to penetrate the deep lung (Smith 1987).

In developing countries, non-smokers, frequently women, form a much larger proportion of patients with lung cancer. Some two-thirds of women with lung cancer in India are non-smokers (Bruce et al. 2000).

5.3.4 Other diseases

Blindness (cataract) in women. India has a larger burden of blindness than any other major region of the world. Indeed, globally, one out of three cataracts occur in India where they are responsible for 80% of blindness in the country. One case-control study in Delhi found an excess cataract risk of about 80% among people using biomass fuel (Smith 2000).

Tuberculosis in women (India: 8% of deaths; 5% of NBD; 5.5% of NBD for women). India has a larger fraction of its national burden of disease attributable to TB than any other region, although the actual risk per person is less than that in Sub-Saharan Africa. Analysis of the 1992-1993 National Family Health Survey found a strikingly strong and statistically significant relationship between reported use of biomass fuel and TB in India. Indeed, women over 20 years in biomass-using households were 3.0 times more likely to have someone reporting TB than households using cleaner fuels, even after correction for a range of socioeconomic factors (National Family Health Survey 1995).

Asthma (India: 0.2% of deaths; 0.5% of NBD). Asthma rates are officially low in India, although there is some recent evidence that the true prevalence is higher than previously thought. Associated with urban outdoor pollution, typical solid-fuel indoor smoke exposures are much higher (Smith 2000). In developing countries, studies on biomass smoke in relation to asthma in children and adults have yielded mixed findings (Bruce et al. 2000).

Adverse pregnancy outcomes (India: perinatal conditions are 6% of deaths; 7.5% of NBD; 20% of NBD for children under 5). A large proportion of perinatal effects consists of diarrhea and ARI, the chief killers of children younger than 5 years, but specific diagnosis/autopsy is difficult with such young infants. Only one study seems to have examined this factor in India as an outcome of biomass fuel use. This study, done in Ahmedabad, found an excess risk of 50% of stillbirth among women using biomass fuels during pregnancy (Smith 2000).

6 BIOGAS TECHNOLOGY IN RURAL INDIA

6.1 Historical aspect of national biogas program

The idea of biogas technology came to India from China where it has had a tradition for thousands of years, and where now is at least 7 millions biogas plants in use. A sewage treatment plant employing the anaerobic digestion process was set up in Bombay in 1937. This generated the interest of scientists and researchers in the field of anaerobic digestion of cattle dung for the production of a combustible gas called biogas and rich organic manure in the form of digested slurry. Pilot experimental plants were designed in the 1940s and the prototypes were developed in the 1950s. Few plants were built for actual users for field demonstration during the next 10 years (Singh et al. 1993).

Other groups became interested, such as the Planning, Research and Action Division of the State Planning Institute of Uttar Pradesh in Lucknow. The Institute set up a biogas research centre. Some of his early plants were more successful including some larger-scale ones (up to $100m^3$ reactor volume). By 1974 over 6,000 plants had been built in India, mainly in the Western states of Gujarat and Punjab and in Uttar Pradesh (Singh et al. 1973).

In 1975 the Department of Science and Technology of the Indian government decided that the biogas programme needed a broader scientific and organisational base. Many more agencies became involved, including those in the local voluntary sector as well as academic institutions. The All India Committee on Biogas was set up in Delhi, with the aim of coordinating all the agencies involved in the programme and, especially, to encourage research institutions to consider problems relating to biogas technology. In all, 192 different organisations became involved, including governmental institutions as well as semi-governmental corporations and non-governmental organisations (NGOs). The most effective sector for biogas extension seems to be the NGOs, although they often lack technical skills and knowledge (Fulford 1988).

Gobar Gas Research Station introduced the first fixed-dome plant, namely the family-sized Janata biogas plant in Lucknow in 1978. Because of comparatively low installation cost in relation to the floating metal drum type plants; known as KVIC model, it coupled the advantage of using locally available building materials and skills in construction. These plants gained acceptance in the rural areas in a short period (Singh et al. 1993). The promotion, transfer and extension of the Janata model were taken up by state government agencies and one NGO, Action for Food Production (AFPRO) through its network of grassroots level voluntary organisations. Up to 1980 state government agencies, AFPRO and other extension agencies had set up about 100 000 biogas plants (Singh et al. 1993).

Development of the Deenbandhu model, nowadays most popular family-sized biogas model in India, dates back to 1981, when AFPRO´s workgroup leaded by Raymond Myles had organised and conducted an international training programme on biogas technology. Based on testing for two years some design modifications were made in this model, different parameters were standardized in 1984 and the plant was christened Deenbandhu, meaning "friend of the poor" (Singh et al. 1993).

The government of India launched the National Project on Biogas Development (NPBD) in 1982. It accelerated implementation and about half a million plants were set up during the next four years (Singh et al. 1993). The policy of the Indian government has been to give subsidies for biogas plants in many areas of the country. These range from 1800 rupees for most applicants to up to 6000 rupees for scheduled tribes and for people in hilly areas where deforestation is becoming a problem (MNES 2000, 22).

The difficulties faced by a farmer attempting to set up a biogas plant include the paperwork required to obtain a loan and the subsidy, and the need to arrange for supplies of materials to be available at the correct time (Moulik 1982). The cumulative number of biogas plants installed, and the annual new installation made, in India are displayed in Figure 23.

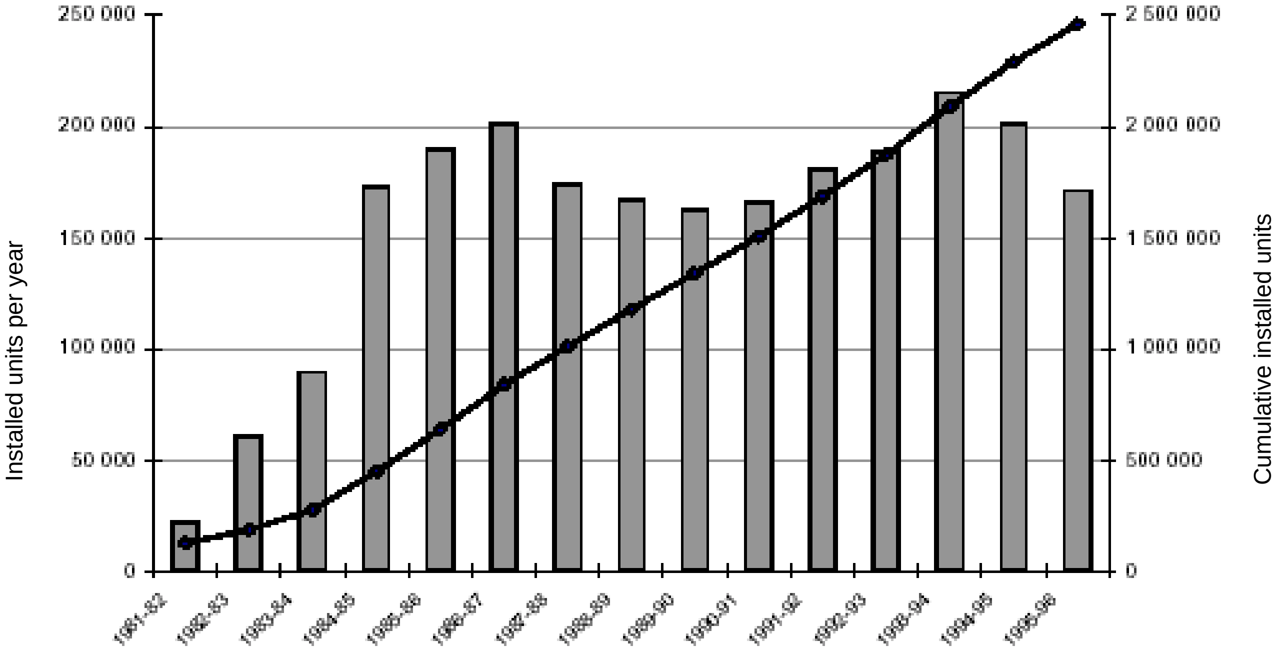


Figure 23. Number of installed biogas units in India between 1981/82 and 1995/96 (TERI 1998c).

6.2 Present status and potential of biogas program

In India, the large scale dissemination of biogas plants has began in the mid-seventies and the process has become consolidated with the advent of the National Project on Biogas Development (NPBD) in 1981 which has been continuing since. Against the estimated potential by MNES of 12 million biogas plants, 3.030 million family type biogas plants have been set up till December 2000, thereby covering over 25 per cent of the potential estimated by MNES (MNES 2001, 21). This official figure of Government of India is based on the bovine population in 1980 and an average size of 3-4 m^3 capacity plants (Myles 2001). The present status of biogas program is estimated to have helped in a saving of 3.9 Mt of fuelwood per year and manure containing nitrogen equivalent to 0.9 Mt of urea (MNES 2001, 21).

Myles (2001) point out that even if the above figure of achievement looks very impressive, it is only a drop in the ocean for India. Even a conservative estimate would put the present potential of rural households biogas plans in the country to over 20 millions units of average size of 2 m^3 capacity from the bovine (cattle and buffalo) manure alone, living in about 600,000 villages. At least 2.5% of these 20 millions potential households (500,000 of rural families) would fall in either remote or in accessible areas of the county.

The estimation of rural biogas potential made by TERI (1994) is based on the bovine population of 260 millions (adult bovine produces an average of 10 kg of dung per day). Since grazing is a common practice in India, all the dung produced cannot be collected. If it were assumed that 75% of the dung could be collected, nearly 2 Mt of dung would be available everyday. At 25 kg per one m^3, this dung can feed as many as 40 millions biogas plants of 2 m^3 capacity, which can be considered the potential for biogas technology based only on cattle dung (TERI 1994b).

With the present implementation strategy and the present allocation of financial resources by the Government of India, 150 000-200 000 biogas plants are constructed each year. Even if this figure were to be doubled (so that 300,000-400,000 plants could be built per year), it would still take over 50 years to realize the full potential of constructing household biogas units in rural areas of the country from bovine manure itself. Thus there is a need for new implementation strategy, which would encourage the investment by private individuals and groups and mobilizing of external resources (Myles 2001).

But even this high potential of biogas is based on animal dung only. However, all organic matter can technically be used to generate methane; if the scientific experiments that are going on in India under the patronage of MNES to develop alternative feedstock (such as water hyacinth, kitchen waste, and poultry waste) come to fruition, potential for biogas generation could be many times higher. With such high potential, which can be routed to applications of mechanical power and electricity generation, biogas can make a significant contribution to the development of small industries and agriculture, as well as fuel of CNG vehicles (TERI 1994b).

There is an economical barrier in the promotion of biogas technology, which is the installation cost of the plant. In spite of the subsidies provided by the central and state governments, the plant owner still has to invest over 70 € from his own resources. Over the years, the prices of raw materials like bricks and cement have been increasing. In addition, biogas programme in India is completely dependent on cattle dung and hence, on cattle availability. A 2 m^3 plant requires to work at maximum level a dung input of 50 kg daily and for this amount four to six cattleheads are required. In most parts of India, a cattle holding of this size is owned only by a small fraction of the rural population (Dutta et al. 1997).

The community and institutional biogas plants (CBP/IBP) programme was initiated in 1982-83 with the objective of recycling the large quantity of cattle dung available in the villages and institutions by setting up of biogas plants and providing fuel for generation of motive power and electricity, besides meeting the cooking fuel requirements. The installation of night-soil (human excrement) based biogas plants (NBPs) linked with community toilets was included in this programme during 1993-94 to facilitate on-site sanitary treatment of human waste. A total of 3075 CBPs, IBPs and NBPs have been installed up to end of 2000 (MNES 2001, 26).

The Department of Rural Development, Government of Rajasthan has taken up the installation of institutional and night-soil (human excrement) based biogas plants in community toilet complexes, hostels and jails. In this it is involving NGOs with assigned responsibilities to provide long-term maintenance servicing of plants. Generator sets of 5 kVA or 7.5 kVA are being installed for electricity generation. A 35 m^3 capacity NBP, linked with a complex of 20 toilets has been installed in Vatika village in Jaipur district. The toilet complex is being used by about 1000 villagers and a 5 kVA dual fuel genset is operating a submersible pump for water pumping, besides meeting the electricity requirements for lighting the complex and streets. The Maharashtra Energy Development Agency (MEDA) is implementing the programme with active involvement and participation of the community local bodies and NGOs. As a result, almost all the plants installed in recent years have been working on a self-sustaining basis. For example, local NGOs are managing a total of eight NBPs set up in the slum areas of Solapur city and supplying biogas to households on a payment basis (MNES 2001, 27).

6.3 Designs of household biogas plants in rural areas

There are two basic designs of biogas plants which has been popular in India, floating-drum type and fixed-dome type plants. The floating-drum type plants, commonly known as the KVIC (Khadi & Village Industries Commission) plants, were standardised in 1961. Few modifications were made by some extension agencies while others tried to replace metal in floating drum gas holder by fibreglass reinforced plastics (FRP) or ferrocement. The design has remained almost unaltered and can be called a time-tested design (Singh et al. 1993).

A typical biogas plant has the following components (TERI 1994b):

- 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 stored.

Fixed-dome biogas plants incorporate cylindrical digesters with a flat bottom and dome-shaped roof. The surface area of the plant would be minimum if its shape is kept spherical. A spherical shape means the least surface area for a certain volume but this would not be suitable for biogas plants as the inlet and outlet tanks have to be located on its either sides. The closeness of these tanks would result in 'short-circuiting' of raw materials (Singh et al. 1993).

Under the NPBD programme, there are various biogas plant models approved by MNES for implementation. All these models are based on one of the two basic designs available, floating metal drum type, fixed masonry dome type, and FLEXI, a portable model made of rubberized nylon fabric, which has been approved for promotion in the hilly and other terrains (TERI 1994b).

6.3.1 KVIC floating drum

The design of KVIC floating drum was based on Gramalakshmi III, the first workable prototype of a biogas plant in the early fifties. This model has an underground cylindrical digester with inlet and outlet connections at the bottom on either side of a masonry wall. An inverted metal drum, which serves as the gas holder rests on a wedge type support on top of the digester and as the gas begins to accumulate, the drum starts rising in height. The weight of the drum applies pressure on the gas to make it pass through the pipeline to the point of use. As the gas flows out, the drum gradually moves down. Due to this smooth two-way motion, the gas remains at constant pressure, which ensures efficient use of gas (Figure 24) (TERI 1994b).

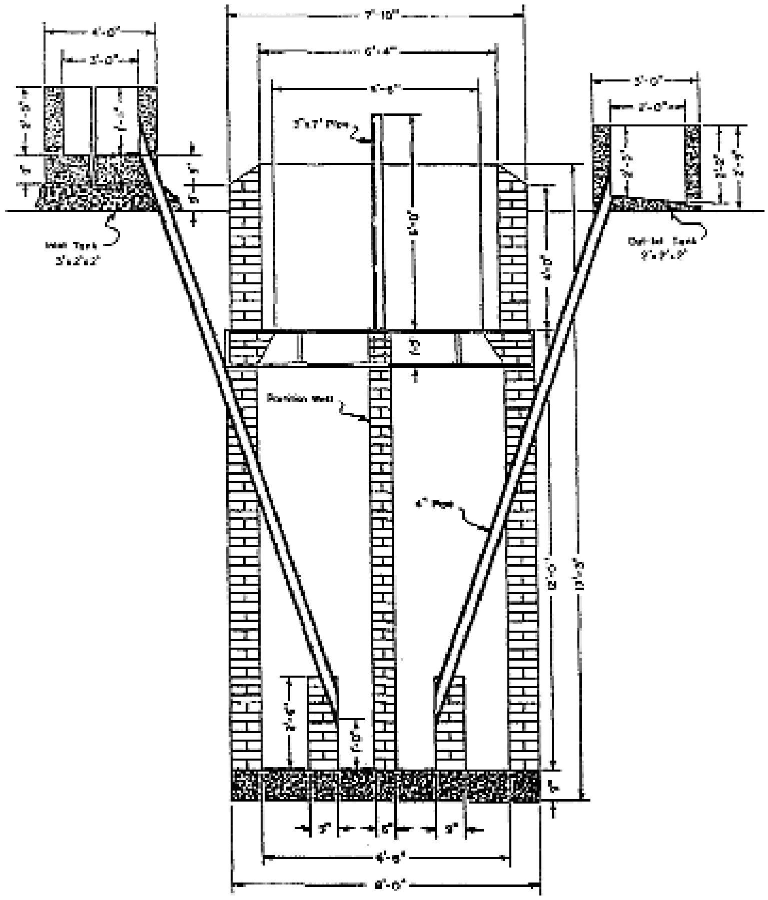


Figure 24. KVIC floating drum biogas plant (TERI 1994b).

The digesters has been designed for hydraulic retention time (HRT) of 30 and 40 days for southern and northern regions respectively. The gas holder alone accounts for about 40% of the total installation cost (Singh et al. 1993).

Though KVIC has been a very popular model since the beginning, it has two major drawbacks. Firstly, the plant cost is high, and secondly, the metal gas holder has to be painted regularly for protecting it against corrosion, which means higher running cost. With the development of cheaper models overtime, the presence of KVIC model is gradually diminishing in NPBD (TERI 1994b).

6.3.2 Janata

The main feature of Janata biogas plant is that the digester and the gas holder (or the gas-storage chamber) are parts of an integrated brick masonry structure. The digester is made of a shallow well having a dome-shaped roof. The inlet and outlet tanks are connected in the digester through large chutes and these tanks above the level of the junction of the dome and the cylindrical portion are known as inlet and outlet displacement chambers. The gas pipe is fitted on the crown of the dome and there is an opening on the outer wall of the outlet displacement chamber for the discharge of spent mass, digested slurry (Figure 25) (Singh et al. 1993).

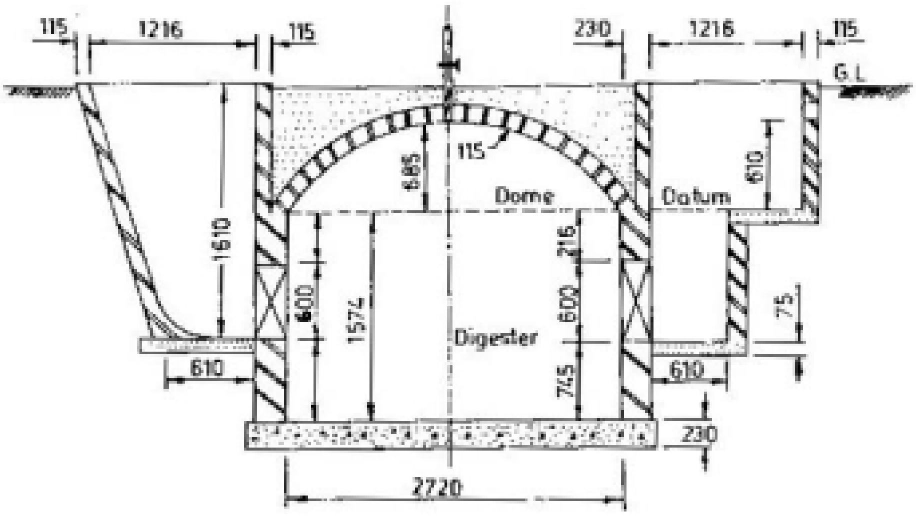


Figure 25. 3 m^3 Janata biogas plant (Kalia & Kanwar 1996).

Family size Janata plants of 2, 3, 4 and 6 m^3 capacities had been designed for the 55 days HRT. Based on the field experience of constructing family size Janata plants of 55 days HRT. AFPRO also designed Janata plants of different capacities of 30 and 40 days HRT for southern and plains of northern regions respectively; thus leaving 55 days HRT for hilly regions of India (Singh et al. 1993).

However, practical training of professional masons on its construction techniques was an essential requirement in the extension of this technology. Wherever this requirement was not met the quality of plants of this design was not up to the desired standard and that resulted in failures (Singh et al. 1993).

6.3.3 Deenbandhu

The Deenbandhu model has been designed by making use of principles of structural engineering as well the long experience of AFPRO of working with fixed-dome biogas plants. The Deenbandhu model plants cost about 30 % less than Janata biogas plants and 45 % less than KVIC biogas plants of comparable sizes (Singh et al. 1993).

Deenbandhu model was developed in 1984 by AFPRO. Main developer of the model was Raymond Myles. Deenbandhu has probably been the most significant development in the entire biogas programme of India as it reduced the cost of the plant to almost half that of KVIC model, and brought biogas technology within the reach of even the poorer sections of the population. The cost of reduction has been achieved by minimizing the surface area through joining the segments of two spheres of different diameters at their bases (TERI 1994b).

While designing Deenbandhu model, an attempt made to minimize the surface area of biogas plants to reduce their installation cost without sacrificing the efficiency. The design essentially consists of segments of two spheres of different diameters joined at their bases. The higher compressive strength of the brick masonry and concrete makes it preferable to go in for a structure, which could be always kept under compression. A spherical structure loaded from the convex side will be under compression and, therefore, the internal load will not have any residual effect on the structure (Singh et al. 1993). This structure acts as digester, pressure is exerted on the slurry again which is pushed into a displacement chamber. Once the gas is drawn out from the outlet, the slurry again enters the digester. The brick masonry dome, which is fixed, requires the skilled workmanship and quality material to ensure no leakage (Figure 26) (TERI 1994b).

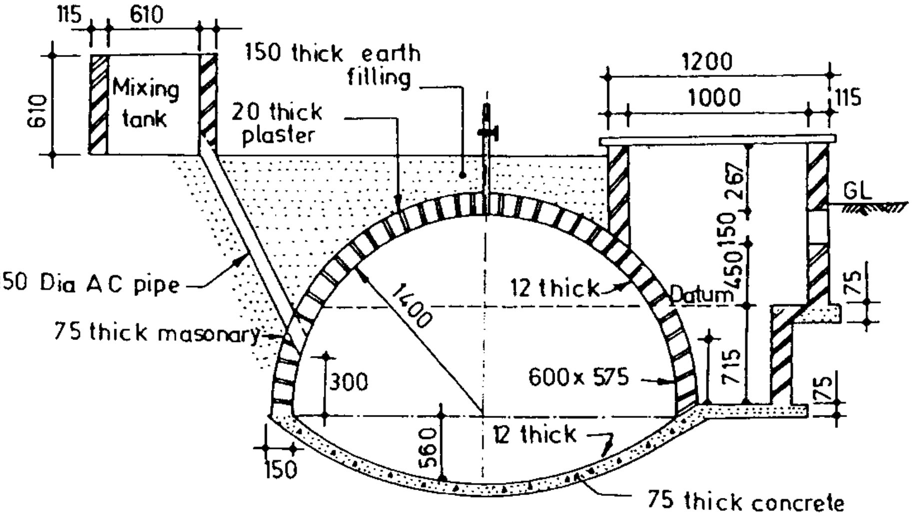


Figure 26. 2 m^3 Deenbandhu biogas plant (Singh et al. 1993).

The digester is connected with the feeding (inlet) pipe and the outlet tank. The upper part (above the normal slurry level) of the outlet tank is designed to accommodate the slurry to be displaced out of the digester with the generation and accumulation of biogas and is known as outlet displacement chamber. Gas yield per kg of fresh dung is 0.04 m^3. The HRT for Deenbandhu plants is 40 days and for hilly region 55 days (Singh et al. 1993).

When the cattle dung is used as feedstock, the Deenbandhu plant is to be filled with a homogeneous slurry made from a mixture of fresh dung and water in a ratio of 1:1 up to the level of the second step in the outlet tank which is also the base of the outlet displacement chamber. As the gas generates and accumulates in the empty portion of the plant, it presses the slurry of the digester and displaces it into the outlet displacement chamber. The slurry level in the digester falls whereas in the outlet chamber it starts rising. This fall and rise continues till the level in the digester reaches the upper end of the outlet opening, and at this stage the slurry level in the outlet tank will be at the discharge opening. Any gas produced after this point of time will escape through the outlet tank unless the gas is used at this stage. When the gas is used the slurry which was earlier displaced out of digester and stored in the outlet displacement chamber begins to return into the digester. The difference in levels of slurry in digester and the outlet tank exerts pressure on the gas, which makes it flow through the gas outlet pipe to the points of gas utilisation (Singh et al. 1993).

6.3.4 Pragati

Designed by United Socio-economic Development and Research Programme (UNDARP), an NGO based in Pune, Pragati model was approved under NPBD in 1987. This model is a combination of KVIC and Deenbandhu designs. The lower part of the digester is semi-spherical in shape with a conical bottom. However, instead of a fixes dome, it has a floating drum acting as gas storage chamber. The spread of Pragati model has been confined mainly to the state of Maharashtra (TERI 1994b).

6.3.5 KVIC plant with ferrocement digester

In order to overcome the problems encountered in construction of traditional models of biogas plants, alternative construction materials have been tried out and ferrocement is but one of them. Ferrocement is nothing but reinforced concrete made of welded mesh, sand, and cement. Layers of thin steel wire mesh distributed throughout the thickness of element, are impregnated with rich mortar. Ferrocement as a building material offers several advantages like 10 – 15% reduction in cost over KVIC digesters, usage of locally available material and less labour, and little or no maintenance. The only limitation suffered by ferrocement is damage due to impact on by pointed loads, which however can be easily repaired. The ferrocement digester design approved under NPBD has been developed by Structural Engineering Research Centre, Ghaziabad (TERI 1994b).

6.3.6 KVIC plant with fibre reinforced plastic (FRP) gas holder

FRP has been used in place of metal in the floating drum gas holder. Contact Moulding Process, a technique of moulding without the application of external pressure, is adopted to manufacture the FRP. It employs one of the less expensive types of moulds resulting in lower cost for the plant. The major advantage of FRP is its good resistance to corrosion which saves the recurring expenditure on painting the drum (TERI 1994b).

6.3.7. FLXI

This is a portable model in which the digester is made of rubberized nylon fabric. The model is particularly suitable for hilly areas where high transportation cost of construction materials, such as cement and bricks substantially increases the cost of installing the regular type of biogas plants (TERI 1994b).

6.3.8 Shramik bandhu

The Shramik bandhu biogas plant (SBBP) was developed by AFPRO during 1995/96. It reduces the construction cost by using locally available low-cost material. The plant design and working principle is similar to that of Deenbandhu biogas plant. However, the construction material used for both the plants differs - bamboo is used in SBBP and bricks used in Deenbandhu. This can be advantageous in areas where there is difficulty in procuring bricks. The technology is being tested and the cost of the plant (even if bamboo is purchased from the market) works out to be approximately 1000 rupees less than the Deenbandhu model. In areas where bamboo is abundantly available, the cost of the plant would be still lower. As the model is labour intensive, it would also create more employment opportunities, especially for rural women since weaving of bamboo is primarily undertaken by them (Dutta et al. 1997).

6.4 Impacts of biogas technology

Promoted as an appropriate rural technology for several decades in India, the application of biogas technology in the rural areas lies mainly in the fact that it enables an effective utilization of a locally available resource. For the rural people, this technology provides a clean and convenient fuel at a low cost, being environmentally benign at the same time (Dutta et al. 1997).

Benefits of the biogas technology at the family level (Dutta et al. 1997):

- Clean and convenient cooking fuel
- Time and labour saving in cooking and fuel collection
- Reduction in pollution levels in kitchen, affecting family health and that of women in particular
- Monetary saving in case of purchased fuels
- Cost-free organic fertilizer

Benefits of the biogas technology at the village/community level (Dutta et al. 1997):

- Reduces pressure on already scarce sources of biomass fuels like wood and crop residues
- Better health and sanitation through removal of cattle dung from open spaces

The study by Dutta et al. (1992) showed that while both men and women valued the time saving aspect of biogas the most, there is a considerable difference in their perception towards other benefits.

However, biogas technology is not an appropriate solution for everyone. For example, in some areas there can be shortage of water. Many potential benefits of biogas technology are not often easy to realise in practice. To get the benefit from the effluent as good fertiliser needs proper management of it, which is not always possible to realize. The gas amount will, however, require good conditions and proper management of the unit or otherwise the gas amount produced will be less. Often the produced gas will not meet the requirements, and hence need to be supplemented by other sources of energy (Gustavsson 2000).

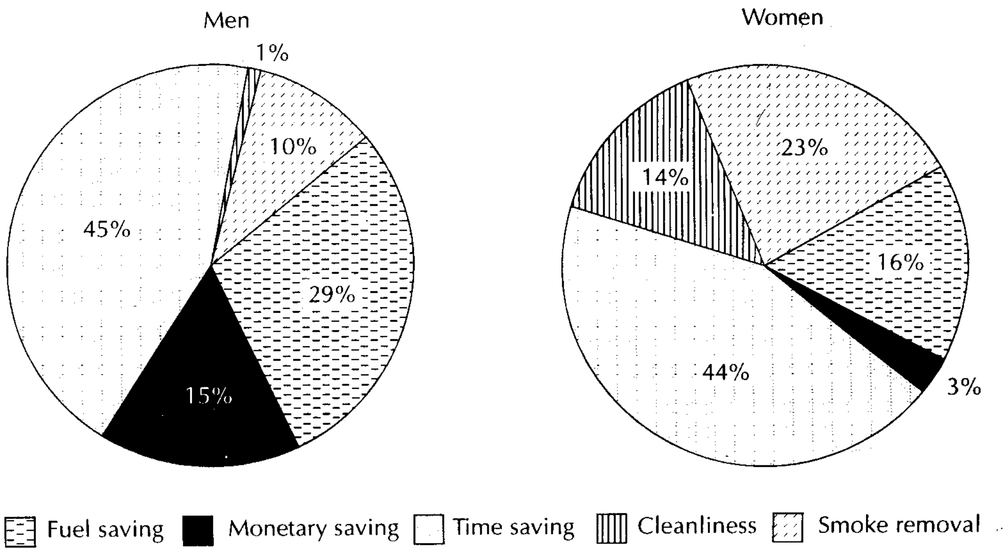


Figure 27. Benefit perceptions of biogas technology by rural biogas users (Dutta et al. 1997).

The biogas plant users reported that need for an alternative to traditional fuels, particularly fuelwood is the primary reason for adopting biogas. About 26% of the biogas owners (both men and women) considered wood saving most important benefit, while 32% ranked it second. It is felt that because of increasing population and a limited supply of fuels like LPG and kerosene, the total physical availability of these fuels is grossly inadequate (Figure 27) (Dutta et al. 1997).

One advantage is that, unlike centralized systems such as thermal power plants and fertilizer factories, which entail huge capital investments and need elaborate distribution networks, biogas plants are decentralized systems which can be installed even in remote areas with low investments (TERI 1994b).

6.4.1 Time saving

The human effort involved in gathering fuelwood is a cause for drudgery for women and children who travel long distances in search of fuelwood. It has been estimated that at the national level, the average number of hours spent in gathering biomass is about two hours per day per household which is likely to increase in future due to increasing scarcity of fuelwood sources (Ravindranath & Hall 1995).

The use of biogas as a cooking fuel brings about an improvement in the overall quality of life in many ways for the user families, and for women in particular. The benefits are in terms of time saved in fuel procurement and cooking, improved kitchens and convenience, and reduction of drudgery of transporting fuelwood and other fuels like agricultural residues to the homesteads, processing them (i.e. cutting them into smaller pieces to be used in the cookstoves), and storing them for later use. These benefits mean more for women, as they have traditionally been responsible for the procurement, processing, and use of cooking fuel for their families (Dutta et al. 1997). A biogas stove (Figure 28) has an efficiency of about 55%, which is comparable to that of an LPG stove. Cooking on biogas is free from smoke and soot, and can substantially reduce the health problems, which are otherwise quite common in most rural areas in India where biomass is the chief source of fuel. The use of biogas is helpful to improve the quality of life in household (TERI 1994b).

Figure 28. Biogas stove.

The study made by Dutta et al. (1997) showed that the biogas user families spend less time in collecting fuelwood than those using biomass fuels. On an average, a biogas user family makes 31 trips in a year for fuelwood collection spending five hours per trip. As compared to this, a non-user family is required to make around 40 trips in a year, spending an average of nine hours per trip. Thus the time saved by a biogas user family per trip is as high as four hours. About one hour per day is saved in cooking time in the biogas user families as opposed to the non-users (Figure 29) (Dutta et al. 1997).

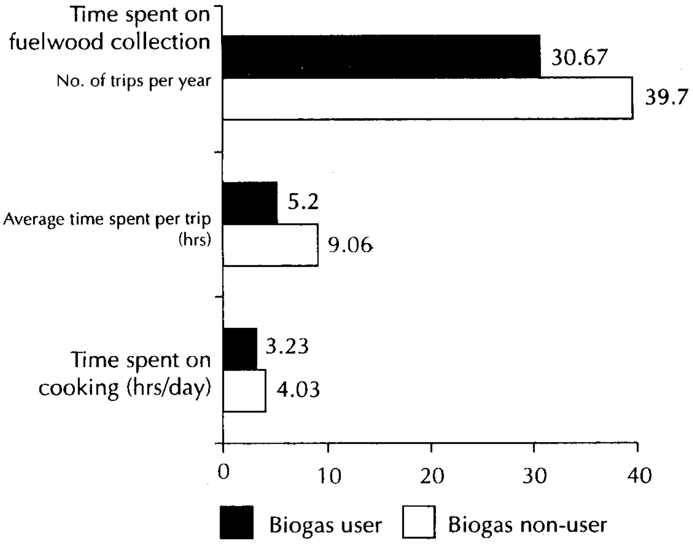


Figure 29. Time saved from use of biogas (Dutta et al. 1997).

6.4.2 Fuel Saving

Biogas technology makes optimal utilization of the valuable natural resource of dung; it provides nearly three times more useful energy that dung directly burnt, and also produces nutrient-rich manure. As a cooking fuel, it is cheap and convenient. Based on the effective heat produced, a $2m^3$ biogas plant could replace, in a month, fuel equivalent of 26 kg of LPG (nearly two standard cylinders) or 37 litres of kerosene or 88 kg of charcoal or 210 kg of fuelwood or 740 kg of animal dung. In terms of cost, biogas is cheaper, on a life cycle basis, than conventional biomass fuels (dung, fuelwood, crop wastes, etc.) as well as LPG, and is only fractionally more expensive than kerosene; the commercial fuels like kerosene and LPG, however, have severe supply constraints in the rural areas (TERI 1994b).

An analysis made by Dutta et al. (1997) was carried out to arrive at estimates for fuel consumption at the rural household as well as per capita levels with biogas users and non-users. The fuel saving brought about by the use of biogas was estimated by asking the 482 households to calculate the percentage reduction in different fuels. The users perceived the wood saving as an important benefit of the technology. About 26% of the biogas plant owners considered wood saving to be the most important benefit, while 32% ranked it second.

From a strategy point of view, people's perceptions on fuel saving are of special relevance in areas where fuelwood scarcity is a serious problem and a majority of the households have to purchase wood and fuelwood is the primary source of energy for cooking due to lack of availability of fossil fuel or poor purchasing power of the people. Significant regional variations are observed in the fuel consumption levels across the country. However, for all the regions studied by Dutta et al. (1997), the use of fuelwood was found consistently lower in case of households using biogas plants than those who rely entirely on traditional fuels There is considerable variation in the estimates provided on the actual quantity of wood saved by the use of biogas. However, most households informed that they are using about 25% to 40% less fuelwood after switching to biogas. It is however, interesting to note that most users of biogas are also using other traditional fuels like wood and agricultural residues. For some specific purposes like making of rotis (Indian bread), brewing alcohol, etc. people prefer using traditional chulhas rather than biogas stoves and the savings in use of dungcakes and crop residues as fuel were minimal according to the answers of users. A 30% saving in kerosene was also observed in the case of biogas user households (Figure 30) (Dutta et al. 1997).

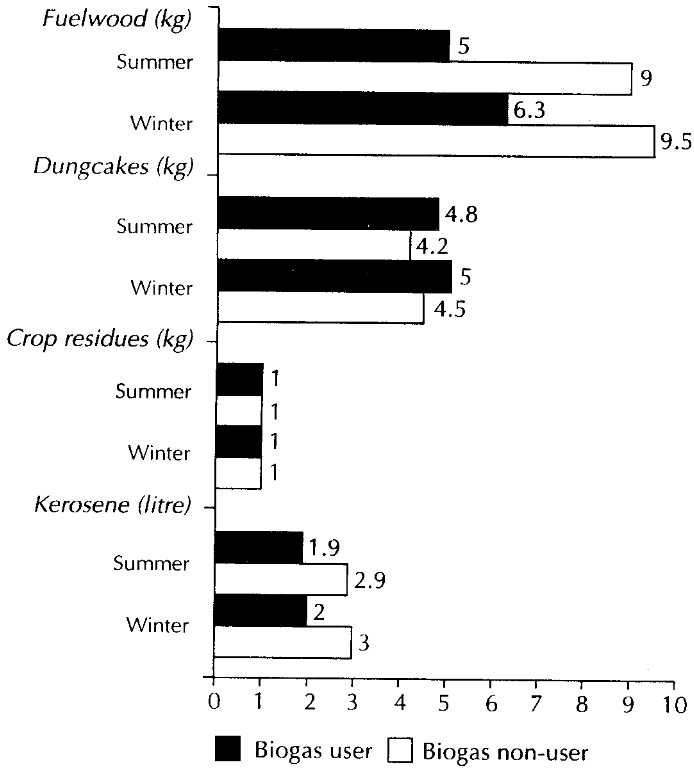


Figure 30. Rural biogas users′ and non-user′ household fuel-use pattern (kg/day) (Dutta et al. 1997).

However, the use of biogas is by no means confined to cooking alone. It can be used, through a specially designed mantle, for lighting, too. Further, biogas can partially or fully replace diesel to run IC (internal combustion) engines for water pumping, small industries like floor mill, saw mill, oil mill, production of electricity and traffic etc. This would not only reduce dependence on diesel, but also help in reducing carbon pollutants, which adversely affect the atmosphere. Dual-fuel engines (80% biogas and 20% diesel) has been commercially manufactured in India. Biogas can be similarly used to produce electricity, though this has not been attempted on a large scale in the country so far. Nevertheless, the versatility of biogas is its greatest advantage as a source of energy for the rural areas (TERI 1994b).

6.4.3 Monetary saving

The use of a biogas plant can help the user save money in three ways. The first case is that of households where cooking fuel was being purchased prior to installation of biogas plant and the use of biogas plant has either eliminated or reduced the quantity of purchased fuel. Cash savings also accrue when commercial fertilizer is replaced by biogas slurry. The third case is when the use of biogas slurry brings about an increase in the yield of crops and a higher income for the farmer. However, rural biogas users′ perceptions regarding monetary savings are mixed (Figure 31) (Dutta et al. 1997).

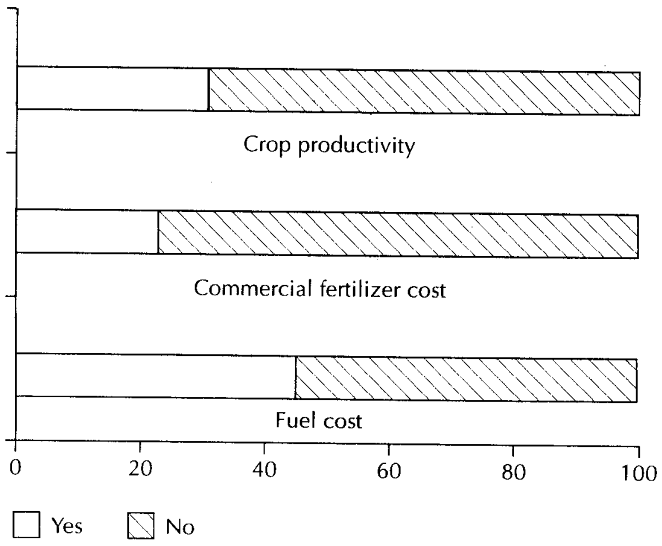


Figure 31. Rural biogas users′ perceptions on monetary savings (%) (Dutta et al. 1997).

There have been many economic analyses of rural domestic biogas plants. They all reach a similar conclusion, that domestic biogas is only marginally economic. If biogas is used for cooking and lighting in a rural area it replaces fuels such as firewood, crop residues and kerosene. The capital costs of building a family-sized digester can easily be defined, especially if figures are available from on-going extension programme. The running costs are less easy to define: they include the labour required to collect and mix the dung each day and the cost of maintenance. Regular maintenance costs depend on the design of plant used (Fulford 1988).

Many people in rural areas do not pay for fuel. They collect their firewood or crop residues themselves. The value of the fuels replaced might be calculated in terms of the labour and time required to collect them. Since most of the work of collection is done by women and children it is difficult to place a monetary value on their time (Fulford 1988).

In a study made by Dutta et al. (1997) cooking with wood collected free by family members is the cheapest option, as long as the time spent on fuelwood collection does not have an opportunity cost (equivalent monetary value). After collected wood, biogas is the second cheapest option and remains cheaper even when dung is valued at a price (Dutta et al. 1997).

The value of the fertilizer produced by a biogas plant is also difficult to define. Some analysts assume the dung would otherwise be burnt, so put a price on the total fertilizer value of the slurry (Fulford 1984). Others try to assess the improvement of the fertilizer value of the slurry digested in a biogas plant and stored in pits with that of raw cattle dung stored in heaps until it is needed for the fields (Cui 1985). These assumptions depend very much on the practice of the local farmer.

However, a biogas plant demands a relatively high capital investment from a small farmer and he has to be convinced that it is worth it. A farmer might expect a higher return on his investment (Fulford 1988).

6.4.4 Environmental impacts

While biogas has multiple benefits at the individual family level, it also has several qualitative and quantitative benefits at the societal level. Firstly, a shift to biogas from traditional biomass fuels results in less dependence on natural resources such as forests, checking their indiscriminate and unsustainable exploitation (TERI 1994b).

No direct correlation between deforestation and rural energy use has been established so far. In fact, the contribution of forests (via felling of trees) to total fuelwood used in the domestic sector mainly for cooking is 8.7% (Ravindranath & Hall 1995). Anyway based on the effective heat produced, a 2 m^3 biogas plant could replace fuel equivalent of about 2520 kg of fuelwood or 8880 kg of animal dung in a year.

Nevertheless, there is enough evidence at the micro level to suggest that fuelwood use contributes to degradation of biomass resources, especially in areas where external factors like timber extraction cause forest denudation. The total fuelwood use in the domestic sector is estimated at 252 Mt annually in India (Rural energy database 1992). On the supply side, it is estimated that the annual sustainable supply from different land resources (forests, plantations, private lands, waste lands, etc.) is about 86 Mt. It is believed that this wide gap between the current demand and sustainable supply of fuelwood is met from illicit and unsustainable exploitation of biomass resources (TERI 1995c).

In national parks and sanctuaries, the population inhabiting the surrounding areas is largely dependent on the protected area for fuelwood. Biogas has been used effectively in such areas to reduce wood consumption (Dutta et al. 1997). Using of dung in traditional stoves (with 11% efficiency) as cooking fuel require more time and bigger quantity to produce same effective heat compared to utilization the energy, by recycling and digesting it through biogas plants (Myles 2001).

The use of slurry as organic manure can yield substantial benefits in terms of increased crop productivity (TERI 1995d). Anaerobic digestion not only breaks down plant materials into biogas, it also releases plant nutrients, such as nitrogen, potassium and phosphorous and converts them into a form that can be easily absorbed by plants. These fertilizer chemicals are not removed or created in a biogas plant, although the removal of carbon, oxygen and hydrogen as methane and carbon dioxide means that the concentration of other chemicals is increased (Table 16). For example, protein and amino acids in the feedstock are converted into ammonia, which forms soluble ammonium compounds with the fatty acids (Fulford 1988).

Table 16. Plant nutrients in air-dried manure and effluent (Fulford 1988).

Material	Nitrogen %	Phosphorous %	Potassium %	Indigestible ash %
Buffalo dung	1.01	1.11	0.92	26.43
Biogas effluent	1.41	1.18	1.48	28.64

If biogas slurry is handled carefully it makes an excellent fertilizer and soil conditioner. It is free from odour and does not attract flies. Most of the harmful bacteria and parasites in the original feed are either killed or considerably reduced in number. The benefits of slurry use build up over several years (Fulford 1988). Since dung is collected systematically when used in biogas plant, environment can be kept clean and hygienic (Dutta et al. 1997). The dung, which is used directly as manure, is often dumped either in heaps or in pits just outside in the back yard the farmer's house. The decomposition of this manure in a traditional manner, close to the house, contributes to the breeding of flies and mosquitoes, which spreads all sorts of diseases (Myles 2001).

The major problem with effluent slurry is transporting it to the fields as it is in liquid form. The usual practice in India and Nepal is to collect the effluent in shallow ponds and allow it to dry in the sun. This reduces its weight and volume considerably. Any toxic substances, such as hydrogen sulphide, evaporate and any remaining harmful bacteria are killed. However, ammonia is also lost by evaporation into the air and by leeching, as water drains into the soil. The loss of nitrogen from dried slurry (7 per cent to 15 per cent) appears to be less than from drying raw cattle dung (20 per cent to 45 per cent). However, sun drying takes up a lot of space and is difficult in the rainy season (Yawalker 1977).

However, a general feeling among the users in the study by Dutta et al. (1997) is that the use of slurry does not make a significant difference to the yield (Figure 32). About 48% of the respondents felt that the use of biogas slurry marginally increased the crop yield, while the remaining 52% felt that the application of slurry has not made any difference to the yield. However, most farmers (75%) rated the quality of biogas slurry good as organic manure (Dutta et al. 1997).

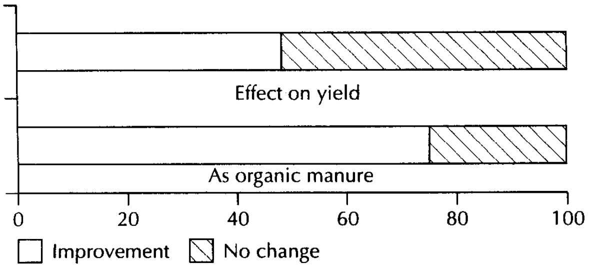


Figure 32. Rural biogas users′ perception of biogas slurry as fertilizer (Dutta et al. 1997).

In Maharashtra and Gujarat, the farmers felt that even if they feed the entire fresh dung available into the plant, the slurry produced from biogas is not good enough to replace chemical fertilizers. Another common perception was that the biogas slurry was not as good as fresh dung since it would get burnt in the biogas plant. Such misconceptions prevent many farmers from feeding the entire amount of dung available into the biogas plant (Dutta et al. 1997).

Mehla et al. (1986) constructed a model to integrate the process of recycling of feed nutrients through a crop, animal and biogas system (Figure 33). According to this from 1 ha of land it is possible to produce 83 GJ of energy and 906 kg of protein from milk; 267 kg of nitrogen; 149 kg of P_2O_5 and 91 kg of K_2O fertilizer from biogas slurry and 2897 kW of power per year for farm operation from biogas using the dual-fuel biogas engine. Compared to traditional system the recycling of feed nutrients through biogas system in the available straws of rice and wheat crop can yield an additional 16 GJ of energy and 167 kg of protein from milk; 81 kg of N; 56 kg of P_2O_5 and 25 kg of K_2O fertilizer from biogas slurry and 1097 kW of power per hectare annually (Mehla 1986).

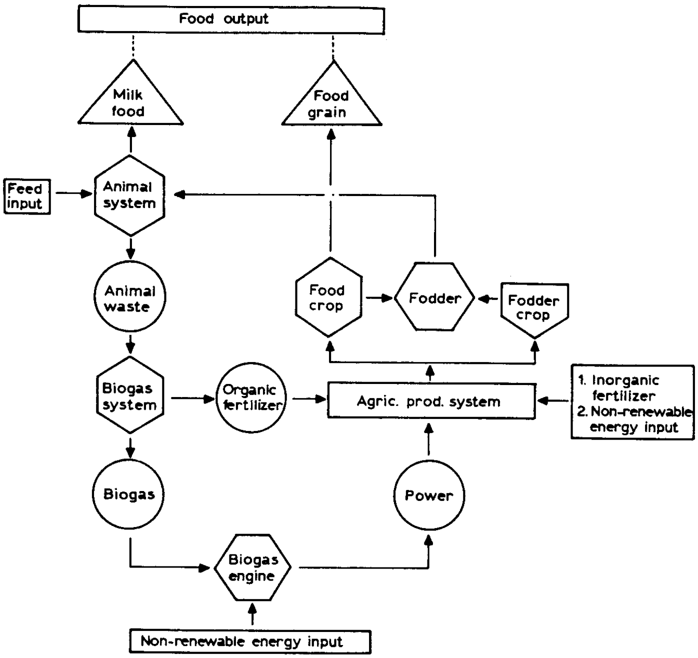


Figure 33. Model for recycling feed nutrients in crop, animal and biogas systems.

Methane emission from flooded rice fields is a matter of great concern. It was found by Debnath et al. (1996) that biogas effluent as manure in combination with inorganic fertilizer (biogas effluent + urea) over the other treatments like use of urea or combined fertilization (farm yard manure + urea) results relatively in lower methane emissions from the rice fields without the sacrifice in grain fields.

Concentrations of indoor pollutants in households that burn traditional fuels are alarming. Daily averages often exceed current guidelines by factors of 10, 20, or even more. Although there are many hundreds of separate chemical agents that have been identified in the smoke from biofuels, the four most serious pollutants against health are particulates, CO, polycyclic organic matter and formaldehyde (TERI 2001c).

Biomass on combustion emits pollutants such as respirable particulate matter, carbon monoxide, nitrogen oxides, and methane and non-methane organic compounds. Incomplete combustion of biofuels produces smoke, which can cause a number of health problems such as conjunctivitis, acute respiratory infections, upper respiratory tract irritation, etc. Continuous inhalation of smoke could lead to chronic bronchitis and even cancer of the lung. Continuous exposure to fire could also cause burns and cataract (Batliwala 1995).

Shifting to biogas technology can lead to a reduced incidence of many respiratory illnesses through removal of smoke in the kitchen. In the study by Dutta et al. (1997), 38 % of the women felt that the use of biogas has led to a reduction in the smoke level and contributed towards cleaner and more comfortable kitchens. The women also said that earlier, sitting in a crouching position in front of the chulha, was very difficult with persistent watering of eyes and irritation of throat. In a certain household, an elderly woman had to undergo an eye operation due to exposure to intense heat and high levels of smoke over the years. Use of biogas has considerably reduced smoke and vessels and kitchen walls do not blacken (Dutta et al. 1997).

6.5 Functional status of biogas plants

Dutta et al. (1997) made an evaluation study of 482 biogas plants implemented by NGOs. The plants represented the complete range in terms of age (constructed in 1981-1996) and varied from 2 m^2 to 6 m^2. However, 70% of the plants surveyed were of 2 m^2 capacity reflecting the general trend in NPBD. The finding of the study was that 81 % of the plants were in use and only a fraction of the functional plants were found to work at an optimum level of efficiency (because of e.g. underfeeding). The suboptimal functioning gets reflected in a variety of symptoms like low gas production, insufficient gas for cooking all meals, need to give frequent breaks while using gas, etc. Significant regional variations in functionality were observed among the NGOs as well as the states. The reasons for disfunctionality were mainly non-technical. The most common reason was found to be fluctuation in cattle holding and hence, dung availability. In the water scarce region of Maharashtra, during drought, farmers are forced to sell their cattle. On the other hand, in the Vaishai area of north Bihar, a cattle selling is a seasonal phenomenon. Very few plants had constructional defects (Dutta et al. 1997).

In same study it was found that the awareness regarding usage aspects was low among the biogas plant users. The most common problem was that of underfeeding. The problem of shortage of dung and consequent underfeeding of biogas plants is rampant throughout the country. The extent of underfeeding is higher in the case of large plants. This is to be expected, given the fact that the daily dung requirement is higher for large biogas plants as compared to the smaller ones. It can be seen from the Table 17 that while the average dung fed is 44% less than the required 50 kg per day in case of 2 m^2 plants, it was found to be 57% less in the case of 3 m^2 plants, 71 % less for 4 m^2 plants, and 60% less than the prescribed feeding level for 6 m^2 plants. The problem of underfeeding is not necessarily related to cattle-holding patterns alone. Even in households and areas where the average cattle holding is sufficient, plant owners were found to underfeed the biogas plants (Dutta et al. 1997).

Table 17. Daily dung input in rural household biogas plants (Dutta et al. 1997).

Biogas plant capacity (m^2)	Daily dung requirement (kg)	Average daily dung fed* (kg)
2	50	28
3	75	32
4	100	29
6	150	60

*Estimates based on information given by the plant owner.

The national average of 66% was reported to be functional by the National Council for Applied Economic Research (NCAER 1992), which monitored 27 000 plants in 3600 villages in 251 districts in India, between 1985 and 1990. More recent evaluation study was made by the state governments and agencies, which comprised 9000 plants in some states in 2000 and 79% of the plants have been found to be functional (MNES 2001).

6.6 Using biogas in lighting and engines

Although biogas is mostly used in rural areas for cooking purposes, it can be used for lighting and as fuel in engines (Table 18). Where there is no electricity, as in many parts of India, biogas can be used to give light. While biogas lights are inefficient, expensive and need regular servicing, they give as good a light as a kerosene pressure lamp and are easier to use. A gas lamp gives the same illumination as a 40 to 60 W electric light bulb and uses between 90 l and 180 l of gas an hour (Fulford 1988). Almost 87% of the total 580 000 villages of India have been electrified, but in 1996 only 37% of the rural households were having electricity connections, which indicates that still the majority of households in rural areas solely depend on kerosene for lighting (TERI 1998d).

Table 18. Biogas consumption of various appliances (Fulford 1988).

Biogas appliance	Biogas consumption litre/min	 m^3/hour
Gas lamp (per mantle)	2.4	0.14
Refrigerator burner	2.4	0.14
Domestic burners (stoves)	4 to 15	0.2 to 0.9
Commercial burners	20 to 50	1 to 3
Dual fuel engines (per kW) (diesel + biogas)	9	0.56
Spark engines (per kW) (Otto engine)	11.5	0.7

A biogas lamp uses incandescent mantles, which glow brightly when heated (Figure 34). The gas supply is controlled by the size of the main jet and by the control valve. The Indian jet is of brass (it is made of glass in the Chinese lamp), with a steel needle partially closing it to adjust the gas flow. The primary air is drawn into a ventury, a tapered tube in which the gas and air mix (Fulford 1988).

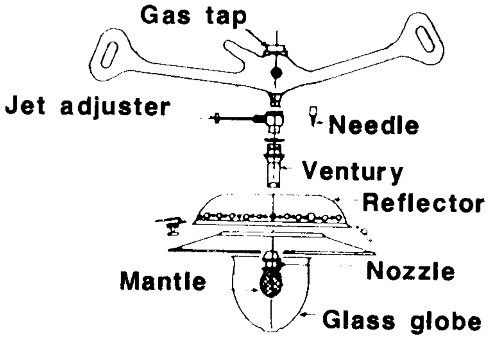


Figure 34. Indian-made biogas light (Fulford 1988).

Biogas can be used directly in Otto engines, but it is not commonly done. Biogas is used inefficiently in such an engine, because of the low compression ratio (7:1 to 9:1) and it produces only 60 per cent of the power available when the engine is run on petrol (gasoline). Hydrogen sulphide is burnt to sulphur dioxide in the engine and this tends to corrode the exhaust valves and manifold (Maramba 1978).

Biogas is used in a dual-fuel engine, based on the diesel cycle, the much higher compression ratio (14:1 to 21:1) means that the fuel is used more efficiently. The power loss is just 20 per cent of diesel-only operation, at full power. At other power levels there is little difference. There seems to be much less corrosion in a dual-fuel engine, probably due to its far heavier construction. An advantage of the dual-fuel approach is that the engine can run on diesel alone if supplies of biogas are inadequate. There are many dual-fuel systems running in China, India and Nepal. The Indian-made Kirloskar dual-fuel engines (2kW upwards) are designed for village use. They have a relatively low compression ratio (17:1) and run at 1500 rpm at normal load (Fulford 1988).

A third alternative is to adapt a diesel engine to work on an Otto cycle, by replacing the diesel injector by a spark plug. This type of engine has the advantages of the high compression ratio, good efficiency and heavy construction associated with a dual-fuel engine, but no supplies of diesel are necessary. Such a conversion requires good engineering skills. As well as a mounting for the spark plug, the engine must be fitted with a small generator, a spark-timing and distributor system and a storage battery. This type of engine cannot be run on other fuels if the biogas supply is limited (Fulford 1988).

The most popular use of a biogas-fuelled engine in Nepal is for food processing. A typical small mill, designed for these tasks, can use a 5 kW dual-fuel engine. A second use for engines is to drive irrigation pumps. There are a series of dual-fuel pump-sets, using centrifugal pumps matched to the engines that drive them. Biogas engines have also been used to generate electricity. Biogas can be used much more efficiently for mechanical power via a suitable engine (e.g. in vehicles), than if it were used to generate electricity to do the same job (Fulford 1988).

6.7 GHG emissions and biogas technology

6.7.1 GHG emissions from animal wastes

Animal wastes are principally composed of organics, moisture and ash. Decomposition of animal waste can occur either in an aerobic or anaerobic environment. Under aerobic conditions, CO_2 and stabilized organic materials (SOMs) are produced. Under anaerobic conditions, CH_4, CO_2, and SOMs are produced. Since the quantity of livestock manure produced annually is large, the potential for CH_4 production from animal wastes is significant. However, only a small portion of this emission potential is realized when the manure is kept in contact with oxygen (USEPA 1993).

For India the estimation made by Bhattacharya et al. (1997) is that annually 5150 Gg of CH_4, 445500 Gg of CO_2 and 54 N_2O Gg are emitted from animal wastes based on populations of animals in 1990 (Table 19). The estimation made by USEPA (1992) is 1550.7 Gg/a of CH_4 on populations of animals in India in 1988 is quite different because of uncertainties in the various factors involved. Methane-conversion factor (MCF) represents the potential for emitting CH_4 that is actually realized considering the characteristics of the manure-management systems and environmental conditions. The MCF for a tropical climate (assuming 30ºC) was used in these estimations (Gibbs & Woodbury 1993)

Table 19. GHG emission from the wastes of different animals (kg/head/a) (Bhattacharya et al. 1997).

Animals	CH_4	CO_2	N_2O
Ass	4.413	1492.0	0.167
Buffalo	5.928	1129.7	0.086
Camel	4.917	1383.2	0.250
Cattle	15.854	1315.2	0.131
Chicken	0.110	18.2	0.004
Duck	0.135	12.4	0.002
Goat	1.288	311.9	0.043
Horse	5.824	1812.4	0.241
Human	1.437	51.6	0.016
Mule	5.723	2155.8	0.241
Pig	12.164	430.1	0.057
Sheep	2.891	278.3	0.027

Myles (2001) has estimated that 5 kg fresh dung (manure) could be easily collected per animal per day from the present bovine population of 300 million. Then at least 1,500 million kg of dung is collected each day in India. Out of this, about 1/3rd (500 million kg or 0.50 million tones dung) would be burnt each day as cooking fuel, in the form of dried dung, in the traditional cook stoves, which are only about 11% efficient. Out of the balance of approx. 2/3 (1.0 Mt), the major percentage, about 75% (0.75 Mt per day) is used as organic manure in agricultural fields, in an inefficient manner. Normally this quantity of dung is dumped each day in heaps or in open pits, just outside the farmers' house, allowing it to get decomposed for 4-6 months till it is used in the next crops. In both these cases (i.e. direct burning and making manure in a traditional manner), the bovine dung that is an excellent resource ends up becoming the source of problems (Myles 2001).

The bovine dung, when allowed to decompose in a traditional manner making organic manure by either dumping in heaps or in open pits just outside in the backyard of the farmers house in Indian villages would release CH_4 to the atmosphere. Myles (2001) estimated that the CH_4 emissions of fresh bovine manure left in an open field (20% TS) would be 10.3 kg/m^3. The estimation was based on the calculation by the Danish Energy Agency for CH_4 emissions of liquid cattle manure, where the fresh manure (dung), urine and water are processed together and its total solids (TS) content is about 7% (Danish Energy Agency Report 1995).

6.7.2 GHG emissions from biogas plants

There are not many studies about CH_4 leaks from biogas digesters and pipelines. The Division of Environmental Sciences, Indian Agricultural Research Institute was assigned a project entitled ´Greenhouse gas emission from exposed areas of biogas plants’ in January 1999. This study is expected to provide data to assess the extent of emission of greenhouse gas, i.e. CH_4 from biogas plants and explore measures. So far there is not yet any published results of the study (MNES 2000, 30).

Khalil et al. (1990) studied trace gases from biogas plants in China. They found that biogas plants are not a significant global source of methane or of any other GHG (e.g. CO_2). They found that even on regional scales biogas generators do not contribute significantly to the excesses of GHG. Their research showed that the leakage is small, probably around 1 % of the production of the biogas plant and not more than 5 % from the size of 4-10 m^3 biogas plants.

There have been some problems with the construction of the biogas plants. In some cases a biogas plant has not been built decently because of e.g. lack of expertise of a mason or savings with quality of materials e.g. bricks. Constructional defects can cause some functionality problems later on and also leakages from a digester or exposed areas. According to monitoring made by Dutta et al. (1997) and National Council for Applied Economic Research (NCAER 1992), technical problems due to false construction are not very usual. Only small proportion, 6 %, of the plants had stopped functioning because of construction-related problems.

Most commonly occurring technical defects can be linked to defective maintenance e.g. lack of spare parts. According to Dutta et al. (1997) 30% of reasons for non-functionality were due to components getting damaged and lack of maintenance of plants by users. One common technical problem is pipeline leakage because of old or damaged pipeline, which cause leakages of methane to atmosphere.

In addition to technical defects, the performance of a biogas plant is by a great deal determined by the user’s mode of operation and maintenance. E.g. Deenbandhu biogas plant is constructed the way that in a case of irregular use of biogas pressure will not increase dangerously high in a digester but the extra gas leaks through outlet opening. Biogas leaks out from a digester even if the plant is not fed that particular day because of a gas production of existing material in a tank.

When figuring the total GHG impact of biogas technology, the impact of construction, e.g. building materials and their transporting should also be included. GHG-emissions of cement industry are remarkable and some there is some emissions also from burning of bricks. However, the average useful working life of Indian household biogas is estimated to be 20 years (Myles 2001), and under the circumstances the impact of the GHG-emissions of the construction compared with the whole life cycle of a biogas plant must be relatively small.

7 MATERIALS AND METHODS

The local environmental and health impacts of biogas technology used in rural areas of India, was estimated by referring to previous studies. It was concentrated on three impacts of rural small-scale biogas technology. These impacts represent the main environmental and health impacts:

- impact on biomass resources,
- impact on soil quality and
- impact on indoor air quality.

The second part of the study was to estimate the global environmental impact of small-scale biogas technology in rural India. In this part of the study the most apparent global impact of the biogas technology, namely greenhouse implication was estimated.

A lot of information and practical ideas have been collected during the planning trip (2001) and expert trip (2002) of the author to a renewable energy technology developing co-operation project in rural areas of Bharatpur, India.

7.1 Estimation of local environmental and health impact

7.1.1 Estimation of impact on biomass resources

The impact on biomass resources was studied by figuring the amount of fuelwood, which could be theoretically saved by using biogas as cooking fuel.

The mean rural family size biogas plant in India was taken as an example. Useful energy (energy delivered to the pot) of biogas was compared to acacia fuelwood combusted in traditional mud stove and eucalyptus fuelwood combusted in 3-rock and improved vented mud stove.

According to the case study made by Dutta et al. (1997) the average amount of dung fed in rural biogas plant is 28 kg (instead of recommended 50 kg) in case of 2 m^3, 32 kg in the case of 3 m^3, and 29 kg for 4 m^3 and 60 kg for 6 m^3. 1 m^3 plants were estimated to be fed as half of the feeding of 2 m^3 since there was no statistics about it. Average feeding of one mean biogas plant was calculated from monitored feeding of different household plant capacities weighted by their distribution.

Weighted by distribution of biogas plants in rural India the mean daily feeding of biogas plant is 29.1 kg. If estimating that the feeding of 1 kg of fresh dung produces 0.035 m^3 biogas (e.g. Mehla et al. 1986) the average feeding of one biogas plant, 29.1 kg, produces 1.02 m^3 biogas, which is actually about half of the optimum production.

According to Gustavsson (2000) household biogas plant can produce 30-40 liters of biogas per 1 kg of fresh dung. 50 kg of fresh dung produces at optimum level 2 m^3 biogas, which means the production of 40 l/kg (TERI 1994b). It was estimated that the average production of a rural biogas plant is 35 liters of biogas per 1 kg of fresh dung. The biogas production was calculated from the mentioned average daily feeding of 29.1 kg of fresh dung.

The basic content of biogas is CH_4 and CO_2, which are found in different proportions depending on input to the system and the conditions during the fermentation process. Traces of hydrogen, sulphur, ammonia and oxygen can also be found in various degrees (Gustavsson 2000). Typical methane content of household biogas plant in India is 55-70 % (Myles 1985, FAO 1996). The energy content of biogas depends on the methane content of biogas. The energy content of biogas can be 14.4-21.6 MJ/m^3 (Alakangas 2000). The energy content of 20.0 MJ/m^3, which has been used as an average energy value for biogas (Myles 1985, FAO 1996), was used. The energy produced by an average biogas plant per day and year was calculated. By multiplying the fuel energy content with overall efficiency (fuel energy going into a pot, 0.574 for biogas stove) (Table 15), useful energy produced by one average biogas plant was calculated per day and year.

Fuelwood, in this case acacia contains 15.10 and eucalyptus 15.33 MJ/kg energy. The overall efficiency of traditional mud stove is 0.182, of 3-rock it is 0.176, and of improved vented mud it is 0.220 (Smith et al. 1998). By multiplying the fuel energy content of eucalyptus and acacia with overall efficiencies of different stoves the useful energy (energy going into pot in cooking) was calculated. The figures for acacia and eucalyptus with different stoves are shown in Table 20.

Table 20. The energy content and useful energy of fuelwood combusted in different stoves.

	Acacia	Eucalyptus	
Fuel energy content [1]	15.10 MJ/kg	15.33 MJ/kg	
Stove	Traditional mud stove	3-rock	Improved vented mud stove
Overall efficiency [1]	0.182	0.176	0.220
Useful energy	2.75 MJ/kg	2.70 MJ/kg	3.37 MJ/kg
[1] Smith et al. 2000b			

When compared the useful energy produced by 2 m^3 biogas plant to energy produced by combusting fuelwood in different stoves the amount of saved fuelwood were calculated for day and year. Also fuelwood saving of all functioning biogas plants in India was calculated at present level (end of year 2000).

7.1.2 Estimation of impact on soil quality

The impact on biomass resources was studied by figuring the amount of dung, which could be theoretically saved by using biogas as cooking fuel instead of direct burning. The useful energy (energy delivered to the pot) of biogas was compared to dung combusted in traditional mud stove, hara and improved vented mud stove. The figures and calculation of the biogas and energy production of an average biogas plant is described in previous chapter.

The energy content of dung is 11.76 MJ/kg (Smith et al. 1998). The overall efficiency of dung combusted in traditional mud stove, in hara and in improved vented mud are 0.088, 0.082 and 0.100, respectively (Smith et al. 1998). By multiplying the fuel energy content of dung with overall efficiencies of different stoves the useful energy (energy going into pot in cooking) was calculated. The figures for dung with different stoves are shown in Table 21. According to measurements by Smith et al. (1998) the overall efficiencies varied with different fuels.

Table 21. The energy content and useful energy of dung combusted in different stoves (figures used in this study).

Fuel energy content [1]	11.76 MJ/kg		
Stove	Traditional mud stove	Hara	Improved vented mud stove
Overall efficiency [1]	0.088	0.082	0.100
Useful energy	1.03 MJ/kg	0.96 MJ/kg	1.18 MJ/kg

[1] Smith et al. 1998

By comparing the useful energy produced by mean family size biogas plant to energy produced by dung combusted in different stoves the amount of dung saved were calculated for day and year. Also dung saving of functioning biogas plants in India was calculated at present level (end of year 2000).

7.1.3 Estimation of impact on indoor air quality

The impact on the indoor air quality of biogas technology was estimated by comparing the total suspended particles (TSP) and carbon monoxide emissions of fuelwood and dung with biogas, when same amount of useful energy is produced. The emissions of some fuel/stove combinations are shown in Table 22. These pollutants were chosen because they are both important health-damaging pollutants of indoor air and recent statistics of these emissions (per energy delivered into pot) in Indian conditions were available.

Table 22. TSP and CO emissions of some fuel/stove combinations (grams per MJ energy delivered into pot) (Smith et al 2000b).

	CO	TSP
Biogas	0.1918	0.0516
Eucalyptus - traditional mud stove	24.19	0.3776
Acacia - 3-rock	23.67	0.7515
Dung – traditional mud stove	44.85	1.999
Dung – hara	63.66	0.5704

7.2 Estimation of global environmental impact

The global environmental impact of Indian family type household biogas technology was studied by estimating the GHG impact of it. The GHG emissions of biogas were compared to solid biofuels and fossil fuels when combusted as cooking fuel.

In the first phase GHG emissions of different cooking fuels were calculated by weighting the distribution of the national household fuel consumption ratio to get average emissions for household biofuels and fossil fuels. In second phase the mean global warming commitment of biofuels and fossil fuels were calculated. The third phase was to figure the overall energy produced by family type biogas plants in India. In the forth phase the reduction of global warming commitment (GWC) was calculated by comparing the GHG emissions when burning biogas or other cooking fuels.

To estimate the climate change implications of different fuels, the GWC as CO_2 equivalent was calculated as

$$GWC = \Sigma GHG_i * GWP_i \tag{1}$$

where GHG_i is the quantity of GHG in question, and GWP_i is the global warming potential of that particular GHG. The GWP values for 100 years was used in this study. E.g. IPCC uses 100 years values most commonly as time horizon for climate change implications.

The greenhouse implication of biogas as cooking fuel has been compared with three prevalent biofuels used as cooking fuel, and fossil fuels used for cooking purposes in India. The biofuels are fuelwood, cattle dung and crop residues, which cover about 95 % of cooking fuels in rural India. Share of commercial fuels, kerosene and LPG, is about 3 %.

The GHG emission values for different fuel/stove combination were got from the study of USEPA made by Smith et al. (1998). In the mentioned study GHG emissions of 26 fuel/stove combinations used in households in India were examined. Root and charcoal were left out of this study since their using, as household fuel, is marginal in India. The GHG emissions of different fuel/stove combinations are listed in Table 23.

Table 23. GHG emissions of different fuel/stove combinations per delivered energy to pot (g/MJ-del) and using ratio in households in India (Smith et al. 2000b).

Fuel/Stove		CO_2	CO	CH_4	N_2O	Using ratio (%)
LPG		125.6	0.608	0.00203	0.0060	
Kerosene[a]		142.8	1.941	0.0331	0.0043	
Biogas		142.0	0.192	0.0989	0.0094	
Wood[b]	- tm	506.3	24.19	1.432	0.0335	86.8
	- imet	405.6	18.06	1.122	0.0499	0.4
	- ivm	375.9	38.35	3.219	0.0508	2.9
	- ivc	322.0	19.02	0.965	0.0430	0.3
	- 3-R	534.5	22.92	2.242	0.0460	9.6
Crop residues[c]	- tm	635.2	31.99	3.698	0.0239	94.8
	- imet	376.9	15.60	1.071	0.0452	0.5
	- ivm	479.0	42.17	11.17	0.0820	4.2
	- ivc	371.2	18.10	1.567	0.0579	0.5
Dung	- tm	929.0	44.85	5.156	0.2786	58.8
	- ivm	905.6	25.77	2.764	0.2713	4.7
	- ivc	694.9	21.01	2.378	0.2086	0.5
	- hara	1010	63.66	18.21	0.3028	36.0

tm = traditional mud, imet = improved metal stove, ivm = improved vented mud, ivc = improved vented ceramic, 3-R = 3-rock. The description of the stoves in Table 13.

[a] the average value of two different kerosene stove were used.

[b] the mean value of acacia and eucalyptus is used here.

[c] mustard husk

The GHG emissions for each fuel were calculated by weighting them with the using ratio of different stoves in rural households in India. Weighted emissions for different household fuels are shown in Table 24.

Table 24. GHG emissions of different fuels per delivered energy into pot (g/MJ-del) weighted by the ratio of using as household fuel in India.

Fuel	CO_2	CO	CH_4	N_2O
LPG	125.6	0.608	0.00203	0.0060
Kerosene[a]	142.8	1.941	0.0331	0.0043
Biogas	142.0	0.192	0.0989	0.0094
Wood	504.3	24.44	1.559	0.0353
Crop residues	626.0	32.27	3.988	0.0266
Dung	955.9	50.61	9.729	0.287

Since there are several GHGs from different fuels, it is necessary to have an aggregate index to make comparisons. GWC was calculated for each fuel by using GWP for GHGs. In this way all the GHG emissions are calculated to CO_2 equivalent and can be compared easily. GWP values for 100 years given by the latest IPCC (2001) report has been used in this analysis.

The GWC of the fuels depends on which gases are included in the calculations. The GWPs of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are well established, but with CO there is some uncertainties (IPCC 2001). The 100-year GWP for CO is estimated to be 1.0 to 3.0 according to IPCC (2001). In this study a mean value of 2.0 was used (Table 25).

Table 25. Global warming potentials (GWPs) used in this analysis (IPCC 2001).

Gas	100 years
CO_2	1.0
CH_4	23
N_2O	296
CO	2.0

GWC value for different fuels depends also whether they are considered to be renewable or not. According to TERI (2002, 323) sustainable supply of fuelwood was 20 % of the total demand. In these calculations 20 % of fuelwood is taken as renewable and 80 % as non-renewable. Dung, crop residues and biogas are always considered to be renewable and fossil fuels, kerosene and LPG, non-renewable. In the case of fuelwood GWC is calculated by weighting the value by taken one fifth as renewable and four fifth as non-renewable.

In the case of renewably harvested, CO_2 in the biomass fuels is completely recycled and there is no net increase in GWC from CO_2. Eventually most of the products of incomplete combustion (PICs) are oxidised to CO_2, but in the meantime they have greater global warming potentials than CO_2 (Smith 2000a). GHG impact of CO_2 emissions are eliminated when the fuel is renewably harvested. In non-renewable harvesting all the GHG emissions are a net addition to the atmosphere. The GWC values calculated for different GHGs are listed in Table 26.

The distribution of biofuels in rural Indian households is: 63.5% wood (20% renewably and 80% non-renewably harvested), 16.9% dung and 19.6% crop residues (Table 14). The average emission of household solid biofuels and fossil fuels as CO_2-equivalent was calculated by weighting the GWCs by their consumption ratio. Kerosene and LPG were used as primary cooking fuel in 1.22 and 1.34% of rural households in 1991, respectively (TERI 2002). Estimation of GWC for fossil fuels was weighted similarly. Biogas was compared to biofuels and fossil fuels used in households in rural India. In this comparison delivered energy to pot was seen to give the most comparable result.

Table 26. GWCs for household fuels (grams CO_2 equivalent per MJ delivered) (including CO_2, CH_4, N_2O and CO) (GWP: 100 years).

Fuel	CO_2	CO	CH_4	N_2O	$\sum CO_2$ eq
Dung	0	101	223	85	410
Crop residues	0	32	164	7.9	164
Wood					
Non-renewable	504	49	36	10	599
Renewable	0	49	36	10	95
Biogas	0	0.4	2.3	2.8	5.4
Kerosene	143	3.9	0.8	1.3	149
LPG	126	1.2	0.05	1.8	129

As mentioned before 1 m^3 biogas was estimated to contain 20.0 MJ/m^3 energy and one mean biogas plant (feeding of 29.1 kg of dung) produces daily 1.02 m^3 biogas, which contains 20.4 MJ energy. Overall efficiency, which means the fraction of fuel energy going into pot while cooking is 0.574 for biogas stove (Table 15). By multiplying the net energy of biogas with the overall efficiency the useful energy produced daily by one mean family type biogas plant was calculated.

GWC of biogas as a substitute for solid biofuels and fossil fuels in cooking was studied. The GWCs of biofuels and fossil fuels were calculated compared to biogas when same amount of useful energy was produced by combusting in cookstoves. In this figuring it was assumed that biogas substitute the other fuels in same proportion as they are used in rural households in India.

Through the National Project on Biogas Development 3.030 million family type biogas plants have been set up till end of year 2000 in rural India. When estimating the actual useful energy production of the biogas program the functionality status of biogas plants should be taken into consideration as well. According to monitoring made by Dutta et al. (1997) 81 % of the studied biogas plants were functioning.

The reduction of GWC as CO_2 equivalent by using biogas as cooking fuel instead of the direct burning of solid biofuels or fossil fuels at present and potential state of biogas program in India was estimated. The results were compared to national GHG emissions from household fuels in India. The inventory of GHG emissions from household cookstoves by Smith et al (2000b) was used (Table 27).

Table 27. GHG emissions from cookstoves in India (1990-91) (Smith et al 2000b).

	CO_2 (Tg/a)	CO (Tg/a)	CH_4 (Tg/a)	N_2O (Tg/a)
Biofuels	418.9	20.74	1.92	0.033
Fossil fuels	18.38	0.55	0.0026	0.0007

From these CO_2 equivalent was calculated for household emissions. 283.9 Tg of the CO_2 emissions from biofuels was from fuelwood. Of these 80 % was taken into consideration in the calculation. Other CO_2 emissions from biofuels were not calculated. The GWPs listed in Table 24 were used to figure GWC value as CO_2 equivalent.

In the rural households biogas replace mostly biofuels as cooking fuel. Thus, the reduction of the GHG emissions of biogas compared with biofuels is used in proportion with the GHG emissions of the national use of household fuels.

8 RESULTS

The subject of this study, environmental impacts of household biogas plants in rural India, was approached from two perspectives: local and global. Impact on biomass resources, soil quality and indoor air quality represent the local perspective. Greenhouse implications of biogas technology reveal the global impact.

8.1 Local environmental and health impact

8.1.1 Impact on biomass resources

The impact on biomass resources has been studied by calculating the savings of fuelwood. Although there is no direct correlation between deforestation and rural energy use according to previous studies (e.g. Ravidranath & Hall 1995), it could be assumed that saving of fuelwood reduces pressure of cutting forests. This is true especially in areas, which are already degraded and suffer scarcity of fuelwood.

Biogas used as cooking fuel was compared to fuelwood. The useful energy production for cooking of one average biogas plant (average feeding of dung) was compared to the using of acacia and eucalyptus fuelwood in different stoves.

It was calculated that one average family size plant (feeding of 29.1 kg of fresh dung) in India produces biogas 1.02 m^3 per day and 372 m^3 per year and that the useful energy of the produced biogas for cooking (going into pot) is 11.7 MJ per day and 4268 MJ per year.

Useful energy from 1 kg of acacia combusted in traditional mud stove is 2.75 MJ/kg, from 1 kg of eucalyptus combusted in 3-rock is 2.70 MJ/kg and 1 kg of eucalyptus combusted in improved vented mud stove is 3.37 MJ/kg. To produce the same amount of useful energy fuelwood is needed

Acacia in traditional mud stove	4.25 kg per day and 1550 kg per year,
Eucalyptus in 3-rock stove	4.33 kg per day and 1580 kg per year or
Eucalyptus in improved vented mud stove	3.47 kg per day and 1270 kg per year.

If taking into consideration the national using ratio of fuelwood in different cooking stoves (Table 14), the saving of one average biogas plant is 4.23 kg per day and 1545 kg per year. It was estimated that the annual saving of fuelwood of all 3.03 million household biogas plants at functionality status of 81% (if biogas replaces only fuelwood as cooking fuel) is 3.8 Mt. If taking into consideration the using ratio of fuelwood (63.5%) compared with other biofuels (it is assumed that biogas is replacing them in the using proportion), the saving of fuelwood is 2.4 Mt/a. The reduction compared to the national consumption of fuelwood (200,5 Mt) is 1.2 %.

8.1.2 Impact on soil quality

The impact on the household biogas technology in India to soil quality is estimated by the potential saving of dung. The useful energy production for cooking of one mean biogas plant (average feeding of dung) was compared to the direct burning of dung in different stoves. With direct burning of dung the possibility to use it as fertilizer is lost. Through anaerobic digestion in a biogas reactor the quality of the slurry as fertilizer is improved (Chapter 6.4.4).

It was calculated that the production of useful energy of one average Indian household biogas plant is 11.7 MJ/d. The useful energy from 1 kg of dung combusted in traditional mud stove is 1.03 MJ/kg, in hara 0.96 MJ/kg and in improved vented mud stove 1.18 MJ/kg. Before combusting dung is dried as dung cakes. Total solids (TS) of fresh dung collected in India is estimated to be 20% (TERI 1994b, Myles 2001). This means that from 5 kg fresh dung it is possible to get 1 kg dried dung to use as cooking fuel.

To produce the same amount of useful energy when fresh dung is combusted in

traditional mud stove	56.8 kg per day and 20700 kg per year,
hara	60.9 kg per day and 22200 kg per year or
improved vented mud stove	49.6 kg per day and 18100 kg per year.

If taking into consideration the national using ratio of different cooking stoves (Table 14), the saving of one average biogas plant is 54.4 kg per day and 19800 kg of fresh dung per year. Instead of losing the fertilizing value of almost 20 tonnes of dung annually by combusting, one average houshold biogas plant converts it to good quality organic manure, biogas slurry.

The saving of 3.03 million household biogas plants, at functionality rate 81 %, (if biogas would replace only dung as cooking fuel) was estimated to be 48.7 Mt of dung per year. If taking into consideration the using ratio of dung compared to other biofuels (16.9 %), and if assumed that biogas is replacing them in same proportion, the annual saving would be 8.2 Mt of fresh dung. The reduction to the national consumption of dung (53.5 Mt dried dung, 267.5 Mt fresh dung) used as cooking fuel is 3.0%.

8.1.3 Impact on indoor air quality

The total suspended particles and carbon monoxide emissions of fuelwood and dung combusted in traditional stoves were compared to the emissions of biogas stove. The figures of the emissions were based on the energy delivered into pot, because it could be assumed to give the most relevant information for the comparison.

It was found that when a meal is cooked with fuelwood in a traditional mud stove and in a 3-rock the CO emissions were over 120 times bigger than with biogas. Cooking with dung in a traditional mud stove and in a hara stove was even worse producing 230 and 330 times bigger CO emissions, respectively, than biogas.

The TSP emissions of fuelwood in a traditional mud stove and a 3-rock were 7 and 15 times bigger, respectively than biogas. The TSP emissions of dung in a traditional mud stove and in a hara 14 and 11 times bigger, respectively, than biogas.

When the emissions were weighted by using ratio of different cookstoves the CO emissions of using biogas as cooking fuel are 120 times smaller than fuelwood and 260 times smaller (weighted by using ratio of cookstoves) than dung and TSP emissions 8 times smaller than fuelwood and 13 times smaller than dung. Indoor air quality could be estimated to be also much better when cooking with biogas.

8.2 Global environmental impact

As the global point of view the GHG emissions of biogas used as cooking fuel were compared with solid biofuels and fossil fuels.

The average feeding of mean household biogas plant, weighted by the distribution of different reactor sizes and their feedings in rural India, is 29.1 kg of dung per day. The figures, which describe the average household biogas plant in India, are shown in Table 28.

Table 28. The biogas and useful energy production of average family size biogas plant in India.

Biogas fuel energy content [1]	20.0 MJ/m^3	
Overall efficiency of biogas stove [2]	0.574	
Production of one average biogas plant (feeding of 29.1 kg of dung per day)		
Production of biogas (m^3)	1.02 m^3/d	372 m^3/a
Production of energy	20.4 MJ/d	7435 MJ/a
Production of useful energy (energy going into pot)	11.7 MJ/d	4268 MJ/a

[1] Myles 1985, FAO 1996, [2] Smith et al. 2000b

For biofuels, fossil fuels and biogas the global warming commitments (GWCs) as CO_2 equivalent were calculated as defined in Chapter 7.2 and are listed in Table 29. The GWCs for biofuels and fossil fuels were calculated by weighting the emissions with the national consumption ratio of different household fuels.

Table 29. GWCs for solid biofuels, fossil fuels and biogas (g CO_2 equivalent) (MJ delivered energy to pot).

Fuel	GWC
Biofuels (dung, wood and crop residues)	425
Fossil fuels (kerosene and LPG)	138
Biogas	5

The GHG emissions as of biogas combusted in household stove produced by an average plant is 64 grams as CO_2 equivalent per day. To produce the same amount of useful energy by direct burning of prevalent solid biofuels (dung, wood and crop residues) and fossil fuels (kerosene and LPG) the GHG emissions are 4965 and 1616 grams CO_2 equivalent, respectively. In these calculations CO_2, CO, CH_4 and N_2O are included and the time horizons of GWPs used here are 100 years.

The reduction of greenhouse gas emissions of biogas compared with direct burning of biofuels and fossil fuels are 420 and 133 g CO_2 equivalent per MJ. When average daily energy production of one biogas plant is 11.7 MJ, the reduction of GHGs per one biogas plant compared to the direct combustion of biofuels or fossil fuels are 4.9 kg and 1.5 kg carbon as CO_2 equivalent per day, respectively. The annual reductions of GHGs compared to biofuels and fossil fuels are 1790 kg and 567 kg CO_2 equivalent per one biogas plant. The results are calculated as biogas is used instead of biofuels or fossil fuels.

The reductions of GHGs of 3.030 million household biogas plants (in the end of 2000) at functioning status 81 % as compared to combustion of solid biofuels and fossil fuels are 4.4 Tg and 1.4 Tg CO_2 equivalent annually. If the estimated potential by MNES of 12 million biogas plants were fulfilled, the annual reduction of GHGs compared to combustion of solid biofuels and fossil fuels would be 21.5 and 6.8 Tg CO_2 equivalent, respectively.

The GHG emissions of household cooking fuel use of biofuels and fossil fuels were 322.5 and 19.0 Tg per year as CO_2 equivalent, respectively and altogether 341.5 Tg per year. The reduction of GHGs when biogas is used instead of biofuels is 1.4 % compared to all GHG emissions of cooking fuels and could be 6.3% at potential level of biogas program. The results are summarized in Table 30.

Table 30. The direct (CO_2, CH_4 and N_2O) and indirect (CO) GHG reduction summarized as CO_2 equivalent of biogas household biogas technology in India in end of year 2000.

	GHG reduction
Production of an average biogas plant	
Biogas substituting biofuels (/biogas plant)	1790 kg/a
Biogas substituting fossil fuels (/biogas plant)	567 kg/a
3.03 million biogas plants (81% functioning)	4.4 Tg/a
Mitigation % compared to all household fuel combusting in India	1.4 %
At potential level 12 million biogas plants Mitigation % compared to all household fuel combusting	21.5 Tg/a 6.3 %

9 DISCUSSION

The objective of the study was to estimate the local and global environmental impact of biogas as a substitute for biomass combustion for cooking purposes. The local environmental impacts were studied by estimating the impact of household biogas technology on biomass resources, soil quality and indoor air quality. The global environmental impact were studied by estimating the greenhouse implications.

The reduction in fuelwood use by adopting biogas as cooking fuel represented the impacts on biomass resources. The reduction in dung use as cooking fuel represented the impacts on soil quality. Fuelwood was seen as biomass resource and dung or actually slurry after the anaerobic digestion process as organic fertilizer, which have a positive effect on soil quality. TSP and CO emissions indicated the impacts on indoor air quality. These chosen viewpoints could be seen as the indicators of the different factors, which have influences but they don´t give the whole picture of discussed matter. However, they have obviously the most important influence on discussed matter.

First the production of biogas and useful energy of an average Indian household biogas plant was calculated. The annual biogas production of an average household biogas plant in India is 372 m^3, which contains 4.3 GJ useful energy. Biogas is mainly used as cooking fuel in rural Indian households but this amount of biogas could give light, when used in a biogas lamp for about 2700 hours per year or about 7 hours per day. If used as fuel in a biogas engine (Kirloskar) it could also generate about 300 kWh power.

The production of biogas was estimated to be 0.035 m^3 per 1 kg of raw dung (e.g. Mehla et al. 1986). However, there are some uncertainties in using of this value. According to performance evaluation of deenbandhu and janata biogas plants by Kalia & Kanwar (1996) the production ranged between 0.016 and 0.036 m^3 per kg dung per day. The evaluation was made in a hilly region, where variations of temperature are higher than in India generally. The optimum biogas production of deenbandhu biogas plant is estimated to be 0.040 m^3. However, it could be that the gas production of 0.035 m^3 per 1 kg of dung is almost at the optimal level, which could fall even half of that for climatic or other reasons.

The production of useful energy of an average biogas plant was compared to energy equivalent of fuelwood combusted in cookstove. An average Indian household biogas plant was found to produce annually energy equivalent of more than 1500 kg of fuelwood. Compared to previous study of TERI (1994b) the production of 2 m^3 biogas plant was estimated to replace energy equivalent of 2550 kg of fuelwood, which probably represents the production of a biogas plant at the optimum level.

Reduction in fuelwood use by adopting biogas is estimated at 6 Mt annually of 2.5 million biogas plants (in 1996). This could be true if biogas plants are supposed to function at the optimal level. In this study all Indian household biogas plants are producing annually energy equivalent of 3.8 Mt of fuelwood and if the using ratio of fuelwood is taking into consideration the annual reduction is only 2.4 Mt representing 1.2 % of natinal consumption. The reduction is significantly smaller than estimated earlier by Indian authors.

As discussed in Chapter 6.4.2 the quantities of spared fuelwood and dung are probably in a reality still smaller because the most users of biogas are also using other traditional fuels like wood and dung cakes. Accoring to Dutta et al. (1997) they were found to use only 25-40% less fuelwood after switching to biogas. One reason for this is that traditional fuels are still used for some specific purposes like making the bread or warming of milk. It could be also that some households use biogas only for some purposes, like making tea or boiling rice whereas traditional fuels are used for other purposes. It is possible that biogas is used for something extra like making tea daily once more. It is also possible that biogas doesn´t fulfill the need of fuel for cooking purposes and that is why traditionals are also used. In this case the full energy production of biogas plant replaces the use of traditional biofuels.

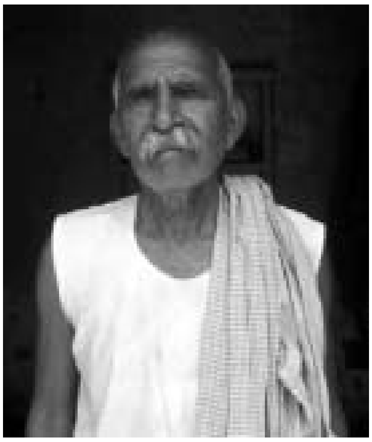
At national level the saving does not sound very remarkable but on village and individual level the lack of firewood is daily problem for millions of families. Fighting for diminishing biomass resources increase specially women's workload and threatens biomass resources especially in areas, which are already degraded and suffer scarcity of fuelwood. As discussed in Chapter 6.4.2 biogas users perceived the wood saving as an important benefit of the technology. About 26% of the biogas plant owners considered wood saving to be the most important benefit, while 32% ranked it second (Dutta et al. 1997). It is estimated by TERI (2002) that sustainable harvesting of fuelwood is only 20 % in India. According to this the reduction of unsustainable fuelwood harvesting is very important and could be realised by increasing biogas technology among the other means.

According to the estimation of this study the biogas technology at present level in rural India produces energy for cooking as fuel equivalent of almost 50 Mt of dung per year. More realistic is to assume that biogas substitutes dung in the proportion that is used nationally as household fuel. In this case the annual saving is about 8 Mt, 3 % of the national consumption. This means that 113 tonnes of nitrogen, 94 tonnes of phosphorous and 118 tonnes of potassium as a form of effluent could be used as organic fertilizer instead of wasting it through combusting in cookstoves. This consumption of same quantity of concentrated chemical fertilizers could be to reduced. It should be reminbered that for example the production and transport of these fertilizers would have also environmental impacts.

To estimate the impact of biogas technology to soil quality was studied by estimating the amount of dung, which could be saved by using biogas technology instead of direct burning. As point out in the study by TERI (1994b) the effective heat produced by one 2 m^3 biogas plant could replace annually fuel equivalent of 8,9 tonnes of dried dung . The amount is probably based on optimal production of biogas plant. The amount calculated was almost 20 tonnes of raw dung, which is little less than 4 tonnes.

There is not much scientific evidences about the impact of biogas technology to soil quality. At general level there is knowledge about positive effect of organic manures for example to micro-organisms of earth. In addition it was easy to get the comprehension of a good impact of biogas slurry to earth and plants on the field from experienced farmers.

As discussed in Chapter 6.4.4 among farmers there is many perceptions about the quality of biogas slurry. Some of them think it is not as efficient as raw dung. About 48% of experienced farmers felt according to Dutta et al. (1997) that the use of biogas slurry marginally increased the crop yield, while the remaining 52% felt that the application of slurry has not made any difference to the yield. However, most farmers (75%) rated the quality of biogas slurry good as organic manure.



An old farmer, living in Bharatpur District, Rajasthan, has a long experience about biogas slurry. He simply praises the effect of slurry to his fields. He uses only slurry on the fields near by his house and uses it a lot on these fields: about five cm layer of slurry on the top. On the fields he and his sons grow wheat and mustard seeds. The crop from these fields they use by themselves because of the better taste of it. The farmer compares effect of slurry to ayurvedic (Indian herbal) medicine: it keeps field and plants in good condition and the crop mature two weeks before other crop (the interview was made by author in April 2002).

There are many health-damaging substances in biomass smoke. The impact on indoor air quality of biogas technology was estimated by comparing the TSP and CO emissions of solid biofuels and biogas. As described in chapter 8.1.3 the CO emissions of biofuels were 120-260 times bigger than of biogas and TSP emissions about 7-14 times bigger. As discussed in Chapter 6.4.4 38 % of women felt that the use of biogas has led to a reduction in the smoke level and contributed towards cleaner and more comfortable kitchens.

As discussed in Chapter 5.2 there were in 1991/92 about 82 million households at full risk for indoor pollution, which means about 460 million people, were at risk of indoor pollution in risk. The range of mortality from indoor air pollution is in range 310 000-470 000 in India. As seen also in comparing of emissions from biofuels and biogas, it could be certainly assume that shifting to biogas technology lead to a reduced incidence of respiratory illnesses through removal of health-damaging substances of biomass smoke in the kitchen.

In the second part of the study the objective was to estimate the global environmental impact of biogas technology. This was done by inspecting the greenhouse implications of household biofuels and fossil fuels and by comparing them to impact of biogas technology at present and potential level of biogas program. At the present level of biogas programme, the mitigation of CO_2 equivalent compared to direct burning of biomass is 4.4 Tg per year and it is 1.4 % of total CO_2 equivalent of biomass combusting in India. At potential level of biogas program (12 millions), the mitigation could be 21.5 Tg per year, which represents about 6.3 % of the total biomass combusting. There were not recent studies available to compare these figures.

For a complete analysis of greenhouse implication of biogas technology, the CO_2 equivalent of the whole cycles of fuels should be included as well as possible leakages of biogas digesters and pipelines. The meaning of the leakages from biogas plants and of storing of dung in heaps were not observed, because there was not available exact data about the matter. As discussed in Chapter 6.7.2 the meaning of leakages of GHGs is quite insignificant, probably around 1% of methane production of a biogas plant. On the other hand, when dung, which is used as manure, is dumped into heaps outside farmers house, it would probably also go through some kind of anaerobic process and release methane. So without further studies and measurements about these matters, it is not possible to get the whole picture.

There have been an idea that the household use of biomass, which is renewably harvested, is GHG neutral. The recent studies (e.g. Smith 2000b) have shown clearly that this is not true. Traditional biomass stoves are thermally inefficient and significant portion of the fuel carbon divert into PICs with high global warming commitment and health-damaging effect. Indian biogas program has shown that household biogas technology is realistic alternative to solve these problems in developing countries.

This study could maybe prove, that the large-scale diffusion of a small-scale renewable energy technology may have positive environmental impacts on both local and global levels. Biogas technology offers possibilities to raise local people's quality of live as well as steer the development of rural Indian villages to more sustainable direction.

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