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Global Climate Change and India

a Research Compendium

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Commissioned by:

The Greenhouse Gas Pollution Prevention Project — Climate Change Supplement

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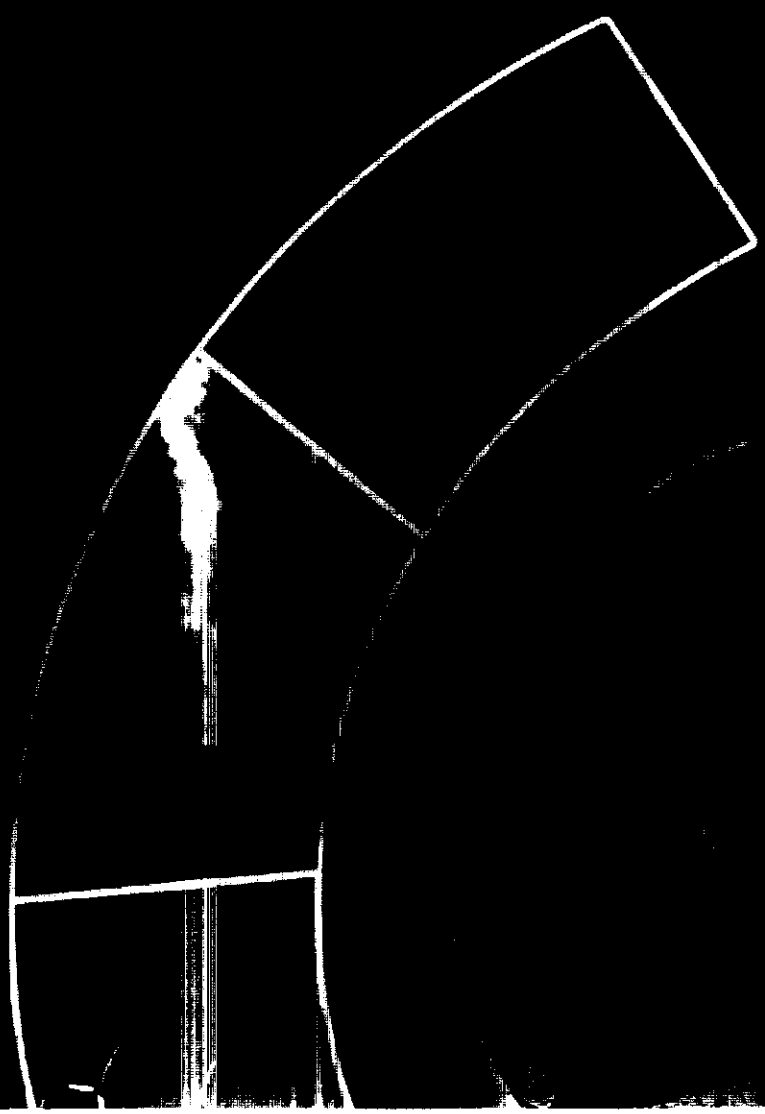
Executive Summary



EXECUTIVE SUMMARY

I. WHY GLOBAL CLIMATE CHANGE RESEARCH IS NEEDED ?

The Intergovernmental Panel on Climate Change (IPCC) has, during the last two decades, brought considerable knowledge and insight to human-induced climate change. These reports have clearly brought out that, due to lack of capacity and resource constraints, the developing countries will suffer most from climate change impacts. There is a need, therefore, for research in the field of climate change to be taken up, particularly in developing countries, to understand various issues that relate to climate change and their repercussions on the developmental activities. In addition, there is a need to create awareness among the civil society and governments in developing countries through research studies in specific geographic areas for proper planning of response strategies to minimize the adverse effects on human life and other ecosystems due to climate change. Such research studies will also develop capacities in developing countries to enable to take appropriate precautionary measures based on the UN precautionary principle. The IPCC's studies and many other studies on climate change are so far mostly limited to global and at best at a regional scale. Very little work has been done to study the climate change issues at the local level.

II. WHY SUCH RESEARCH STUDIES IN INDIA ARE IMPORTANT ?

India is geographically vast, with varied climatic zones and different kinds of representative ecosystems, such as coastal ecosystems, mountainous ecosystems, desert ecosystems, flood-prone ecosystems, etc. Studies taken up in India with varied climatic zones and ecosystems, therefore, can not only help to build strategies for undertaking precautionary measures in India, but can also serve to provide research outputs and knowledge to suit various developing countries. Moreover, India has a very sound scientific base and qualified and experienced manpower to steer such research studies on climate change. India has a very long coast—more than 7,000 km long—and some of the coastal areas are very vulnerable to sea level rise due to global warming. Any such study done in India should be good guidance for island countries and other countries vulnerable to sea level rise, and should provide a very sound guide for deciding on an action plan and for clearly understanding such issues. Another important aspect is that India is the largest democracy in the world, with a huge population of over a billion and a considerable percentage of people leaving below the poverty line. Research outputs and response strategies that are brought out during such studies in India can be appropriate for many developing countries where poverty eradication and improving the quality of life of the people is a major issue. Research in India should focus on how climate change mitigation measures can finally be pro-poor and address to the country's poverty eradication programs.

Since climate change's time scale is in decades, it is prudent to invest in climate change research in India. The ultimate objective of these studies on climate change will not only be to eradicate poverty, but also to help catalyze the sustainable development goals of India.

Impact studies carried out internationally particularly by the IPCC, have brought out clearly that in a country like India, climate changes can have considerable impact on water resources, agriculture and food production, sea level rise along the coast and human health. It is important to initiate in-depth research on all these issues to clearly understand and develop solutions that can be addressed for minimizing the effect of global climate change in India.

III. WHY MITIGATION IS IMPORTANT ?

For abating climate change, there are many routes. The most direct route is through the mitigation of climate change by using **energy efficient technologies** in different sectors or **carbon neutral technologies** or reducing or avoiding carbon emissions from economic activities. Adaptation is another means of reducing the adverse impacts of climate change, but that process is long and drawn-out, such as adaptation of cultivators which are resistant to drought and high temperatures. But such adaptation itself involves considerable research studies and a long-term process. Deciding the suitability of such adaptation measures requires careful scrutiny and country-driven policies. There are many instances of adaptation measures turning to misadaptation and creating more economic problems for the country than solving the issues, whereas mitigation is a more direct and economically viable measure to address to climate change.

IV. COMMISSIONED RESEARCH BY THE GREENHOUSE POLLUTION PREVENTION PROJECT-CLIMATE CHANGE SUPPLEMENT

The Louis Berger Group, Inc. (LBG) Global Environment Team is currently implementing the *"Greenhouse Gas Pollution Prevention Project - Climate Change Supplement (GEP-CCS)"*, a program of the **United States Agency for International Development/India Mission (USAID)**. The program aims to build local capacity and create a forum to foster dialogue and cooperation on widespread clean energy issues between U.S. and Indian government, financial, private, and non-government stakeholders. These initiatives will, in due course, lead to an integrated assessment and subsequent implementation of actions that reduce the rate of growth of greenhouse gas emissions (GHG).

The GEP-CCS Project includes a number of outreach activities designed to generate awareness among stakeholders and will provide information that can be used for awareness building. To implement the latter, GEP-CCS is commissioning a series of "framing" papers on those critical climate change issues in India. The papers have been prepared by eminent Indian researchers who have led the overall design of the research work. The research papers have endured an extensive international review process by those institutions intimately involved in climate change related work or maintain a key interest in India related activities. The papers address the economic, social, and environmental implications of climate change in India and also address technologies and approaches for mitigating the growth of GHG emissions in India.

Over the next few pages, a synopsis has been provided for all of the research papers. The full research papers are included, in their entirety, in the following sections of this compendium.

A. India's Vulnerability to Climate Change

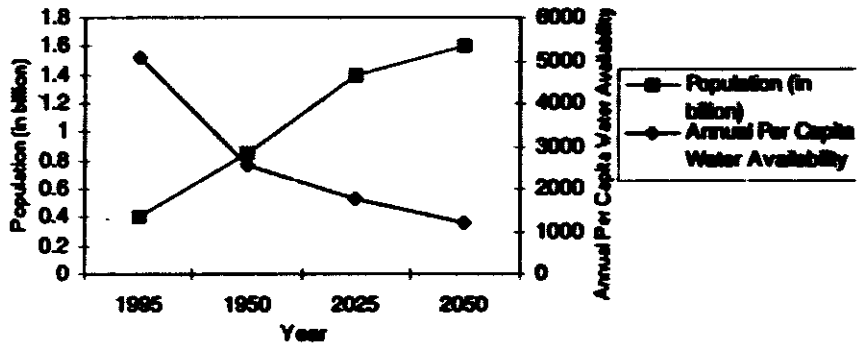
Climate change can adversely impact on the types of cultivators and crops; can impact on groundwater tables and supply, and may adversely affect irrigation systems. Some of the Indian researchers have shown significant effect on wheat yields, as well as on the rice production with the rise in temperature.

There can be considerable economic and welfare impacts due to India's vulnerability to climate change, particularly along the coasts and on islands, due to inundation of many coastal areas and displacement of people and consequent disruption of the coastal economy.

On the whole, India receives plentiful rainfall. India's average annual surface run-off generated by rainfall and snowmelt is estimated to be about 1,869 billion cubic meters (BCM). India's rechargeable annual groundwater potential has been assessed at around 431 BCM in aggregate terms. Many states in India, like Haryana and Punjab, have exploited about 94% of their groundwater resources. Areas with depleting groundwater tables are found in Rajasthan, Gujarat, most of western Uttar Pradesh and in all of the Deccan states.

India's finite and fragile water resources are stressed and depleting. At the same time, India's total annual demand for water is increasing from 552 billion cubic meters (BCM) in 1997 to 1,050 BCM by 2025. India's agriculture and food security are highly vulnerable. Wheat and rice production will fall due to global warming. Various reforms in the management of water resources are necessary and the role of government and the society are very vital. There is considerable scope in the country for water harvesting through community-level efforts to cope with climate events like droughts and recharging ground water by extensive use of checkdams.

Figure - Population and Water Availability Trends in India



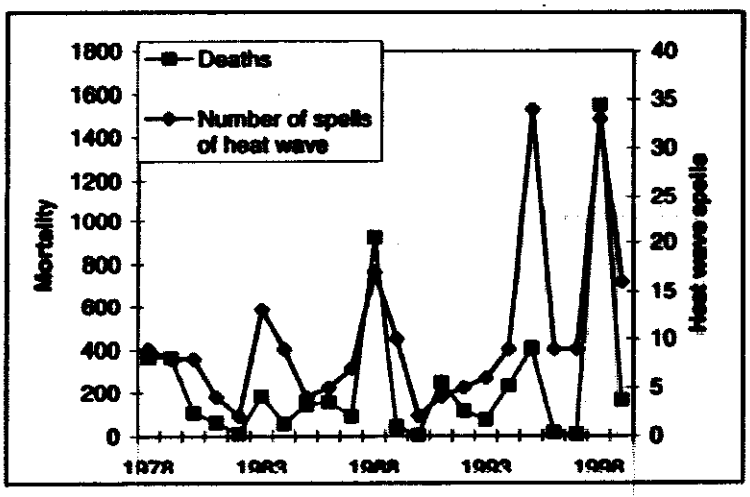


Figure - Heat Waves : Incidence and Mortality

B. Economic Growth, Poverty and CO_2 Emissions in India

In a country like India, where a large percentage of population live below the poverty line, there is a need for rapid economic growth to address poverty eradication and improvement in the quality of life of this people. In the process, the total emissions from India are bound to rise. At present India is contributing 4% of the total CO_2 emissions in the world, though per capita emissions are still very low. It is necessary to examine the impact of CO_2 emission reductions on economic growth and poverty using an economic model and various options. The CO_2 emissions can be reduced by reducing the levels of different economic activities. This, however, has a direct effect of reducing income, consumption and a loss in the social welfare. The other options are changing the composition of production in favor of less CO_2-intensive activities. This can be done in various ways, like changing the structure of trade or changing the structure of consumption or by reducing the share of CO_2-intensive goods in the total demand. In addition, technology options are also available for reducing CO_2 intensity, thus reducing CO_2 emission without any significant loss of output.

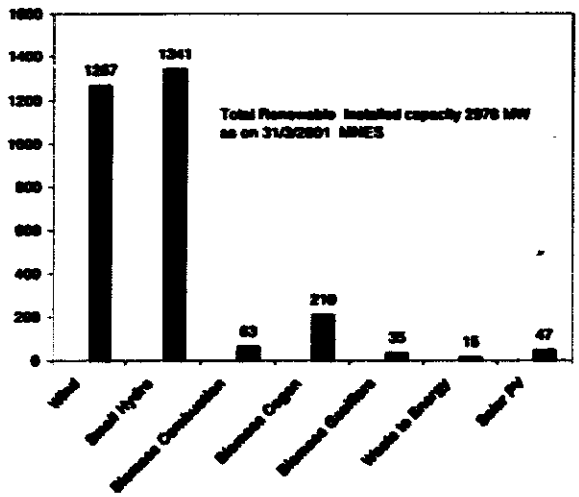
Large annual reductions in carbon emission become possible by diverting substantial resources for this purpose and growth is adversely affected. As the world community is moving toward reduction of such emissions on an urgent basis, it also understands the need for the developing countries under the Protocol to not have any binding GHG reduction commitment. Emission reduction imposes costs in terms of lower GDP and higher poverty. India cannot have any obligation to reduce its carbon emission for quite some time without sacrificing its basic development activities. Technological options such as low-cost and large-scale solar and wind generation, if and when these become available, may open up non-carbon energy options and carbon reduction at the lower cost than what is estimated to support the country's sustainable development program.

C. Assessment of the Role of Renewable Energy Technologies

India has considerable renewable resources which are being harnessed for the generation of power using solar, wind, hydropower, and biomass/agrowaste technologies. Besides these, there is potential for tidal, ocean thermal energy conversion and wave energy. The Ministry of Non-Conventional Energy Sources recently formulated a renewable energy policy, which targets 10% of the additional generation capacity (by 2011) in the country using renewable energy sources.

An assessment of renewable energy technologies (RETs) in India on wind, small hydro, solar photovoltaic and thermal, biomass combustion, cofiring, co-generation, gasification and biogas brings out that India is the fifth largest wind power producer in the world with the present capacity of 1,267 MW; so far, 26 project sites have been developed in high-potential states like Andhra Pradesh, Gujarat, Karnataka, Rajasthan, Maharashtra and Tamil Nadu. The capital cost of wind power projects ranges from Rs. 4.0 - 4.5 crore per MW, and the cost of generation is estimated to be Rs. 2.0 - 2.5 per kwh; these costs compare favorably with conventional power. Targeted capacity for the next five years is about 1,000 MW, requiring an investment of Rs. 40,000 million. The Government of India (GoI) has provided fiscal and financial incentives, with wheeling, banking facility, third party sale and buy-back facility by SEBs. The Indian Renewable Energy Development Agency (IREDA) is playing a significant role in the promotion of renewable energy in India. **Small hydropower** (up to 25 MW capacity) (SHPs): sector has grown four times from 63 MW to 226 MW in the last 10 years. Solar Photovoltaics (SPV): most environmentally friendly; particularly, thin film solar cell is regarded as the technology for the future; a complete PV Solar system has a PV array and an energy storage system, along with the necessary electronic, electrical and mechanical subsystems. India's solar potential is enormous.

Figure - Installed Capacity of Renewable in India



Considerable investment opportunities exist in India, along with various concessions, particularly to entrepreneurs belonging to SC/ST, women, ex-servicemen and the handicapped category. Solar Thermal technology is also being used extensively for obtaining power. An Integrated Solar Combined Cycle (ISCC) of 140 MW is planned in Mathania, Rajasthan with GEF funding. **Biomass:** 1997-98 estimates put India's biomass potential at 545 million tons; of this, about 150 million tons is expected to be available for power generation.

Provision of decentralized energy using renewables is a must for accelerating the development process in rural India, where 70% of India's population lives but cost recovery is a key issue. Such energy therefore must be linked to rural industries like cold storages and oil mills. In the case of grid-connected power generation using RETs, the large utilities are hesitant to enter into power purchase agreements with the RETs. A target of 10% renewable by 2011 is planned in a BAU scenario. Several policy changes are required, such as incorporating externalities in the social choice of deciding appropriate power generation technologies; cost recovery; monitoring and verification of track record of renewable technologies in India; manpower training; etc. Renewable energy has the potential of employment generation in the villages and is the surest option for sustainable development and the eradication of poverty.

D. Carbon Mitigation for the Indian Power Sector

Energy consumption in India is rapidly rising. Electricity demand is growing at 8.7% annually at present, much above the economic growth rate of 6.2%. The present capacity mix in the electricity sector includes a large share of coal (61%), followed by large hydro (24%), nuclear power (8%) and renewables at around 1.5%. Due to unreliable power supply, there is a considerable growth in captive power to almost 16 gigawatts in 2000, with most of them using coal. T&D losses amount to over one-fifth of generated electricity; commercial losses like theft, non-metering and non-billing account for about one-quarter of these losses. The agricultural and household sector consumption has grown over 12% annually, while total power use grew at 8.7%. The electricity tariff structure in India is the main cause of investment disincentives. The electricity subsidy to agriculture and domestic sector consumers amounted to over Rs. 200 billion at the same time. There are several environmental concerns associated with thermal generation of electricity. Analysis shows that carbon emission from India will continue to rise from 212 to about 740 million tons of carbon between 1995 and 2035. Further, the demand for electricity outpaces the growth in energy demand in the economy.

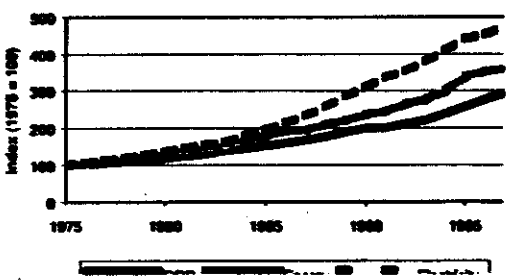


Figure - Growth of energy, electricity, emissions and the Indian economy

The per capita electricity consumption becomes three times the present value in the next 35 years. Coal dominates in the long-term electricity generation scenario. Advanced coal technologies like Super-critical Pulverized Coal (PC) technology and the Integrated Gasification Combined Cycle (IGCC), penetrate in this sector. There are energy security implications for increasing the use of natural gas, as most of the gas requirement has to be supplied by imports due to limited domestic reserves. At present, the nuclear power industry in India operates at very low capacity utilization. Large hydro capacity is projected to double in the next two decades. The capacity of other renewable technologies—including small hydro, cogeneration, biomass-based power generation, wind and solar—increase their capacity by more than three times in the next decade with a three and a half percent share in the capacity mix from the present 1%. Due to rising emission trends, it may be necessary to introduce policy-induced mitigation measures such as a carbon tax.

Inertia of existing technological stock in the energy system prevents significant fuel substitution in the near future for meeting carbon mitigation targets and thus coal continues to dominate the energy system. Analysis of carbon mitigation scenarios provides some useful insights regarding energy supply and demand side contributions to emission reductions, but the supply side contribution to emission reduction increases gradually over the years and reaches a three fourths share in 2035. The inertia of supply side technology turnover is high investment and longer infrastructure development. Long-term options include penetration of carbon-free technologies like nuclear and renewable technologies. India's participation in the global carbon market will depend upon the mitigation costs and the global carbon prices. The power sector has a significant contribution in the overall energy sector emission mitigation. India has gained considerable experience in the operation of conventional coal technologies. However, a barrier remains in the adoption of advanced coal technologies like Sub-critical Pulverized Coal (PC) technology that has high technical and economic potential. However, mitigation of carbon emissions leads to a rise in electricity costs, especially in the long-term. Policies targeted at recycling the revenue generated from emission reductions back to the sectors contributing in emission reduction can assist in the lowering of mitigation costs and ensure the sustainability of the regime in the long-term.

E. Energy and Emissions at Global Levels in Urban Transport in India

Managing the transport sector while minimizing externalities like local pollution, congestion and global pollution is a major challenge. India has witnessed a tremendous growth in urbanization since independence, with the urban population increasing from 62.4 million persons in 1951 to 217.2 million in 1991, a growth of nearly 3.5 times. During 1980, the share of mass transport in total passenger traffic was less than 55%. The composition of personalized vehicles in the Indian cities is very high, particularly in the four major cities (Kolkotta, Delhi, Mumbai & Chennai), where they form nearly 83% of the total. Metropolitan cities account for about one third of the total vehicles. An analysis of energy consumption for transport in India during 1988 to 1997 indicates that petroleum products account for the major fuel consumption in this sector. An analysis of energy use in different types of vehicles - 2 wheelers, 3 wheelers, cars/jeeps, taxis, and buses shows that vehicle composition determines energy intensity of a city in terms of energy /PKM. The more the share of public buses, the less energy needs for meeting the unit travel demand (PKM) - least in Mumbai, Bangalore and highest for Kolkata.

Air pollution due to road transport is of high significance in terms of the quantity of pollutants emitted. In India it is estimated that vehicular emissions of CO, HC, NOx, SO_2 and TSP alone account for about 60% of the total pollution from all sources.

The direct CO_2 emissions in 1993-94 due to the fuel consumption in the transport sector was 27.85 million tons of carbon equivalent (mtc). Road and other transport is responsible for more than 80% of the emissions, followed by rail (13%) and air (6%).

The transport sector is vital for economic growth and quality of life; however, the present transportation trends are unsustainable in the future, as they call for high growth in vehicles, emissions, congestion and costs. A mass transport system results in the least energy consumption. Efficiency improvements in the vehicles can meet the future traffic demand with reduced energy consumption and CO_2 emissions. Alternative transport fuels could provide energy security and a better environment. The most important long-term option is to create an awareness of conserving fuels by reduced travel demands that will bring down local and global pollution and help in attaining a sustainable lifestyle.

F. Municipal Solid Waste Management for Climate Change Mitigation

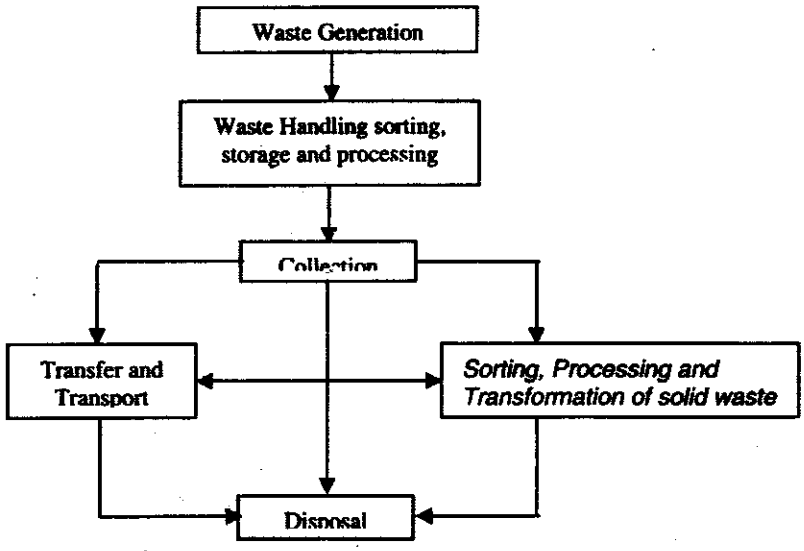
Management of Municipal Solid Waste (MSW) is a very effective means of reducing the methane emissions from solid waste disposal on landfills.

Bacterial decomposition of Municipal Solid Waste (MSW) produces landfill gas (LFG) under anaerobic conditions (in the absence of oxygen). The major constituents of the LFG are 45 - 50% methane and carbon dioxide. The production of methane from an MSW landfill takes considerable time, depending on various factors like moisture, temperature etc. The Government of India (Ministry of Environment and Forests), through a Gazette Notification in 2000, has brought into force the Municipal Solid Waste (Management and Handling) Rule, 2000, applicable to every municipal authority responsible for the collection, segregation, storage, transportation, processing and disposal of MSW. The municipalities are required under the notification to set up a waste processing and disposal facility by 31 March 2003. Landfilling must be restricted to non-biodegradable, inert waste and other wastes that are not suitable either for recycling or for biological processing.

There are various technological options for methane emissions reduction. It is estimated that there is a potential for generating about 1,000 MW of power from Municipal Solid Waste in India. The Ministry of Non-Conventional Energy Sources (MNES), Government of India (GoI) has identified "Energy from Waste" as one of the thrust areas of its activities and has initiated a "National Programme from Urban and Industrial Waste". The GoI has announced various incentives for setting up MSW-based power projects in the country. In spite of a major initiative taken by the GoI and attractive financial and fiscal incentives being made available, the progress in setting up MSW-based Waste-to-Energy projects in the country so far is rather discouraging.

Municipal Solid Waste and its improper handling and disposal methods pose a serious threat to human beings and their environment. A large part of the total waste generated in India is simply dumped in open dump-yards, giving rise to unhygienic surroundings, health hazards, contaminated ground water, an unclean look of the cities, generation of methane contributing to global warming and other obnoxious gases. A proper municipal solid waste management system is a major challenge in the protection of the local and global environment.

Figure - Functional Elements of a MSW Management System

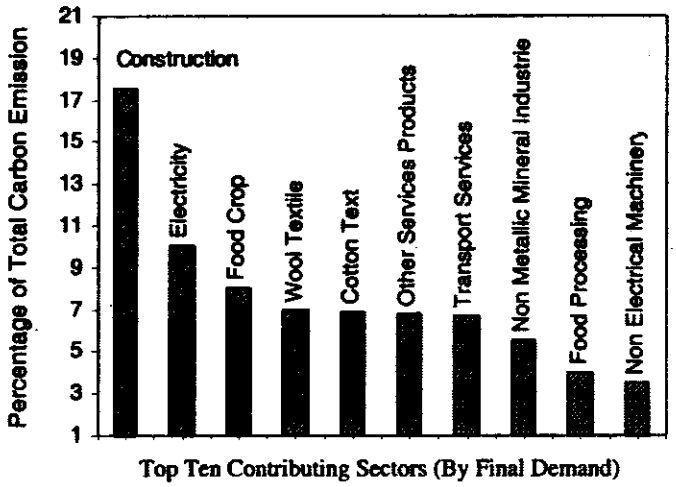


Source : Manual on Municipal Solid Waste Management, Ministry of Urban Development, Central Public Health and Environmental Engineering Organisation (CPHEEO), GOI, New Delhi, January 2000

G. Sustainable Practices for Construction Sector in India

The construction sector is the driving force behind the Indian economy and it accounted for 36.5% of gross domestic income and contributed 5.6% of the total GDP in 1996-97, when both the direct and indirect emissions which were considered construction and the most carbon-intensive sector in the economy, as it required energy-intensive materials such as aluminium, steel, bricks, glass, cement, plastics and so on.

Figure - Direct and Indirect Carbon Emissions : 1989-90



In analyzing Sustainable Practices for the Construction Sector in India, the following two aspects: (a) estimating the future requirements of building materials and (b) analyzing the possibility of substitution among building materials toward less emission- intensive materials, have been examined. Another important aspect that needs to be considered is that the proportion of *pucca* houses has gone up significantly, both in rural and urban areas, almost by 8% during 1981-91. Despite the quantitative and qualitative improvements in housing stock in India, the housing shortage persists. The Planning Commission (1992) estimated the housing shortage at about 18.5 million units in 1991. Demands for building materials in housing arise from two factors: construction of houses and maintenance, extension and repairs of existing houses. India's National Agenda for housing has set a target of constructing two million houses every year. The cost of various inputs for new houses during

2000-01 is 275 billion rupees and carbon dioxide emissions are estimated at 38.9 million tons of CO_2. Carbon dioxide emission from the construction sector under the BAU scenario during 2000-01 is 141 mt of CO_2 and during 2009-10 is 223 mt of CO_2.

There are number of technologies using cost-effective low-energy building materials available in India, such as hollow concrete blocks, hollow concrete blocks with flyash, compressed mud blocks using Balram techniques, and using different tiles and roofing materials for roofs. With a shift among different techniques of construction, there is substantial change in the cost and carbon dioxide emission level. With a carbon dioxide constraint being imposed, the cost of construction rises by 2.54% for a 5% reduction in carbon dioxide from the common practice - BAU scenario and a 10% reduction of CO_2 emissions will increase the cost by 5%. The second group of techniques evaluated are low-cost techniques with less carbon dioxide emissions. The cost of construction of 2 million houses in 2000-01 by using energy efficient technologies is 58% of the cost of the construction by using common practices, business-as-usual technologies, and carbon dioxide emissions for the energy efficient technologies are only 35% of the common practices. Finally, there is a need for change of mindset of people to switch on for the future in functional low-cost housing.

V. CONCLUSIONS

The United Nations Framework Convention on Climate Change (UNFCCC) noted that the largest share of historical and current global emissions of Greenhouse Gases has originated in developed countries, that per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs. The power sector, transportation sector, and building sector are each major emitters of carbon dioxide to the atmosphere. Mitigation of climate change through various energy efficiency measures and using clean coal technologies are viable options to reduce emissions. However thermal generation of power using fossil fuels has many environmental implications, such as increase in local pollution of NOx, SOx and SPM. This has a considerable impact on the health of the people and on other resources. Similarly, thermal generation of power also increases global warming and has a global impact because of the long atmospheric lifetime of carbon dioxide. At present, the power sector has a very large share in the total energy consumption and has almost a 50% contribution to the total carbon emissions. There is a need to switch onto alternate fuels with low carbon emissions, as well as to rapidly introduce clean coal technologies like integrated gasification combined cycle technologies. Along with this, there is a need to remove certain technical barriers like managing ensured high quality fuel supply. One has to take into account, however, the result of studies which have shown that emissions reduction imposes costs in terms of lower GDP and higher poverty.

In addition, carbon-neutral technologies for generation of power using various renewable sources should be taken up, so that at least 10% of the power in India comes from renewables. India cannot have any obligation to reduce its carbon emissions for quite some time without sacrificing its basic development objectives of GDP growth and poverty removal.
If India were to reduce its carbon emission for the sake of the global group it should have sufficient built-in compensation through international processes for such an action.

The transportation sector in India is also responsible for considerable Greenhouse Gas emissions in the atmosphere, along with other pollutants that are harmful for the people, a health hazard and dangerous to the global environment. The present need is to switch from personalized transport to a mass transit system. Many developed countries have adopted this type of transportation long ago, and it's time for India to think seriously in this regard.

The construction sector in India is also responsible for considerable emissions and there is a need to look forward to new technologies which are environment-friendly, have considerably less greenhouse gas emissions, and are of low cost.

There is also a scope for India to abate climate change through vulnerability studies and adaptation measures, particularly in the areas of water resources, agriculture and food production, and coastal zone managements. In the agriculture sector, there is a need to take up research for finding out cultivators which are not only temperature/drought resistant but should not necessitate any change in the present agricultural/irrigation practices. For example, most of the rice paddy cultivation is carried out during monsoon season. The new cultivators should have similar sowing time and other requirements. Otherwise, a cultivator tested in a laboratory may fail in the field and may become a misadaptation. A similar argument holds for new cultivators for wheat crops in India, as well.

India has a long coastline and some of the coastal areas are already vulnerable. The projected sea level rise due to global warming will have considerable impact on the life of the people and the coastal economies. Constructing dykes to prevent sea level rise impact is an option, but unfortunately this is economically not acceptable to the developing countries, due to the very high cost of the construction of dykes. It is therefore necessary in developing countries to have a baseline of such vulnerable coastal areas. We should have data on the existing populations' livelihood, their agricultural practices and the type of dwellings they use, so that in the event of sea level rise causing inundation and displacement, the resettlement and rehabilitation measures do not pose any serious problem to the country.

The GEP - CCS research outputs will have considerable influence among the scientists, policy makers and civil society in India to understand the implications of the impact of climate change and the need for mitigation without taxing India's scarce resources. Such mitigation measures will not only pave the way for the transfer of clean technologies from developed countries, but also will bring financial resources.

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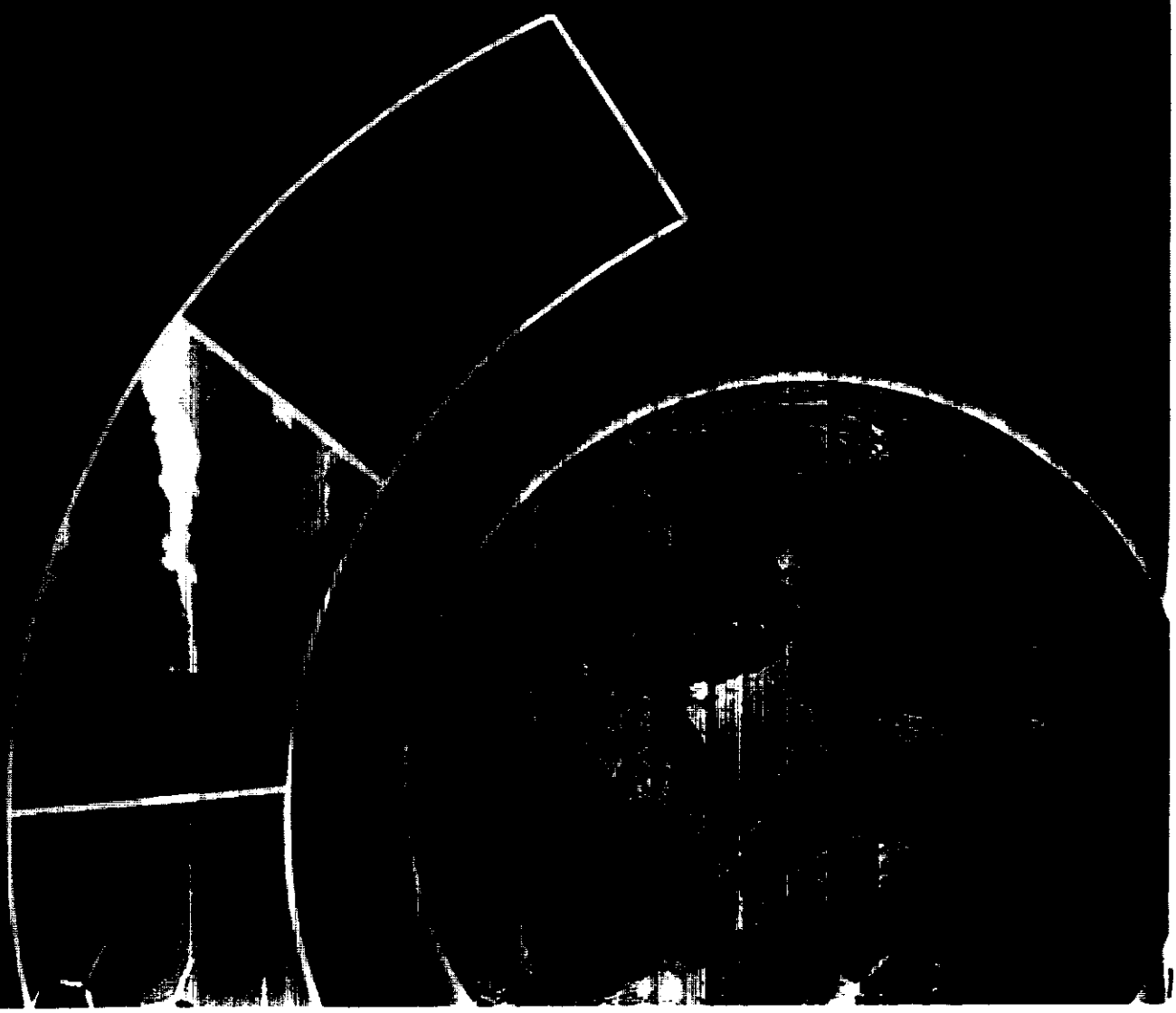
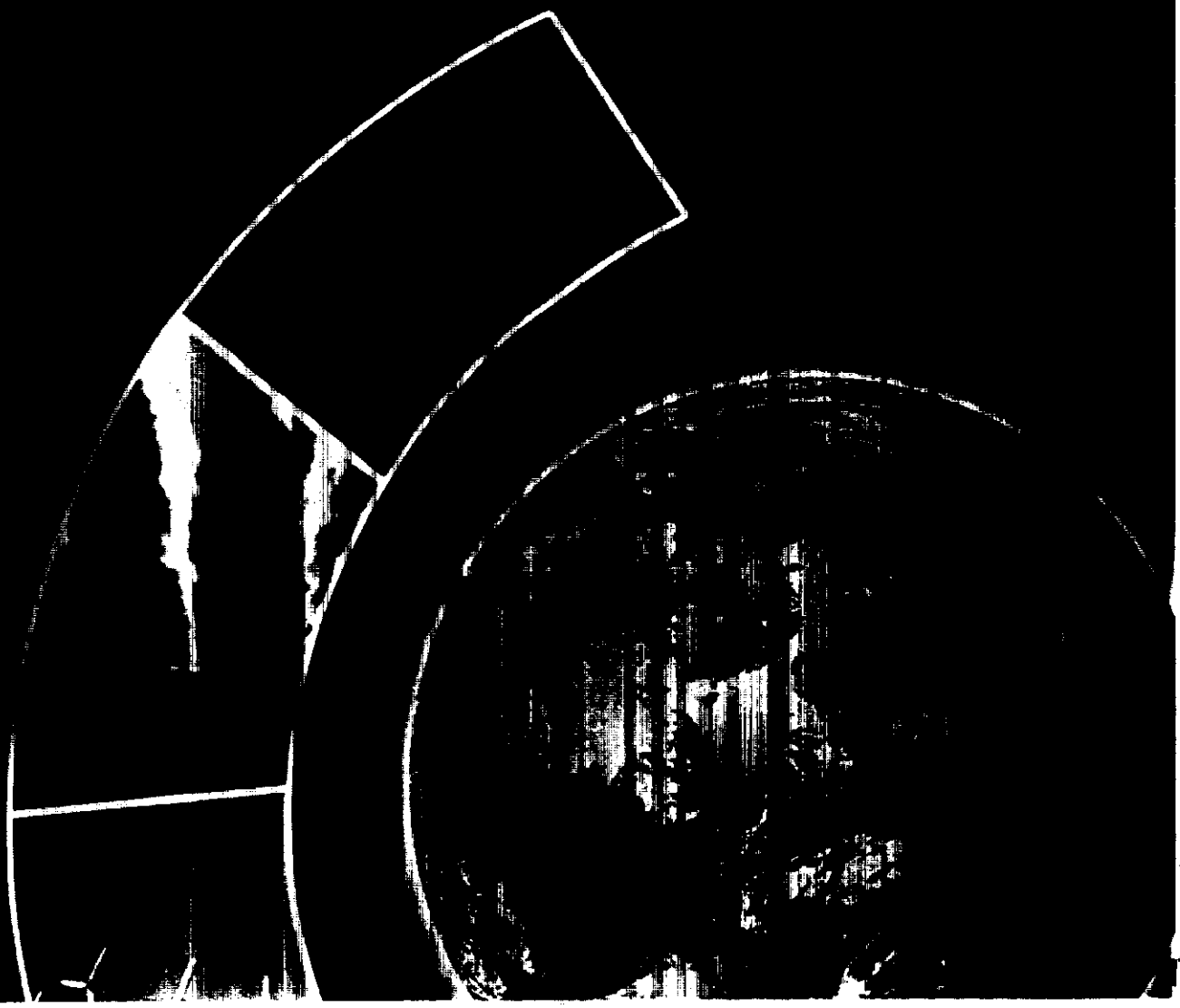
Development Alternatives is a non-profit corporate organization with a mission to sustain development through appropriate technology, institutional design and environmental management.

Impact of Challenges



India's Vulnerability to Climate Change



INDIA'S VULNERABILITY TO CLIMATE CHANGE

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I. INTRODUCTION

A. Climate Change – A Threat

The threat of climate change is real. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) states clearly as follows:

> "Available observational evidence indicates that regional changes in climate, particularly increases in temperature, have already affected a diverse set of physical and biological systems in many parts of the world. Examples of observed changes include shrinkage of glaciers, thawing of permafrost, later freezing and earlier break-up of ice on rivers and lakes, lengthening of mid- to high-latitude growing seasons, poleward and altitudinal shifts of plant and animal ranges, declines of some plant and animal populations, and earlier flowering of trees, emergence of insects, and egg-laying in birds. Associations between changes in regional temperatures and observed changes in physical and biological systems have been documented in many aquatic, terrestrial, and marine environments."

IPCC further observes that:

> "Natural systems can be especially vulnerable to climate change because of limited adaptive capacity, and some of these systems may undergo significant and irreversible damage. Natural systems at risk include glaciers, coral reefs and atolls, mangroves, boreal and tropical forests, polar and alpine ecosystems, prairie wetlands, and remnant native grasslands. While some species may increase in abundance or range, climate change will increase existing risks of extinction of some more vulnerable species and loss of biodiversity. It is *well-established* that the geographical extent of the damage or loss, and the number of systems affected, will increase with the magnitude and rate of climate change."

Many human systems are sensitive to climate change. These include water resources, agriculture, food security, forestry, coastal zones, marine fisheries, human settlements, energy, industry, insurance and other financial systems and human health. The impact of climate change on these systems can have a severe adverse impact on the well-being of human and natural systems in India. The IPCC has also recognized that developing countries are likely to be more vulnerable to climate change.

India may be particularly vulnerable to climate change, being a poor and tropical/sub-tropical country, highly dependent on weather for its agricultural output. For India, its freshwater systems, rainfall, rivers and groundwater are critical for its agriculture and food security. Disruptions, droughts and floods induced by climate change can cause great hardship and impose large costs. Similarly, the large coastline

of India, and the millions who live near the sea and depend on coastal ecosystems for their livelihood, may also be highly vulnerable to climate change. It is thus important to assess India's vulnerability, for it can provide guidance for policy actions both at national and international levels.

B. Vulnerability Concepts

In any multi-disciplinary area of study, there is a danger that people use common terms with a different meaning in mind. It is therefore necessary to clearly define at the beginning what is meant by some commonly used terms such as sensitivity, adaptive capacity and vulnerability. We reproduce the IPCC definitions in Box 1. Other terms that need to be defined at the beginning relate to confidence levels and state of knowledge. Box 2 from the IPCC shows these.

Box 1: Climate Change Sensitivity, Adaptability and Vulnerability

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. Climate-related stimuli encompass all the elements of climate change, including mean climate characteristics, climate variability, and the frequency and magnitude of extremes. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

Adaptive capacity is the ability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Box 2: Confidence Levels and State of Knowledge

Quantitative Assessment of Confidence Levels

In applying the *quantitative* approach, the authors of the report assign a confidence level that represents the degree of belief among the authors in the validity of a conclusion, based on their collective expert judgment of observational evidence, modeling results, and theory that they have examined. Five confidence levels are used. In the tables of the Technical Summary, symbols are substituted for words:

Very High (*****)	95% or greater
High (****)	67 – 95%
Medium (***)	33 – 67%
Low (**)	5 – 33%
Very Low (*)	5% or less

Qualitative Assessment of the State of Knowledge

In applying the *qualitative* approach, the authors of the report evaluate the level of scientific understanding in support of a conclusion, based on the amount of supporting evidence and the

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level of agreement among experts about the interpretation of the evidence. Four qualitative classifications are employed:

- *Well-established:* Models incorporate known processes, observations are consistent with models, or multiple lines of evidence support the finding.
- *Established but incomplete:* Models incorporate most known processes, although some parameters may not be well tested; observations are somewhat consistent but incomplete; current empirical estimates are well founded, but the possibility of changes in governing processes over time is considerable; or only one or a few lines of evidence support the finding.
- *Competing explanations:* Different model representations account for different aspects of observations or evidence or incorporate different aspects of key processes, leading to competing explanations.
- *Speculative:* Conceptually plausible ideas that are not adequately represented in the literature or that contain many difficult-to-reduce uncertainties.

As these definitions indicate, vulnerability depends not only on the sensitivity of the system, but also on its capacity to adapt. Adaptation, however, is not costless and the ability to adapt depends on one's resources. Thus, a developing country like India and the poor in it have the least capacity to adapt and are therefore the most vulnerable. India's adaptive capacity is severely constrained by its low level of per-capita income, high incidence of poverty and inescapable need for economic development. Similarly, the constraints on the availability of arable land limit the range of adaptation options in agriculture and impose large costs. Developmental indicators are useful in characterizing the state of adaptive capacity. Some common indicators and their evolution over the last few decades are described in Table 1.1.

Table 1.1: Selected Indicators

Economic Indicators										
Population (million)[a]	361.1	439.2	548.2	683.3	843.4	856.8[b]	964.4[b]	982.7[b]	1001.1[b]	1027.0
GDP at factor cost										
(i) At current prices (Rs Crore)	9547	16220	42222	130178	510954	589086	1390148	1598877	1755638[c]	1895843[d]
(ii) At Constant Prices	140466	206103	296278	401128	692871	701863	1016399	1082472	1148500	1193922[d]
Per Capita Net National Product at 1993-94 prices (Rs.)	3687	4429	5002	5352	7321	7212	9242	9647	10067	10254[d]
Index of Industrial Production (Base 1993-94 = 100)[e]	7.9	15.6	28.1	43.1	91.6	92.2	139.5	145.2	154.9	162.7[f]
Index of Agricultural Production (Base, Triennium ending 1981-82=100)	46.2	68.8	85.9	102.1	148.4	145.5	165.3	177.9	175.6	163.9
Gross Domestic Capital Formation (as percentage of GDP)	8.7	14.4	15.4	20.3	26.3	22.6	24.6	22.7	24.3	24.0[d]
Output Indicators										
Foodgrains (million tones)	50.8	82.0	108.4	129.6	176.4	168.4	192.3	203.6	209.8	195.9
Finished Steel (million tones)	1.0	2.4	4.6	6.8	13.5	14.3	23.4	23.8	27.2	29.3[f]
Cement (million tones)	2.7	8.0	14.3	18.6	48.8	51.7	82.1	88.0	100.1	99.5[f]

Table 1.1: Selected Indicators (Continued)

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Coal (including lignite)(million tones)	32.3	55.2	76.3	119.0	225.5	243.8	319.0	315.7	322.1	332.6[P]
Crude Oil (million tones)	0.3	0.5	6.8	10.5	33.0	30.4	33.9	32.7	31.9	32.4[P]
Electricity Generated (Billion KWh)	5.1	16.9	55.8	110.8	264.3	287.0	421.7	448.5	480.7	499.5[P]
Wholesale Price Index (93-94=100)*	6.8	7.9	14.3	36.8	73.7	83.9	132.8	140.7	145.3	155.7
Consumer Price Index (1982= 100)@@	17	21	38	81	193	219	366	414	428	444
Plan Outlay (Rs Crore)	260#	1117	2524	15023	58369	64751	129757	149404	167981	187931(RE)
Center's Budget Deficit drawdown of cash balance (Rs Crore)	-33#	-117	285	2576	11347	6855	-910	-209	864	2605 (RE)
Trade										
(i) Exports (Rs Crore)	606	642	1535	6711	32553	44041	130100	139752	159561	203571
US $ million	1269	1346	2031	8486	18143	17865	350006	33218	36822	44560
(ii) Imports (Rs Crore)	608	1122	1634	12549	43198	47851	154176	178332	215236	230873
US $ million	1273	2353	2162	15869	24075	19411	41484	42389	49671	50536
Social Indicators										
Birth Rate (per 1000)[a]	39.9	41.7	36.9	33.9	29.5	29.2	26.5	26.1P		
Death Rate (per 1000)[c]	27.4	22.8	14.9	12.5	9.8	10.1	9.0	8.7P		
	1950-51	1960-61	1970-71	1980-81	1993-94	1995-96	1997-98	1998-99	1999-2000	2000-01
Life Expectancy at birth (in years)[d]										
(i) Male	32.5	41.9	46.4	50.9	60.4					
(ii) Female	31.7	40.6	44.7	50.0	61.8					
Total	32.1	41.3	45.6	50.4	61.1					
Literacy rate(percentage)[e]										
a. Male	27.16	40.40	45.96	56.38	69	69	73			75.85
b. Female	8.86	15.35	21.97	29.76	44	46	50			54.16
Total	18.33	28.30	34.45	43.57	57	58	62	63.1		65.38
Health and Family Welfare f										
Registered Medical Practitioners (Doctors)-thousands	61.8	83.7	151.1	268.7	442.6	477.6	514.8	535.4		
RMP - Doctors per 10,000	1.7	1.9	2.8	3.9	5.0	5.1	5.3	5.5		
Beds of all types** per 10,000	3.2	5.7	6.4	8.3	9.4	9.1	9.3			

P - Provisional Estimates
Q – Quick Estimates
@@ - Figures for period upto 1988-89 obtained by converting indices on earlier bases into 1982=100
# - Relates to 1951-52
* - Figures for period upto 1993-94 derived by converting indices based on earlier bases into base 1993-94
** - Includes beds in hospitals, dispensaries, Primary Health Care Centers, Clinics
RE – Revised Estimates

Notes:

a- as on march 1951 and so on upto 2001 as per Census of India
b- Relates to October 1, 1991, 1993, 1995, 1997, 1998, 1999 based on estimated figures of Provisional Population totals, Paper –1 of Census of India, 2001, Government of India

Notes (Cont.):

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c- Data for 1950-51, 1960-61, 1970-71 and 1980-81 are census estimates and relate to decades 1941-50, 1951-60, 1961-70 and 1971-80 respectively. The estimates for 1990-91 onwards are based on Sample Registration System, Office of Registrar General, India

d- Data for 1950-51, 1960-61, 1970-71, 1980-81, 1990-91 and 2000-2001 refer to previous decades and centered around the mid points of the decade, i.e. 1946, 1956, 1966, and 1976. The estimates for 1990-91, 1991-92 and 1993-94 refer to period s 1988-92, 1989-93 and 1993-97 respectively

e- Data for census years are according to the Census. Figures for 1951, 1961, and 1971 relate to age 5 and above and for 1981 and 1991 to age 7 years and above. All India Literacy rate exclude Assam for 1981 and J&K for 1991. Data between 1993 and 1997 relate to NSSO survey. 53rd round upto 1997. Data for 1998 relates to National Family Health Survey and the data for 2000-2001 relates to the 2001 Census.

f- Relate to calendar year, e.g. 1950-51 pertains to 31st December 1951 and so on.

g- The index of Industrial Production has been revised since 1993-94.

x- The 1970-71 figures relate to 1973-74.

y- The 1980-81 figures relate to 1983-84

This report surveys the current literature pertaining to India's vulnerability to climate change. The next section summarizes the baseline pertaining to climate variability and climate change. We also provide some information regarding projections of future climate change. The next 3 sections consider climate change impacts on three major sectors and systems in the country – agriculture, coastal zones and water resources. Section 6 explores the issue of adaptation and adaptive capacity through an examination of local community-level responses to climate variability and change. The final section summarizes the key findings and concludes with some recommendations for policy.

II. CLIMATE VARIABILITY AND CHANGE: BASELINE AND SCENARIOS

Climate change induced by human activities is now recognized as perhaps the most serious environmental problem and developmental challenge in the world today. The Earth's climate system is likely to undergo significant change over the course of the next century and longer, as a result of forcing due to the increasing atmospheric concentrations of greenhouse gases. The consequences of these changes in the climate system will lead to impacts on natural and social systems. Evaluation of these impacts, therefore, requires the specification of scenarios or projections of changes in future climate. At the same time, the climate system exhibits significant natural variability on interannual to decadal time-scales. This variability and the occurrence of extremes of weather already pose a challenge to the socio-economic system. Considering that even future climate change will be perceived largely in terms of changes in variability or extreme events, it is important to understand the baseline of impacts that result from current patterns of variability and extremes. Understanding the current impacts of climate variability is also important from the vantage point of informing natural hazard mitigation policies, which have the potential for helping developing countries enhance their adaptive capacity with respect to climate change.

This chapter begins with a review of the characteristics of current climate over the Indian subcontinent, with special attention to extreme weather events. We examine climate variables such as temperature and precipitation, as well as more complex phenomena such as tropical cyclones and floods. In addition to the climatology, we also provide information on the associated impacts. Finally, we summarize some of the recent projections with regard to climate change.

A. Climate Characteristics and Trends

The climate in the Indian subcontinent, as in most of tropical Asia, is dominated by the two monsoon seasons – the Southwest Monsoon, from June through September and the Northeast Monsoon, from November through March. The monsoons bring most of the region's precipitation and are the most critical climatic factor for the provision of drinking water and water for rain-fed and irrigated agriculture. The Indian subcontinent is also home to some of the largest river basins in the world, including those of the Ganges, Brahmaputra and Indus. A significant proportion of the Indian population and economic activity is concentrated in the deltaic regions of the major rivers of the subcontinent, such as the Ganges, Godavari, Mahanadi and Kaveri.

1. Temperature

Over the last 100 years, mean surface temperature has increased by 0.3 – 0.8 degrees C over the tropical Asian region (IPCC, 2001). In India, Rupa Kumar et al. (1994) have demonstrated that mean maximum temperatures have increased by 0.6 degrees C for a period from 1901 – 1987. They also observed a decrease in mean minimum temperature of 0.1 degrees C; however, this decrease was not statistically significant. In another study, Srivastava et al. (1992) found an increased warming trend in the last two decades (1971 – 1980, 1981 – 1990) as compared to previous decades. Figure 2.1(a) plots the annual average maximum temperature over a 90-year period, from 1901 – 1990. For comparison, the monthly average maximum temperature is also plotted for the hottest month of the year (May). Figure 2.1(b) plots similar data for the annual average minimum temperature, including, for comparison, the minimum temperature in the coldest month of the year (January).

In addition to average temperature, it is also important to examine temperature extremes. Indeed, heat waves during the summer and cold waves during the winter are important routes for the manifestation of climate-related impacts. As an example, Figure 2.2 plots the mortality associated with temperature extremes. They are also good examples of the role of multiple stresses. For example, mortality during a heat wave is often due to a combination of heat and water stress – heat waves typically occur during the summer months, which are also months of water stress and shortage. The interaction of air quality and heat stress is also important.

The thermo-hygrometric index (THI), which combines temperature and relative humidity is a commonly used discomfort index (Besancenot, 1990). In temperate countries, values of the THI in excess of 28.5 C are considered to be high-discomfort situations. In most parts of India this value is exceeded for a large percentage of the time. As a result, there is already a greater susceptibility to heat-related health conditions in India. The IMD typically regards a heat wave as occurring if the daily temperature exceeds the normal maximum by 3-4 degrees, and it is considered to be a severe heat wave if the temperature exceeds the normal maximum by 5-6 degrees. The average annual mortality due to heat waves has been estimated at 153 (Sinha Ray et al, 1999). Figure 2.3 plots the incidence and mortality associated with heat waves over a period from 1978 – 1999. As may be expected, the mortality resulting from a heat wave depends significantly on the socio-economic conditions of the exposed population. For example, during the 1978 – 1999 period, while the number of heat waves was roughly equal in Punjab and Orissa (17 and 15, respectively), the mortality in Orissa was more than four times that in Punjab (114 as compared to 529) (Chaudhury et al, 2000). Further cross-sectional and longitudinal analyses of impacts associated with heat waves are likely to provide useful insights into the role and effectiveness of adaptation and adaptive capacity.

Figure 2.1(a): Maximum temperature[1]

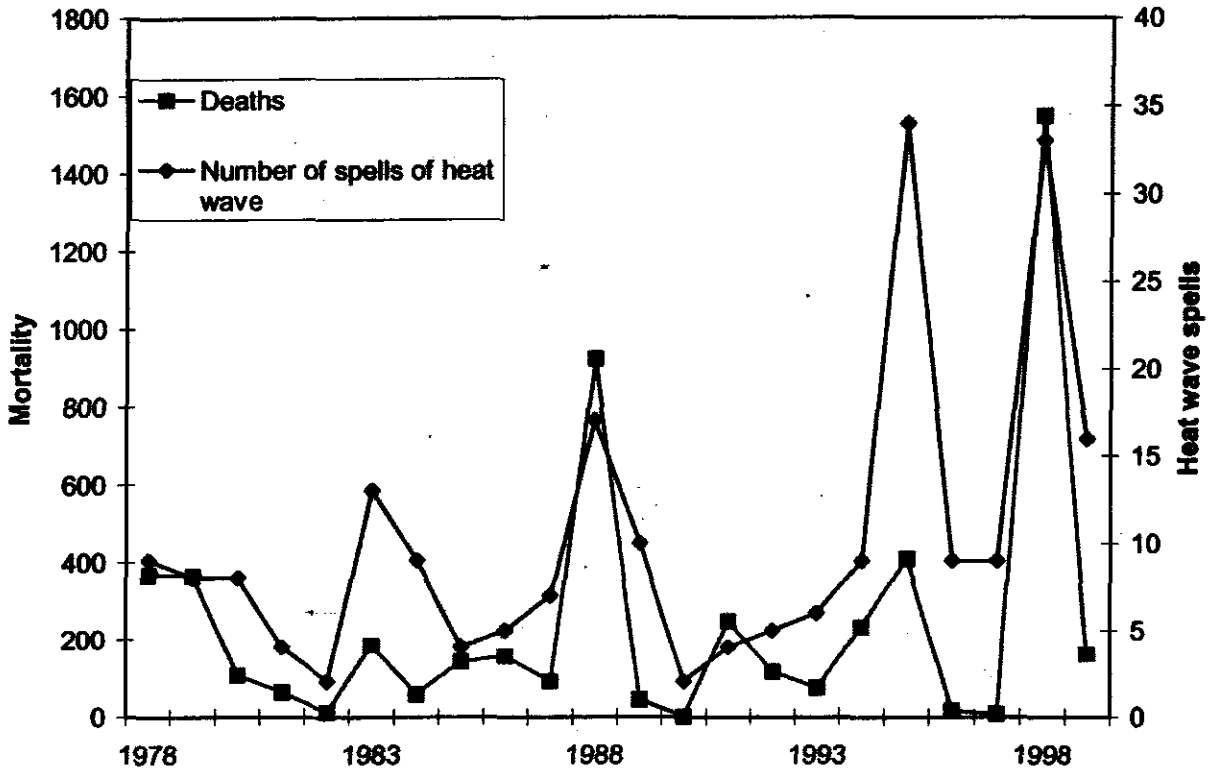
[1] Source: Pant and Rupa Kumar (1997)

Figure 2.1(b): Minimum temperature

Figure 2.2: Mortality due to temperature extremes[2]

[2] Source: CRED database on natural hazards

Figure 2.3: Heat Waves: Incidence and Mortality



2. *Precipitation*

India receives its rainfall through two distinct monsoon seasons – the Southwest monsoon that lasts from June through September and the Northeast monsoon, which occurs during the winter months, and is significant particularly in the Southern part of the country. With regard to summer monsoon rainfall, Parthasarthy et al (1993) have shown that there are no significant increasing or decreasing trends over the last 100 years, although there is significant interannual and interdecadal variability. Figure 2.4 plots the All-India Summer Monsoon Rainfall (AISMR) series, which uses data from an almost uniformly distributed network of 306 stations across the country to obtain an area-averaged estimate of the total monsoon rainfall in the country[3]. This is widely regarded as a reliable index of summer monsoon activity over the Indian sub-continent. Years in which the AISMR exceeds 1 standard deviation above the mean are regarded as "flood" years, while years in which the AISMR is 1 standard deviation below the mean are regarded as "drought" years. Based on this classification, there appear to be 19 flood and 21 drought years in the period from 1981 to 1997. Interdecadal time-scale variability in the monsoon is seen clearly from Figure 2.4, for example it appears that there have been alternating periods extending to 3-4 decades with less and more frequent weak monsoons over India.

[3] For example, see: Mooley et al (1981), Parthasarthy et al (1987), Parthasarthy et al (1995) and Pant and Rupa Kumar (1997).

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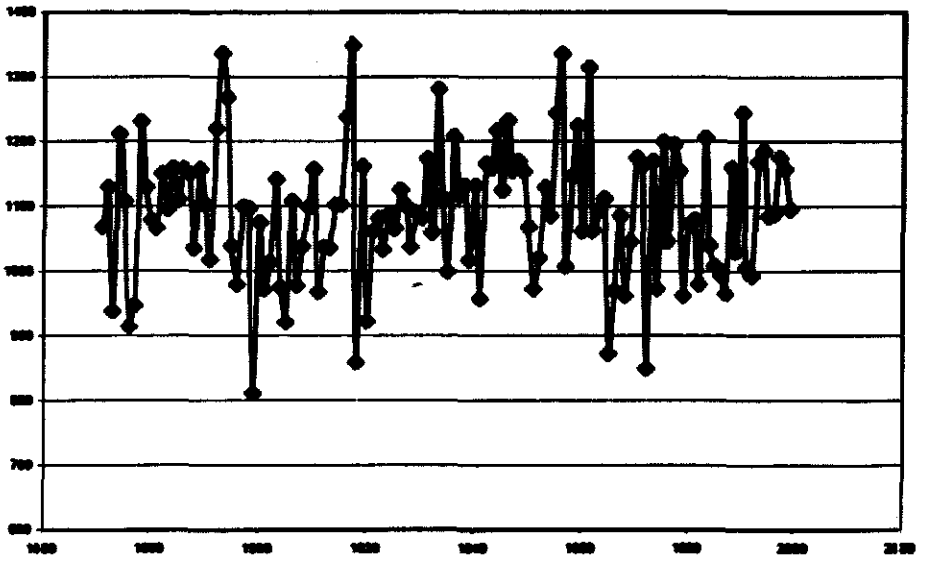
Figure 2.4: AISMR Series



In addition to aggregate rainfall over spatial (regional) or temporal (seasonal) scales, it is also important to examine intra-seasonal and spatial variability in the monsoon. The summer monsoon exhibits characteristic active and break periods that cause wet and dry spells of varying duration. This intraseasonal variability in rainfall is particularly important for agriculture, and is a key issue in terms of forecasts of future climate change. The India Meteorological Department (IMD) considers days in which daily rainfall exceeds 7 cm as heavy rainfall days. Heavy rainfall days are important from the perspective of floods. Trends in heavy rainfall have been explored by Sinha Ray and Srivastava (2000), who find a decreasing trend in heavy rainfall during the winter (January – February), pre-monsoon (March – May) and post-monsoon (October – December) seasons; and mixed results during the monsoon itself. They suggest that the decrease in pre and post-monsoon seasons could be related to the decreasing trend in cyclonic activity found by Srivastava et al. (2000). Recent decades have exhibited an increase in extreme (or heavy) rainfall events over northwest India during the summer monsoon (Singh and Sontakke, 2001). Patwardhan and Singh (2002) have explored the temporal variations in wet spells, defined as consecutive days with rainfall exceeding the 7 cm threshold. While there are no significant long-term trends in the average duration or number of such wet spells across the country, the number of wet spells in any monsoon season exhibits significant interannual and long-term variability. Figure 2.5 plots the average number of wet spells as evaluated across a nationwide sample of 32 stations.

B. Extreme Events

The Indian subcontinent is subject to a wide variety of climate-related extreme events, including tropical cyclones, floods, and landslides, as well as heat waves and cold waves. Significant impacts are associated with these events, as can be seen from Figure 2.6. While tropical storms appear to be the most important, it should be noted that the numbers for earthquakes and storms are high due to a single very destructive event – the Latur event in the case of earthquakes and the Orissa super-cyclone in the case of storms, both of which had mortalities close to 10,000. If one adjusts the data for these two specific events, a more balanced picture emerges, and floods are then the most significant natural hazard in terms of mortality.

Figure 2.5: Average annual number of wet spells

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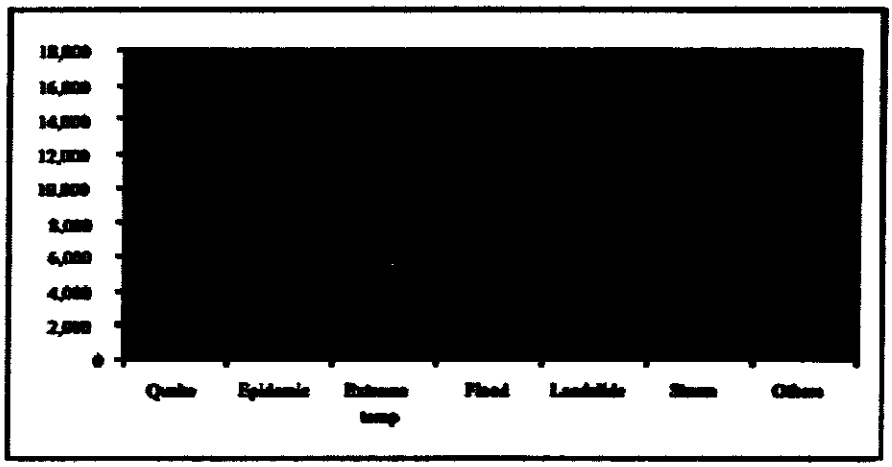
Figure 2.6: Total Mortality from Natural Hazards Over the Last Decade (1990-2000)[4]



1. *Tropical Cyclones*

Tropical cyclones are an important part of the weather and climate in India. The primary area of cyclogenesis of concern for India is the Bay of Bengal, although tropical cyclones originating in the Arabian Sea do affect parts of the Indian coastline, particularly the state of Gujarat. Most analysis of tropical cyclones classifies the events into depressions (wind speed < 62 km/hr), cyclonic storms (wind speed between 62 and 87 km/hr) and severe cyclonic storms (wind speed > 87 km/hr). Severe cyclonic storms correspond to a Category 1 Hurricane on the Saffir-Simpson scale that is commonly used for describing systems in the North Atlantic Ocean. For a 100-year period (1891 – 1990) around 914 events made landfall on the Bay of Bengal coastline (India, Bangladesh and Myanmar). Almost 70% of all tropical cyclones originating in the Bay of Bengal eventually make landfall on the coast.

The observational record suggests that no significant changes in the number, frequency, or intensity of tropical cyclones or depressions have been observed in the Northern Indian Ocean cyclone region (Bay of Bengal and Arabian Sea) over the past 100 years, although spectral analysis suggests variability on a range of time-scales. For example, Gadgil (1995) has shown decadal-scale variations—with a rising trend during 1950–75 and a declining trend since that time—and Singh et al. (2000) suggest cycles of various periodicities, the most important being 2-5, 10, 13 and 29 years. However, there is some disagreement with regard to the inferences from the observational record, as Srivastava et al. (2000) suggest that there is a statistically significant decreasing trend in the frequency of storms when evaluated over a period of 1891 to 1997 for the Bay of Bengal. The same study concludes that there is no significant trend when one examines cyclonic disturbances as a whole.

Tropical cyclones lead to a variety of impacts, some immediate, due to storm surge, high winds and flooding. However, there are also significant impacts due to long-term dislocation of public infrastructure and consequent public and private economic output. Impacts associated with tropical cyclones are discussed further in a subsequent section.

[4] Based on data from the CRED database

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2. *Floods*

Riverine flooding is perhaps the most critical climate-related hazard in India. Flood control has been a key element of national policies for water resource management. There are a variety of types of floods, including flash floods, single event floods, multiple event floods and seasonal floods, all of which are typically caused by heavy rainfall. In addition, there can also be coastal floods caused by storm surge, floods due to dam failure and estuarine floods. In this section we will focus on rainfall-induced floods of rivers. At present there are about 120 major and medium rivers in India that are broadly grouped under 12 major river basins: Indus, Ganga-Brahmaputra-Meghna, Sabarmati, Mahi, Tapi, Brahmani, Mahanadi, Narmada, Krishna, Godavari, Cauvery and Pennar. Flood and river discharge data is collected through a network of about 340 gauge/discharge sites located on the major and medium rivers of India. The rivers are said to be in flood when the water level crosses the Danger Level (DL) at the particular site. Major floods are defined as events when the DL is exceeded by 1 meter and most severe floods are events where the DL is exceeded by 5 meters. For a period from 1987 – 1997 the most flood prone states were Assam and Bihar, followed by Uttar Pradesh and West Bengal. A good source that describes the all-India distribution of flood hazard is the Vulnerability Atlas of India, from the Building Materials Technology Promotion Council (BMTPC, 1997). The maximum number of flood events are experienced in the month of August.

A large part of the Indian subcontinent is exposed to annual floods and droughts. The occurrence of floods and droughts is closely linked to the summer monsoon activity. Variations in heavy rainfall and meteorological floods have been analyzed by Chowdhury and Mhasawade (1991), who have used rainfall data to develop a flood index. The average annual flood covers vast areas throughout the region; in India and Bangladesh alone, floods cover 7.7 Mha[5] and 3.1 Mha, respectively (GOI, 1992; Mirza and Ericksen, 1996), while the total flood-prone[6] area in India is of the order of 40 Mha, or about 12% of the total land area of 329 Mha.

a. Impacts

Floods cause significant damage in India. Average flood damage over the period from 1953 – 1987 has been estimated at Rs 298 crores annually, with a mortality rate of around 1,318 per year (Roy, 1998). Figure 2.7 describes the trends in flood damages for a period from 1953 – 1987 (CSE, 1991). As the Figure indicates, the flood damages have increased steadily over a period of time. This is only partly due to changes in the hazard itself – a much larger contribution is perhaps due to the increased exposure to the hazard.

Floods not only cause immediate consequences such as loss of life and property, but are also important in terms of the damage to public infrastructure and utilities. This damage in turn leads to a loss of overall economic activity that depends on the availability of the infrastructure and the utilities. For example, the destruction of roads, bridges and other transport/communication infrastructure needs to be considered carefully while evaluating impacts.

Flood damages have risen over the years, as described above (Figure 2.7). The outlay on flood protection has also increased consistently, as have the expenditures on relief and recovery. All of these suggest a pattern of increasing vulnerability, which might worsen as a result of climate change. The increase trend in flood damages is suggested even when the data are adjusted to a common year (constant Rupees). This is described in Figure 2.8, which displays average annual damage in different plan periods (including some years when there were only annual plans).

[5] Million hectares, or xx sq. km.

[6] Definition of "flood prone"

Figure 2.7: Trends in Flood Damage

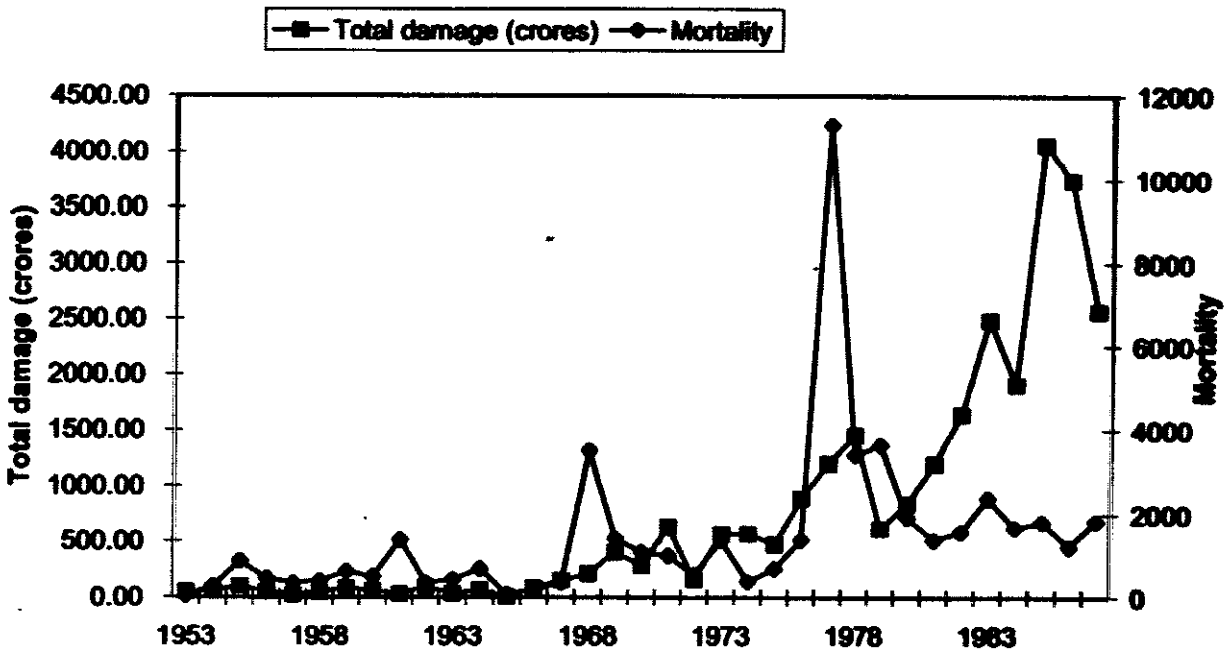
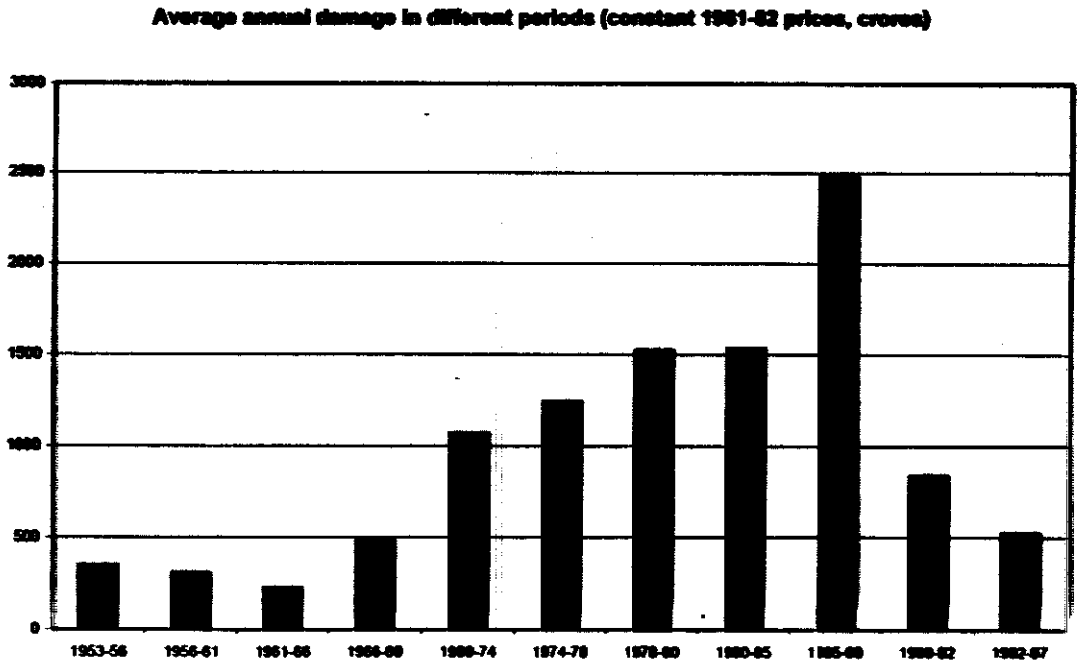


Figure 2.8: Damage Trends (Constant Prices)



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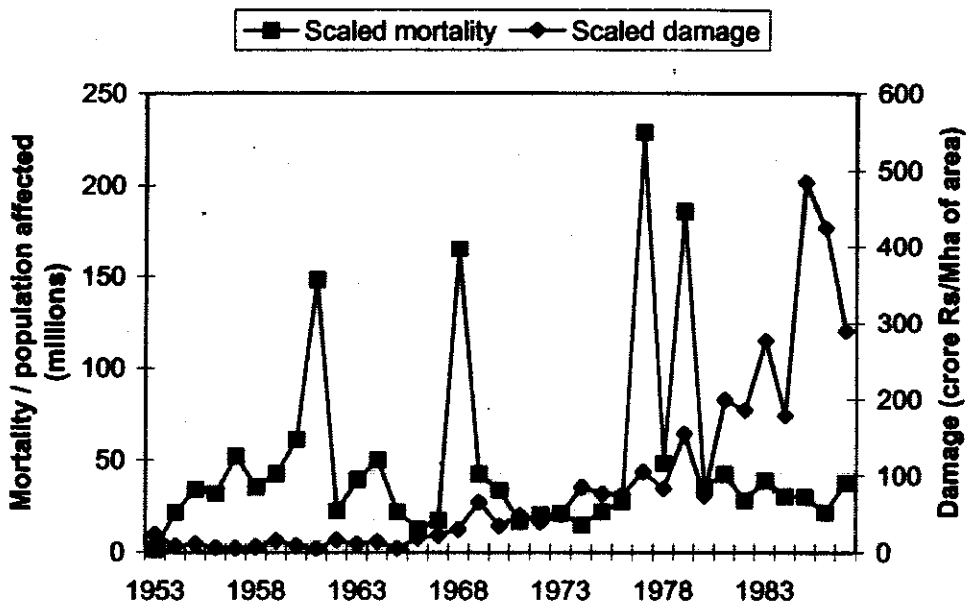
While a part of the increase in damage might be attributable to the overall increase in the area exposed to the hazard (flood-affected area), it is important to analyze the degree to which systems are also becoming more resilient, particularly in the case of factors such as mortality which can be reduced through a number of policy interventions and adaptation strategies. Figure 2.9 provides a first attempt at addressing this question by plotting the scaled mortality and damages (i.e. the ratio of total mortality to the total flood affected population, and the ratio of total economic damage to the total flood affected area). While scaled mortality does not appear to have any clear trends, scaled damage does seem to increase in a fashion similar to the overall damage. This suggests that there is perhaps increased concentration of housing, public infrastructure and other capital stock in flood-prone areas. Impact data like those shown in Figure 2.8 and 2.9 could be used to formulate damage functions for use in climate change impact assessment.

Figure 2.9: Scaled Mortality and Scaled Damages



C. Projections of Future Climate Change

Scenarios of future climate change are generated starting from projections for the emissions of greenhouse gases. Complex three-dimensional models of the atmosphere, ocean, cryosphere and biosphere are used to evaluate the effect of the changes in radiative forcing associated with increased concentrations of greenhouse gases. These models also include the effect of factors such as sulfate aerosols. A variety of approaches are then used to develop regional and local scenarios for changes in climate variables. These include, for example, nested models, statistical downscaling and related techniques. Before using a particular climate model for developing regional scenarios of future climate, it is necessary to assess the degree to which that model simulates the current climate conditions, including current patterns of climate variability. This is particularly important, as impacts are often most sensitive *not* to the climate variables best simulated (such as regionally or globally averaged surface temperature), but to variables such as precipitation or higher order climate statistics, such as exceedences over a threshold, or runs (series) of exceedences (such as a heat wave or a cold wave in the case of temperature). For example, many models do not capture the intraseasonal and spatial variability in the summer

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monsoon rainfall very well. Model validation exercises of this kind have been carried out (Lal et al., 2000, Lal and Harasawa, 2000). A number of models and model experiments were rated to have some effectiveness in simulating the broad features of the current climate and its variability (IPCC, 2001). Plausible changes for South Asia in area-averaged surface air temperature and percentage changes in precipitation based on an ensemble of these models are summarized in Tables 2.1 and 2.2 (IPCC, 2001).

Table 2.1: Area-Averaged Surface Air Temperature Change (degrees C). Numbers in Parentheses are Changes when Direct Effects of Sulfate Aerosols are Included

Annual	1.36	2.69	3.84
	(1.06)	(1.92)	(2.98)
Winter	1.62	3.25	4.52
	(1.19)	(2.08)	(3.25)
Summer	1.13	2.19	3.2
	(0.97)	(1.81)	(2.67)

Table 2.2: Area-Averaged Change in Precipitation (percentage). Numbers in Parentheses are Changes when Direct Effects of Sulfate Aerosols are Included

Annual	2.9	6.8	11
	(1.00)	(-2.4)	(-0.1)
Winter	2.7	-2.1	5.3
	(-10.1)	(-14.8)	(-11.2)
Summer	2.5	6.6	7.9
	(2.80)	(0.10)	(2.5)

As Table 2.1 indicates, significant warming is expected over the Indian subcontinent, with greater warming in the winter than in the summer. The direct effect of sulfate aerosols acts to reduce the extent of warming (negative feedback). However, with regard to precipitation, sulfate aerosol appears to produce a deleterious effect; it tends to lead to a decrease in precipitation rather than an increase. In fact, the inclusion of aerosol forcing can actually change the sign of the expected change, from an increase in precipitation to a decrease. Recent scientific efforts such as the INDOEX project thus have great significance in terms of improving predictive capability for the Indian subcontinent. The implications of climate change for the summer monsoon have been explored by Stephenson et al. (2000).

The best estimate of surface warming for the IPCC's B-A-U scenario is warming of 1 to 2°C over the South Asian Region by the year 2030. The precipitation changes over South Asia are likely to increase throughout the region by 5 to 10% in the summer, while marginal changes are expected during the winter. The projected largest warming of > 3.5°C occurs over the northwest, particularly over Rajasthan and adjoining areas. Relatively uniform warming of approximately 2.5°C occurs over both the Arabian Sea and the Bay of Bengal. The most pronounced greenhouse gas induced warming over the landmass of the Indian sub-continent is expected to be during the pre-monsoon season. The simulated changes in annual as well as seasonal surface temperature over the entire study area are found to be statistically significant at a 95% confidence level.[7]

[7] *Actual And Anticipated Changes In India's Climate : M.Lal Et Al In The Book Global Warming Ed. M. Lal, P117, Tata Mcgraw Hill, 1993.*

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With regard to extreme climate events, there is significant uncertainty about the nature of the expected changes. The possibility of increased heavy rainfall events has been suggested (IPCC, 2001). Increased heavy rainfall events could lead to increased probabilities of flash floods and floods overall. The intensity and frequency of cyclone storms in the Arabian Sea and the Bay of Bengal could also be affected under changed climatic conditions. While early work (Haarsma et al, 1993) suggested that, in the case of the North Indian Ocean, the average number of tropical disturbance days could increase from 17 to 29 per year in a doubled CO_2 scenario, the current evidence is still inconclusive.

III. AGRICULTURE AND FOOD SECURITY

A. Importance of Agriculture

The importance of agriculture in India is manifold. More than 28 percent of GDP was generated in agriculture in 2000-01. More than 60 percent of the workers have their primary employment in agriculture as per the census of March 2001. Agriculture provides the bulk of the consumption economy of India's people. The bottom 50 percent of India's population spends two thirds of their consumption expenditure on food. Thus, when the agricultural production system is disturbed it affects everyone in India. It disrupts the livelihood of the poor. It threatens their food security. It aggravates the depth of poverty and enlarges its extent as high food prices push those on the margin of poverty line, below the line.

Indian agriculture has made significant progress in the last four decades. Irrigated area has expanded from 38 million hectares in 1970 to 83.6 million hectares in 1998. Thus, it is now less vulnerable to variability of weather. This, however, does not mean it is less vulnerable to climate change. Climate change can change suitability of different crops, can disrupt groundwater tables and supply and also surface water flows. This may change the effectiveness of irrigation systems.

The changes in temperature, monsoon activity and level of carbon dioxide (CO_2) affect the productivity of crops. A higher concentration of CO_2 can increase the rate of photosynthesis and crop yields (Cure and Acock, 1986; Kimball et al, 1993). Recent research suggests that beneficial effects of CO_2 fertilization "may be greater under certain stressful conditions, including warmer temperatures and draught" (IPCC-TS of WGII Report). While this is "well established for some crops under experimental conditions, knowledge about them is incomplete in sub-optimal conditions of actual forms". Acute water shortages combined with thermal stress should adversely affect wheat and more severely, rice productivity in India even under the positive effects of elevated CO_2 in the future.

Other threats to agricultural productivity arise due to increased incidence of pests and diseases, greater frequency of floods and draughts, increased frequency of other extreme events such as cyclones, greater soil erosion due to increased intensity of rainfall and stronger winds.

B. Impact of Climate Change

An early global study by Rosenzweig and Parry, 1994 showed that agriculture in developing countries could suffer a larger disadvantage than developed countries due to climate change.

> "The results from climate models predict the average temperature in India to change between 2.3 to 4.8°C following a doubling of ambient concentration of carbon dioxide (CO_2) from their pre-Industrial revolution levels (Lonergan, 1998). The climate models also predict higher monsoon activity over the Indian sub-continent. The changes in temperature, precipitation, and ambient concentration of carbon dioxide (CO_2)[8] are

[8] Higher CO_2 concentrations in the atmosphere are expected to increase the rate of photosynthesis and hence the crop yield (Cure and Acock, 1986; Kimball et al., 1993). This phenomenon is referred to as the carbon fertilization effect in the literature. However recent work(Smith and

shown to have an effect on the productivity of crops. These effects, referred as agronomic effects, are assessed using crop simulation models. A number of studies in the past have analysed these physical impacts of potential changes in climate on Indian agriculture. Using a dynamic crop growth model, WTGROWS, Aggarawal and Sinha (1993) have showed that in north India, a 1°C rise in mean temperature would have no significant effect on wheat yields, while a 2°C increase would decrease yields in most places. Rao and Sinha (1994) have assessed the changes in wheat yield using CERES-Wheat crop simulation model under various climate change scenarios. They have estimated that the wheat yields could decrease between 28 to 68 percent without considering the carbon fertilization effects; and would range between + 4 to –34 percent after considering carbon fertilization effects. In a study of rice crop in northwest India, Lal et al. (1996) showed that carbon fertilization effects would not be able to offset the negative impacts on yields due to higher temperatures under the changed climatic conditions. More recently Saseendran et al. (2000) studied the impact of climate change on rice production in the southern Indian state of Kerala and showed that for every one degree rise in temperature the decline in yield is about 6 percent."

Kumar K and Jyoti Parikh (2001)

These studies have looked at one crop and in a particular region. Kumar K and Parikh J (2001) have used the EPIC model to assess the impact on climate change on wheat and rice yields in India. Since they have also used these estimates to assess the consequential impact on production, prices, consumption and welfare of different classes, we look at their assessment of yield impacts in some detail.

"The EPIC crop model used by Kumar K. and Jyoti Parikh (2001) is a field-scale model operating on daily time steps. The model has detailed modules on weather, hydrology, erosion, nutrient cycling, soil temperature, tillage, crop growth, and farm management. The model was originally developed to study the effect of erosion and Jones et al. (1991) discuss the model structure in detail. Stockle et al. (1992) have subsequently modified the model to study the impacts of climate change on crop output. The model captures the impact of changes in various climate parameters on crop production as follows:

Wheat and Rice are the most important crops in the country. In 2001-2002, of the 209 million tons of expected output of food grains, wheat and rice account for 164 million tons or 80% of the total. Most farmers grow one of these and some farmers grow both these crops.

Temperature: Through its influence on the rate of plant phenological development, the length of the growing period, and the rates of evaporation and transpiration.

Precipitation: Through its influence on soil moisture stress. The moisture stress days during the growing period are accounted for while evaluating their effect on plant growth.

Ambient CO_2 concentration: Through increases in radiation use efficiency (which is defined as photosynthesis per unit of solar radiation absorbed). Increase in radiation use efficiency would result in improvement in the leaf area index, and also reduction in transpiration. Both these effects would lead to improvement in crop yields.

They have calibrated the EPIC model parameters so that it reproduces observed yields at a number of places in the country for which all the relevant data were available. There were 12 sites for rice and 10 for

Huxman, 2001) has shown that the carbon fertilization effect is complex, depends on climate parameters, can increase variability and cannot be taken for across the board increase in yield.

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wheat, which covered the important rice and wheat growing areas in the country. The model is then used to generate yields under climate change scenarios generated by different global circulation models.

The normal climate corresponding to the period 1930 – 1960 is used as the base climate. The climate change scenarios are generated using the results from the equilibrium experiments conducted at Goddard Institute of Space Studies (GISS) (Hansen et al., 1988), Geofluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1987), and United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell, 1987). These were the only climate projections available when K. Kumar and J. Parikh carried out their study. They differ from the scenarios given in Chapter 2 that use more recent information. Nonetheless, while assessing the vulnerability of Indian agriculture to climate change, the newer scenarios would not make much difference.

The predicted changes in climate from these scenarios are expected to manifest by the year 2060. The output from these three scenarios varies substantially, with the UKMO scenario projecting maximum temperature change and GFDL scenario projecting minimum change. The average temperature change across India projected by these scenarios ranges from 2.3 to 4.8°C. All the scenarios project the temperature rise in Northern India to be higher than that in Southern India. Though all the scenarios predict higher precipitation during monsoon season, the projections vary significantly across scenarios. Their estimated impacts on wheat and rice yields are shown in Table 3.1 and Table 3.2.

Table 3.1. Percentage Change in Rice Yield at Different Sites under Various Climate Change Scenarios

	Nabha		Anantpur		Daryapur		Coimb.		Nabha		Anantpur		Daryapur		Coimb.	
	R	I	R	I	R	I	R	I	R	I	R	I	R	I	R	I
UK	-43.2	-50.1	-30.5	-40.8	-40.1	-48.1	-42.6	-40.2	-24.2	-34.1	-11.5	-24.9	-20.2	-29.1	-23.3	-22.2
GI	-39.1	-48.5	-26.3	-29.2	-36.2	-45.5	-22.6	-33.3	-20.1	-33.4	-6.6	-13.1	-20.1	-30.0	-3.1	-16.6
GF	-24.6	-39.8	-20.7	-28.8	-26.2	-36.3	-21.7	-30.3	-5.2	-23.3	-1.5	-12.1	-6.3	-19.3	-2.8	-13.3

Note: UK – UKMO; GI – GISS; GF – GFDL; R – Rainfed; I – Irrigated.

Source: Kumar and Parikh (2001b)

Table 3.2 Percentage Change in Wheat Yield at Different Sites under Various Climate Change Scenarios

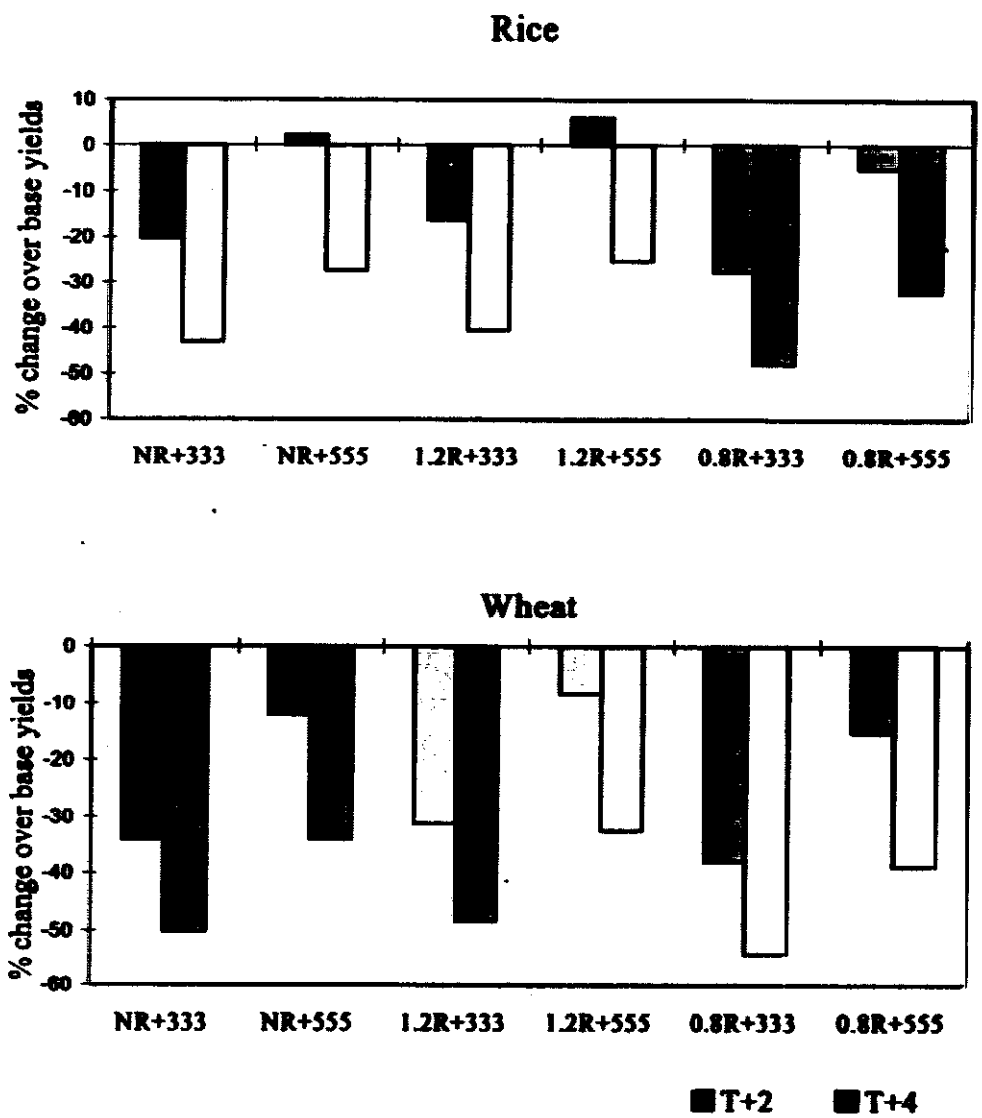
	Kakra		Hisar		Fatehpur		Isri		Kakra		Hisar		Fatehpur		Isri	
	R	I	R	I	R	I	R	I	R	I	R	I	R	I	R	I
UK	-36.3	-51.5	-31.7	-57.8	-39.5	-49.7	-43.0	-54.5	-13.3	-32.6	-7.8	-38.3	-11.5	-32.2	-18.0	-33.5
GI	-24.3	-53.2	-27.0	-53.5	-19.5	-43.8	-33.2	-49.0	-0.3	-25.2	-2.3	-23.5	6.6	-24.6	-8.2	-21.5
GF	-34.9	-44.0	-30.5	-45.7	-28.2	-42.5	-33.7	-41.2	-11.5	-19.5	-8.1	-16.2	-7.8	-14.9	-12.3	-16.2

Note: UK – UKMO; GI – GISS; GF – GFDL; R – Rainfed; I – Irrigated.

Source: Kumar and Parikh (2001b)

Figure 3.1 from Kumar K and Jyoti Parikh (2001b) shows the sensitivity of EPIC model to changes in climate.

Figure 3.1: Sensitivity of EPIC Crop Model to Changes in Climate



NR : Normal rainfall
1.2R: 20% increase over normal rainfall
0.8R: 20% decrease over normal rainfall
333: Ambient CO_2 concentration
555: Enhanced CO_2 concentration under changed climate

T+2: 2°C increase over base temperature
T+4: 4°C increase over base temperature

We can summarize their findings as shown in Table 3.3. These changes are large and can have significant impact on human conditions.

Table 3.3: Range of Impact on Wheat and Rice Yields over Scenarios for Selected Cities

2.3° to 4.8° C increase in average temperature	-20 to -50	-16 to -43	-37 to -58	-19 to -44
Same as above with CO_2 fertilization	–5 to –34	+2 to -24	-8.5 to -38	+6.6 to -22

The national averages are obtained by averaging the proportions of irrigated and rainfed areas. These are shown in Table 3.4.

Table 3.4: Change in Wheat and Rice Yields: All India Averages

Percent change in yield

Without CO_2 fertilization	-32 to -40	-41 to -52
With CO_2 fertilization	-13 to -25	-15 to -33

C. Economic and Welfare Impacts: Vulnerability

To assess the macroeconomic and welfare consequences of changes in yield levels, namely for production, relative prices, incomes, consumption and welfare levels of different groups of people, Kumar and Parikh have used the general equilibrium model, AGRIM, developed by Narayana N.S.S., Parikh, K and Srinivasan T.N. (1991).

AGRIM can study as many as 25 crops (16 major and 9 minor crops). Assuming climate change to affect only a few crops would not be appropriate. Hence, out of the 25 crops, the ones under the rice group have been assumed to experience similar yield changes as expected for rice, and similarly for the ones under the wheat group. The crops that do not fall into either of these groups are clubbed into two groups – others and small millet group. The yield changes for these two groups are assumed to be 7.5 and 12.5 percent lower than the average yield change estimated for rice and wheat[9].

The average yield changes obtained through the EPIC model represent shifts in yield-input relationships, i.e., they show by how much the yield would be lower for a given level of inputs. The actual levels of inputs applied will depend on relative prices. AGRIM determines cropping patterns and input levels endogenously and thus reflects some adaptation by farmers.

Kumar and Parikh generate scenarios with AGRIM covering the period 1990-2060. The climate change scenarios are compared with a base scenario. Table 3.5 compares some major macro indicators for the terminal year, viz. 2060. As the climate change-induced yield changes in crops are assumed to manifest fully over the long run, it would be appropriate to study the impacts for the terminal year in the simulation period, viz. 2060.

[9] In the absence of more accurate estimates of yield changes for other crops, such assumptions are inevitable and somewhat similar assumptions are made by Rosenzweig and Parry (1994) in their study on global food security.

Table 3.5: Percentage Change Over Base Scenario in Various Macro and Welfare Indicators under Various Climate Change Scenarios

		GFDL	GISS	UKMO	GFDL	GISS	UKMO
Macro and Welfare Indicators							
GDPA70	437052	-25.85	-28.69	-32.90	-10.07	-13.02	-18.43
GDPNA70	2871753	1.83	1.52	1.045	-0.05	-0.26	-0.66
GDP70	3308805	-1.83	-2.46	-3.44	-1.37	-1.95	-3.00
INVEST	689264	3.91	3.22	2.15	0.37	0.01	-0.68
PA/PNA	1.1012	107.80	111.73	118.22	25.39	29.69	38.23
UPOP	870037	2.46	2.30	2.05	0.87	0.85	0.79
PARITY	0.868	7.94	7.30	6.30	1.88	1.80	1.61
CAL/CAP	2698.9	-18.23	-19.55	-21.63	-5.38	-6.38	-8.29
AVR.EQY	893.08	-25.16	-27.28	-30.57	-5.02	-6.10	-8.13
Sectoral Production							
WHEAT	93852	-38.31	-43.65	-50.08	-13.98	-20.82	-31.74
RICE	135605	-30.53	-33.56	-38.69	-12.13	-15.77	-24.10
Non-AGRI.	384130	1.72	1.45	0.96	-0.07	-0.30	-0.70

Note: GDP70: Gross domestic product, GDPA70: GDP-agriculture, GDPNA70: GDP-non-agriculture, INVEST: Investment, all in 1970-'71 prices, in 10^6 Rs.; PA/PNA: Ratio of agricultural to non-agricultural price deflator; UPOP: Urban population, in '000 persons; Parity: Rural-urban income parity; CAL/CAP: Food energy calorie intake/capita, in Kcal/person-day; A.EQY: Average equivalent income (income needed at 1970-71 prices to provide same utility as provided by current consumption at current prices), in Rupees; Wheat and Rice: Wheat and Rice production, respectively in '000 tons; Non-Agri: Non-agricultural production in million US $ in 1970-'71 prices. The figures correspond to the terminal period of the simulation.

Depending on the climate change scenario under consideration, the expected decline in agricultural GDP ranged from 26 to 33 percent. The overall effect of climate change has resulted in a loss in GDP under all scenarios, with the decline ranging from 1.8 to 3.4 percent. (The losses are greatest under the UKMO scenario and least under the GFDL scenario.) The impacts on agricultural GDP are substantially reduced after considering the CO_2 fertilization effects. Nonetheless, they are sizeable. This gain in agricultural sectors under the scenarios with CO_2 fertilization effects results in only a marginal loss in non-agricultural sectors' performance.

The agricultural production losses are compensated for somewhat by higher agricultural prices, and the results show higher losses in urban income as against the rural income under climate change scenarios.

The population distribution by levels of total consumption expenditure is shown in Table 3.6. The bottom two classes correspond to those below the poverty line and the bottommost class shows the abject poor. We see that climate change increases the number of rural poor from 18.3 percent to as much as 31.1 percent. The abject poor increase by 10 percentage points in rural areas. The number of urban poor increases from 3.4 percent to 8 percent and abject poor by 1.0 percent. Even with carbon fertilization effects, which as shown by Smith and Huxmann (2001) are not unambiguous, the number of rural and urban poor increases by as much as 6 and 2 percent, respectively.

This means that climate change could increase the number of poor in India by more than 130 million persons in 2060. Indian agriculture and India's food security are highly vulnerable to climate change.

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Table 3.6: Proportion of People Across Income Groups Under Various Climate Change Scenarios

Rural							
Less than 216	0.091	0.169	0.177	0.191	0.118	0.124	0.135
Less than 336	0.092	0.114	0.117	0.120	0.100	0.102	0.106
Less than 516	0.143	0.140	0.142	0.143	0.143	0.145	0.149
Less than 900	0.261	0.241	0.239	0.237	0.257	0.258	0.257
More than 900	0.412	0.336	0.326	0.310	0.382	0.372	0.353
Urban							
Less than 216	0.004	0.013	0.014	0.015	0.007	0.007	0.008
Less than 336	0.030	0.058	0.060	0.065	0.040	0.042	0.047
Less than 516	0.111	0.137	0.140	0.146	0.124	0.127	0.134
Less than 900	0.304	0.290	0.291	0.293	0.304	0.305	0.307
More than 900	0.551	0.503	0.495	0.481	0.526	0.519	0.504

Note: The expenditure classes are defined in 1970-'71 prices and relate to rupees per person per month. The exchange rate in 1970-71 was Rs 7.50 to 1 US $. The figures correspond to the terminal period of the simulation.

One should emphasize that the Kumar and Parikh analysis has not fully accounted for many other threats to agriculture from climate change. Thus, the damage due to land loss, irrigation capacity loss and higher incidence of droughts and floods has not been factored in.

IV. COASTAL IMPACTS OF CLIMATE CHANGE

A. Basic Characteristics

The coastal zone is an important and critical region for India, which is endowed with a coastline of over 7,500 km. 3 of the 4 major Indian metropolitan areas are located in the coastal region (Mumbai, Kolkata and Chennai). The total area occupied by coastal districts is around 457,000 sq. km, with an average population density of 425 persons / sq. km, which is almost twice the national average of 267. Table 4.1 provides the population density for the coastal states in India.

While the average decennial growth rate over the 1981 – 1991 period was similar for the coastal zone as compared to the country as a whole (26.4% vs 23.86%), this hides a significant asymmetry between the East and West coasts. According to the data from the 1991 census, there are 21 cities in the coastal zone with a population in the range of 100,00 – 500,000, 7 in the range from 500,000 – 8 million and two (Mumbai and Kolkata) with a population exceeding 10 million.

The Indian coastal zone exhibits a number of geomorphologic features, including shorelines with coastal cliffs, dune and beach ecosystems, coastal wetlands and estuaries. Coastal cliffs are prominent in many locations, for example, Chilka Lake in Orissa, Tiruchendur and Nagercoil in Tamil Nadu, all on the East Coast; extensive parts of the shoreline south of Trivandrum, and the Konkan coast in Maharashtra, all on the West Coast.

Table 4.1: Population Density in the Different Coastal Belts in India

West Bengal	616
Orissa	165
Andhra Pradesh	196
Tamil nadu	372
A & N Islands	23
Kerala	655
Karnataka	194
Maharashtra	2040
Gujarat	174
Lakshadweep	1258
Pondicherry	1229

India has an estimated total brackish water area of 1.2 million hectares (Mha). The maximum area is in West Bengal (0.4 Mha), with Gujarat (0.37 Mha) close behind. Andhra Pradesh, with 0.15 Mha, has a network of 172 brackish water bodies in 9 coastal districts. The brackish water areas are important for a variety of economic activities including aquaculture. However, the penetration of aquaculture is still somewhat low, as the total area under brackish water aquaculture in the country is only around 68,000 hectares.

B. Key Climate-Related Issues in the Coastal Zone

The coastal zone is one of the most climate-sensitive regions, as it is subjected to a range of climate-related forcing drivers, including sea level change, local precipitation, and ocean currents, as well as local ecosystems. Future climate change is likely to be manifested through the worsening of some of the existing coastal zone issues. Therefore, some of the main issues in the context of the Indian coastline are discussed below:

Erosion: Gully erosion and the formation of badlands is developed to a high degree in the coastal zone around the Gulf of Cambay in the valleys of Tapti, Narmada, Mahe and Sabarmati, particularly north of the Narmada. Sheet wash of soil and sediments also occurs to a marked degree in the region of the Western Ghats. A good deal of these sediments pass into the sea and contribute to the building of the beaches and other shore features in the region of their discharge. Coastal erosion problems are also severe along the coastline of Central and North Kerala, and Southern Tamil Nadu. Erosion due to cyclonic storms takes place all along the coast.

Flooding: Coastal flooding is a problem in all the coastal states that experience tropical cyclone incidence. These include states on the East coast, such as West Bengal, Orissa, Andhra Pradesh and Tamil Nadu, as well as Gujarat on the West coast. River flooding (i.e. temporary inundation of the coastal zone by river water) also occurs in coastal areas, estuary formations, and deltaic areas of major rivers. This particularly happens in the case of rivers Godavari, Krishna, Ganges, Mahanadi, Subernarekha, Cauvery, Tapi & Mahi.

Subsidence: Coastal subsidence is a serious problem in the Ganges – Brahmaputra delta in West Bengal, as well as regions in the Gujarat coast, such as Kathiawar and the Gulf of Cambay.

Ecosystems: The Indian coastline is richly endowed with a range of coastal ecosystems, including mangroves, salt marshes and other wetlands, lagoons, coral reefs, dunes and sand/mud flats. For example, lagoon formations like Chilka (Orissa), Pulicat (Tamil Nadu), Vembanad (Kerala), and near Tuticorin are

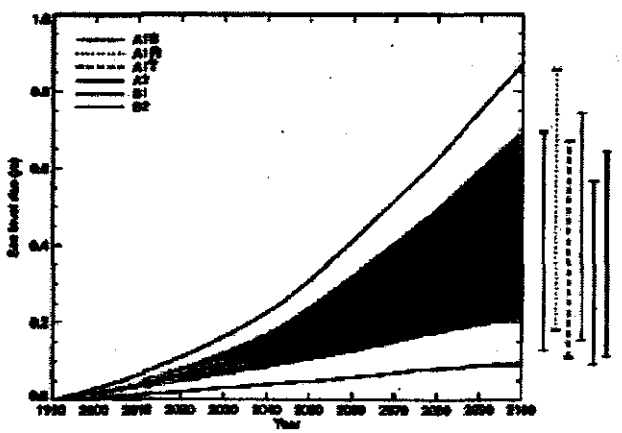
well known. These are threatened by various activities related to industrial production (effluents), new construction (dredging) and sedimentation. Virtually all the rivers flowing into the Arabian Sea, including the Narmada, Mahi, Tapti, Sabarmati and others have extensive mud flats and salt marshes. Extensive mangrove forests are found in the Sunderbans, as well as on the Orissa coast, North Andhra Pradesh coast, and Southern Gujarat. Many of these ecosystem regions are under severe pressure as a result of rapid development of the coastal zone. Climate change is likely to lead to further deterioration of the ecosystems.

Salinization: Salinization of agricultural land is commonly associated with tropical cyclone occurrence on the East Coast. Districts that are particularly affected include: Sundarbans, South 24 Parganas, Balasore, Puri, East & West Godavari, Krishna, Ongole and Nellore. Many coastal regions also suffer from longer-term saline intrusion into coastal aquifers and groundwater, including the coastal districts of Nellore and Prakasam in Andhra Pradesh, Northern Tamil Nadu and the Saurashtra region of Gujarat.

C. Sea Level Rise

Sea level rise at a particular location is the combination of both global (or eustatic) sea level rise and local trends. Global sea level rise is due to the glacial melt from mountain glaciers and the ice caps, as well as thermal expansion of the water column. It is expected that global sea level rise will range from 9 to 88 cm by the year 2100 (IPCC 2001). The range of projections for global mean sea level rise are provided in Figure 4.1 (source: IPCC Working Group I).

Figure 4.1: Sea Level Rise Projections



However, in many coastal regions where subsidence or uplift are important, local factors can often dominate the global signal. Therefore, while assessing the impacts of sea level rise, it is important to account for the long-term local sea level trends. Traditionally, observations of local (or relative) sea level are made using tide gauges, and there are around 24 stations on the Indian coast for which relative sea level data from tide gauges are available. Studies of historical rates of relative sea-level rise in the South Asia Seas region, reported by Gable and Aubrey (1990), indicate an average annual relative sea-level rise of 0.67 mm/yr (or 6.7 cm over a century). In addition, during the past half-century or so, relative sea-level changes in the region have ranged from a fall (i.e., land emergence) of 1.33 mm/yr to a rise (i.e., land submergence) of 2.27 mm/yr. Relative sea level trends as inferred from these tide gauges on the Indian East coast are summarized in Figure 4.2. These trends indicate a relative sea level rise throughout most of the coast, excepting in the South.

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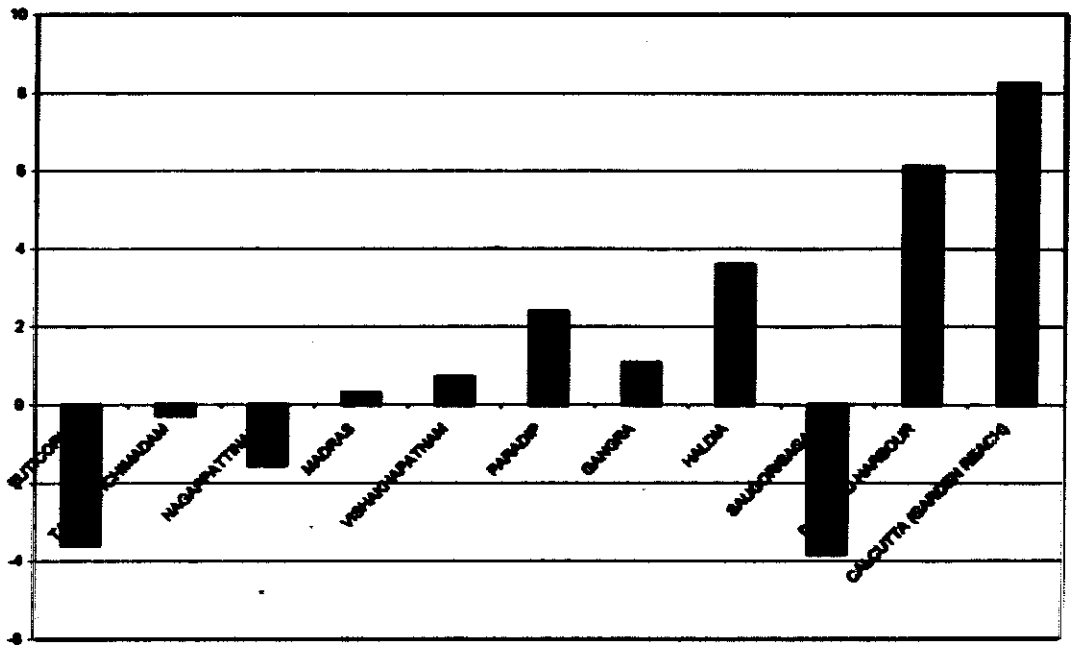
Figure 4.2: Relative Sea Level Trends on the East Coast (mm/year)



A variety of impacts are expected as a result of sea level rise. These include:

- Land loss and population displacement
- Increased flooding of low-lying coastal areas
- Agricultural impacts (e.g., loss of yield and employment) resulting from inundation, salinization, and land loss
- Impacts on coastal aquaculture
- Impacts on coastal tourism, particularly the erosion of sandy beaches.

The first of these impacts is considered the most serious for a number of regions in South Asia by Nicholls et al. (1995). They estimate that a 1-meter rise in sea level could lead to a land loss of 6,000 sq. km and displace over 7 million people in India. There have been a few other studies that have explored sea level rise impacts for India. One of the first studies was done by the Jawaharlal Nehru University (JNU, 1993), in which the consequences of a 1-meter sea level rise scenario were evaluated. The study concluded that, in the absence of protection, approximately seven million people would be displaced, and 5,764 km^2 of land and 4,200 km of roads would be lost. The dominant cost estimated was that due to the loss of land. Table 4.2 summarizes the results of the study. A subsequent study by the Tata Energy Research Institute (TERI, 1996) explored the relative vulnerabilities of different coastal regions, the effect of adaptive responses on the sea level rise impacts and the value of coastal protection for selected regions.

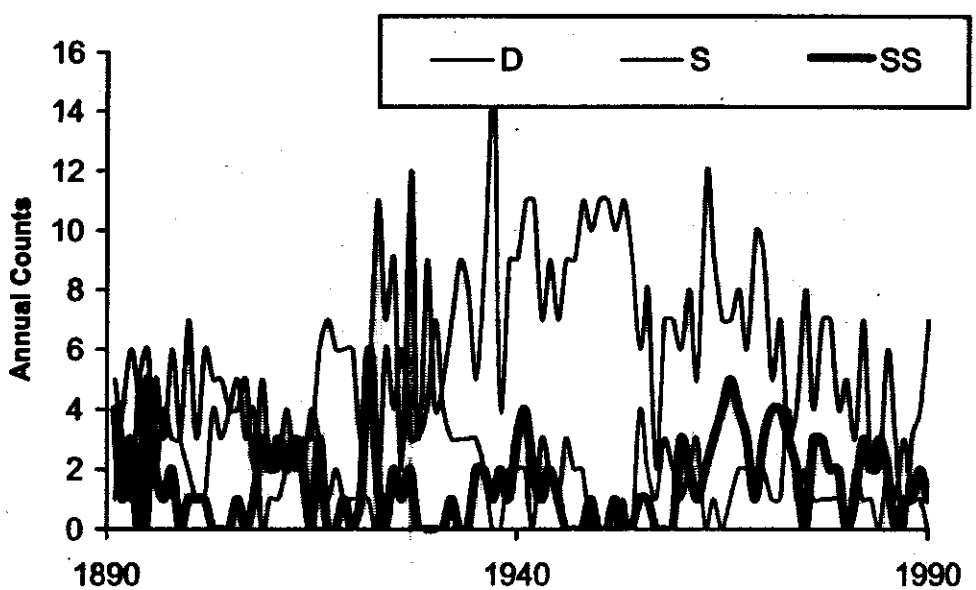
D. Tropical Cyclones

Tropical cyclones are a key climate-related factor for determining the vulnerability of coastal regions. As was mentioned earlier, the Indian East coast is most susceptible to cyclone impacts. Figure 4.3 plots the incidence of depressions, cyclonic storms and severe cyclonic storms for the East coast. While there are no long term trends, there is significant variability on interannual and interdecadal time scales. In addition to temporal trends, spatial patterns of incidence are also important. While depressions are often concentrated around the West Bengal coastline, cyclonic storms and severe cyclonic storms are distributed more evenly throughout the East coast. However, it is important to note that the spatial

Table 4.2 Effect of 1–m Sea-Level Rise (source: JNU, 1993)

Andhra Pradesh	27.504	0.055	0.19	66.36	0.617	0.93
Goa	0.37	0.016	4.34	1.17	0.085	7.25
Gujarat	19.602	0.181	0.92	41.17	0.441	1.07
Karnataka	19.179	0.029	0.15	44.81	0.25	0.56
Kerala	3.886	0.012	0.3	29.08	0.454	1.56
Maharashtra	30.771	0.041	0.13	78.75	1.376	1.75
Orissa	15.571	0.048	0.31	31.51	0.555	1.76
Tamil Nadu	13.006	0.067	0.52	55.64	1.621	2.91
West Bengal	8.875	0.122	1.38	67.98	1.6	2.35
Union territory						
Andaman and Nicobar Islands	0.825	0.006	0.72	0	0	0
India	**139.594**	**0.571**	**0.41**	**416.74**	**7.1**	**1.68**

Figure 4.3: Historical Trends in Landfalling Storms



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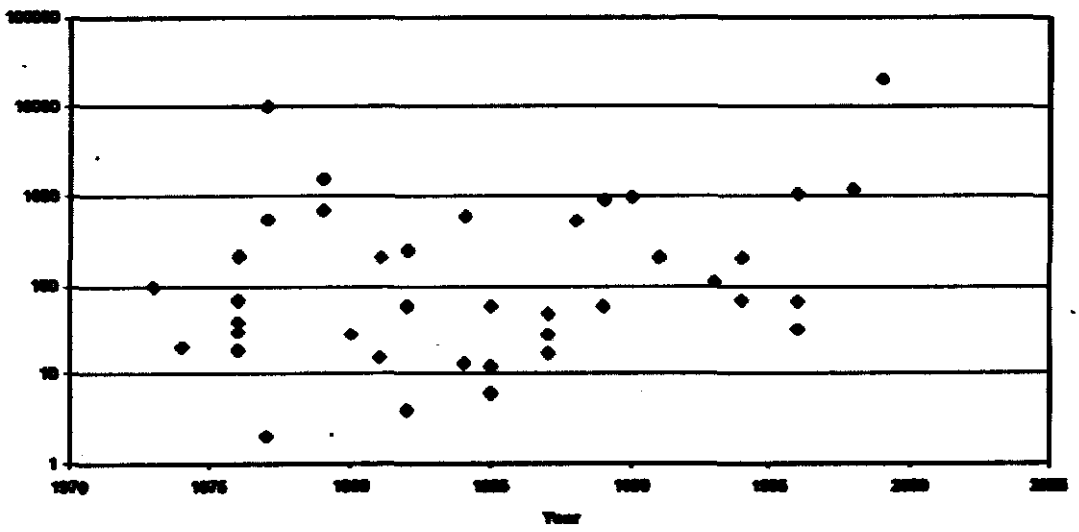
distribution is not stationary – there are shifts in the spatial distribution on decadal time scales. This is quite significant in terms of coastal development – a region that has experienced a moderate storm climate in the past could experience a more severe storm climate in the future, and there may be a lack of adequate planning for this purpose. Similarly, while there is no significant relationship between the number of events and phenomena such as ENSO, the spatial patterns of incidence appear to depend on the phase of the El NiZo oscillation.

Assessment of vulnerability to cyclone hazard requires an evaluation not only of the hazard, but also the exposure to the hazard, coastal geomorphology and complementary factors such as sea level rise and the extent of adaptive capacity and adaptation potential in the region. A detailed examination of the vulnerability process is likely to yield a number of insights with regard to the impacts of future climate change.

Data for tropical cyclone impacts are quite scanty and scattered. Annual summaries are available in Mausam (Journal of the India Meteorological Society). However, there is considerable variation in terms of classifying and systematically reporting damage data. Mortality is one of the variables that is commonly reported, and Figure 4.4 plots the variation in mortality for the last three decades. A slight increase in mortality may be seen. The actual consequences of cyclones are critically dependent on the exposure and on the overall adaptive capacity for the region. Figure 4.5 plots the mortality with storms affecting Andhra Pradesh, to give an indication of the possible advantages of building adaptive capacity and improving the overall developmental baseline of the region.

Figure 4.4: Tropical Cyclone Mortality (all-India)



1. Projections

Current atmosphere-ocean general circulation model (AOGCM) simulations have limited ability to suggest likely changes in tropical cyclone activity; until high-resolution GCM simulations are available, it is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity, or maximum intensity of tropical cyclones will change in Tropical Asia. However, more recent studies with models of higher resolution appear to be able to simulate tropical cyclone climatology (Bengtsson et al., 1995). Bengtsson et al. (1995) found a decrease in the number of tropical cyclones under enhanced greenhouse scenarios, especially in the Southern Hemisphere, although their geographical distribution remained unchanged.

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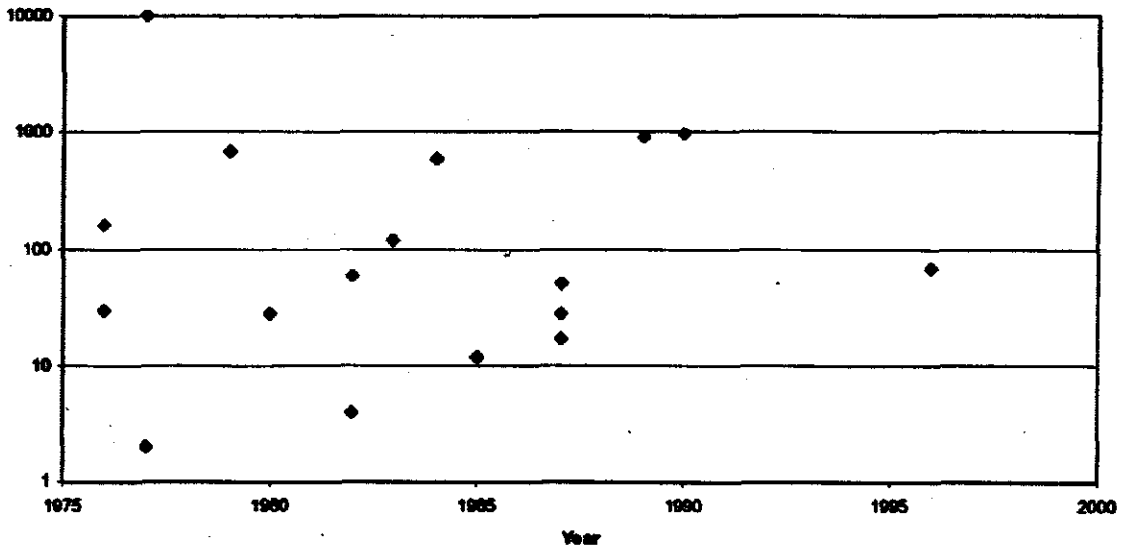
Figure 4.5: Tropical Storm Mortality (Andhra Pradesh)



A study by Holland (1997) indicated that tropical cyclones are unlikely to be more intense than the worst storms experienced under present-day climate conditions, although some potential exists for changes in cyclone intensity in tropical oceanic regions, where sea-surface temperature (SST) is betwen 26°C and 29°C. According to Henderson-Sellars and Zhang (1997), recent studies indicate that the maximum potential intensities of cyclones will remain the same or undergo a modest increase of up to 10–20%; they add that these predicted changes are small compared with observed natural variations and fall within the uncertainty range in current studies. Lal et al. (1995a), in their ECHAm^3-T106 experiment, found no significant change in the number and intensity of monsoon depressions in the Indian Ocean in a warmer climate. Similarly, likely changes in the ENSO phenomenon under enhanced greenhouse conditions and their possible impact on the interannual variability of the summer monsoon are not known.

V. WATER RESOURCES OF INDIA

A. India's Vulnerability to Global Warming

The vulnerability of the Indian sub-continent to the impact of climate change is most relevant in the tropics, for the majority of people in India and its neighboring countries depend on agriculture for their livelihoods and agricultural production depends a great deal on the Asian Summer monsoon and its variability on a variety of time scales.

Water is essential for human civilization, living organisms, and natural habitat. It is used for drinking, cleaning, agriculture, transportation, industry, recreation, and animal husbandry, producing electricity for domestic, industrial and commercial use. Due to its multiple benefits and the problems created by its excesses, shortages and quality deterioration, water as a resource requires special attention. Table 5.1 illustrates the land and water resources of India. On a global scale, the total quantity of water available is about 1600 million cubic km. The hydrologic cycle moves enormous quantities of water around the globe. However, much of the world's water has little potential for human use because 97.5% of all water on earth is saline water. Out of the remaining 2.5% freshwater, most of which lies deep and frozen in

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Antarctica and Greenland, only about 0.26% is in rivers, lakes and in the soils and shallow aquifers, which are readily usable for mankind.

Table 5.1: Land and Water Resources of India[10]

Particulars	Quantity
Geographical Area	329 million ha.
Flood Prone Area	40 million ha.
Ultimate Irrigation Potential	140 million ha.
Total Cultivable Land Area	184 million ha.
Net Irrigated Area	50 million ha.
Natural Runoff (Surface Water and Ground Water)	1869 Cubic km.
Estimated Utilizable Surface Water Potential	690 Cubic km.
Groundwater Resource	432 Cubic km.
Available Groundwater resource for Irrigation	361 Cubic km.
Net Utilizable Groundwater resource for irrigation	325 Cubic km.

Source: National Institute of Hydrology

B. Water Resources[11]

1. *Surface Water*

India's average annual surface run-off generated by rainfall and snowmelt is estimated to be about 1,869 billion cubic meters (BCM). However, it is estimated that only about 690 BCM, or 37 percent of the surface water resources, can actually be mobilized. This is because (i) over 90 percent of the annual flow of the Himalayas rivers occurs over a four-month period and (ii) the potential to capture such resources is complicated by limited suitable storage reservoir sites.

2. *Rainfall*

The average annual rainfall in India is about 1,170 mm. There is considerable variation in rain, both temporarily and spatially. Most rain falls in the monsoon season (June-September), necessitating the creation of large storages for maximum utilization of the surface run-off. Within any given year, it is possible to have both situations of drought and of floods in the same region. Regional variations are also extreme, ranging from a low value of 100 mm in Western Rajasthan to over 11,000 mm in Meghalaya in North-Eastern India. Possible changes in rainfall patterns in the coming decade, global warming and climate change and other predicted or observed long-term trends on water availability could affect India's water resources.

[10] Water Resource India, National Institute of Hydrology. Website : www.nih.ernet.in

[11] Initiating and Sustaining Water Sector Reforms : A Synthesis World Bank in collaboration with the Government of India, Ministry of Water Resource.

3. *Ground Water*

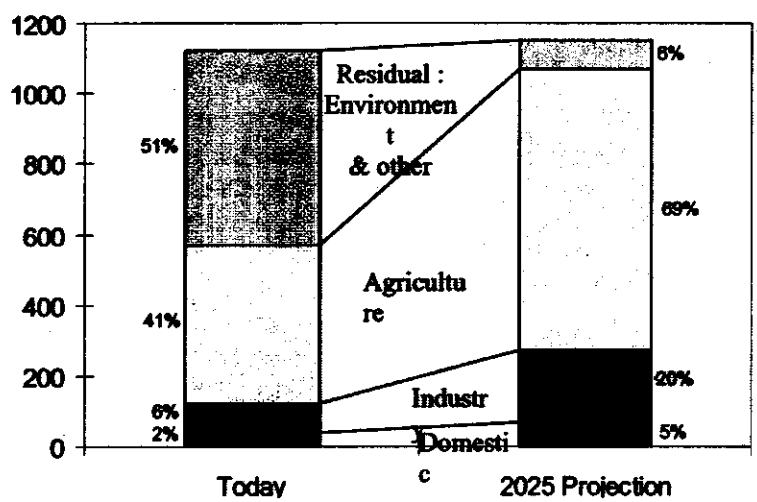
India's rechargeable annual groundwater potential has been assessed at around 431 BCM in aggregate terms. On an all-India basis it is estimated that about 30 percent of the groundwater potential has been tapped for irrigation and domestic use. The regional situation is very different, and large parts of India have already exploited almost all of their dynamic recharge. Haryana and Punjab have exploited about 94 percent of their groundwater resources. Areas with depleting groundwater tables are found in Rajasthan, Gujarat, most of western Uttar Pradesh and in all of the Deccan states.

Occurrence of water availability at about 1,000 cubic meters per capita per annum is a common threshold for water indicating scarcity (UNDP). Investment to capture additional surface run-off will become increasingly more difficult and expensive in the future. Over time, both for surface and groundwater resources, a situation where resources were substantially under-utilized and where considerable development potential existed, has transformed in little more than a generation to a situation of water scarcity and limited development options.

India faces an increasingly urgent situation: its finite and fragile water resources are stressed and depleting while various sectoral demands are growing rapidly. Historically, relatively plentiful water resources have been primarily for irrigated agriculture, but with the growth of the Indian economy and industrial activities' water demands, the share of water is changing rapidly. In addition, increases in population and rapid urbanization also put an additional demand on water resources. Summing up the various sectoral projections reveals a total annual demand for water increasing from 552 billion cubic meters (BCM) in 1997 to 1,050 BCM by 2025 (Fig 5.1).
Under current sectoral trends, precious little water will remain for environmental and other needs. This is untenable.

At Independence, the population was less than 400 million and per capita water availability over 5,000 cubic meters per year (m^3/yr). With the population above the 1 billion mark, water availability has fallen to about 2,000 m^3/yr per capita. By the year 2025, per capita availability is projected at only 1,500 m^3/yr, or 30% of availability levels at Independence.

Figure 5.1: Sectoral Water Demand Trends



Note: Government projections; Increasing sectoral demands planned to be met through new construction.
Source: GOI (1997d).

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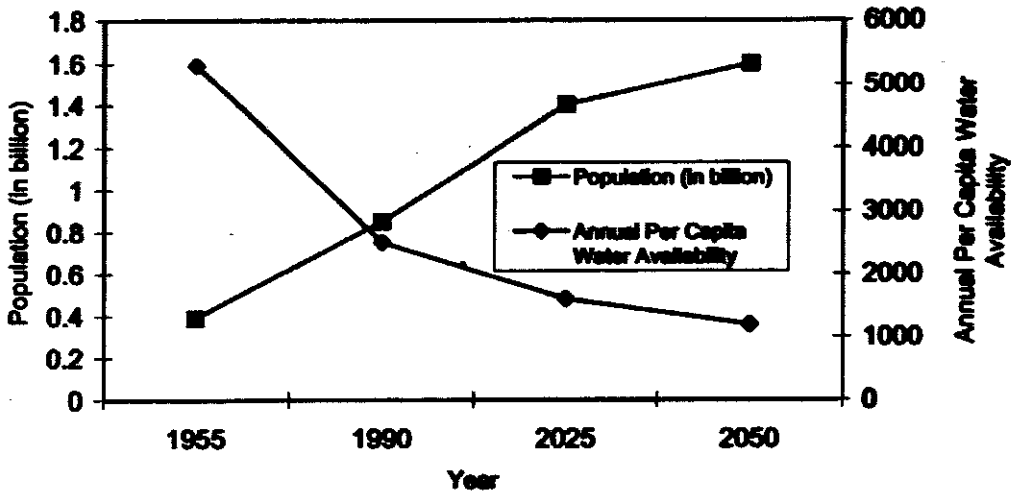
Figure 5.2: Population and Water Availability Trends in India



Source: Population Action International, 1995; World Bank, 1997a.

The water availability index includes surface water only, yet groundwater is an important component of water availability that factors significantly in the Indian economy. Ground water is an important source of drinking water and food security for India, supplying about 80 percent of water for domestic use in rural areas and about 50 percent of water for urban and industrial uses. Groundwater provides a significant percentage of the water supply for irrigation, and contributes significantly to India's agricultural and overall economic development. With more than 17 million energized wells nationwide, groundwater now supplies more than 50 percent of irrigated area.

C. Populations Food Grain Requirement

In India, the food grain availability is, at present, around 525 gms per capita per day, whereas the corresponding figures in China & USA are 980 gms and 2,850 gms, respectively. If a small raise is made in per capita consumption to 650 gms, the food grain requirement will be about 390 MT of food grain. Taking the projections of about 1,800 million by 2050 AD as reasonable, it would require about 430 MT of food grain annually at the present level of consumption. This will mean a much greater use of available inputs. The first input is water, the second input would be fertilizers and the third input would be a much larger emphasis on research. This would also require increasing the area under irrigation from the present 28% to roughly 40% by the year 2050 and adopting drip and sprinkler irrigation in India.

The total geographical area of land in India is 329 mha, which is 2.45% of the global land area. The total arable land is 165.3 mha, which is about 50.2% of total geographical area against the corresponding global figure of 10.2%. India possesses 4% of the total average runoff in the rivers of the world. The per capita water availability of natural runoff is at least 1,100 m^3 per year.

Water availability of both surface and groundwater is further reduced due to water pollution and inappropriate waste disposal practices. There are now few states or river basins in India where water quality issues are not present. Environmental problems include water quality degradation from agro-chemicals, industrial and domestic pollution, groundwater depletion, water-logging, soil salinization, siltation, degradation of wetlands, ecosystem impacts and various health related problems. Though India is facing various serious water constraints today, it is not on the whole a water-scarce country. The

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both surface and groundwater, water conserving crop patterns and irrigation and production technologies. The National Water Policy in its present form appears to be a statement of intentions as it is not supported by any legislation and does not have an action component. The NWP is undergoing revision.

4. Water Sharing Issues

The existing Constitutional provisions and legislation in India do not provide an appropriate framework to deal with water sharing issues between states, sectors and individuals. In the present setup, (i) primary powers are vested at state levels which do not correspond to river basin boundaries; (ii) surface water rights are not clearly defined and such rights cannot be commercially transferred; (iii) ground water rights are purely private; and (iv) environmental laws have not been comprehensively operationalized and regulatory standards are either not enforced or do not exist.

The legal and absolute right to groundwater rests with the owner of the overlying land, irrespective of the social and environmental consequences.

5. Institutional Arrangements and Mechanisms

The present institutional arrangements in India, including central, state and local institutions, and both formal and informal structures, do not enable comprehensive water allocation, planning and management. The main problems that exist are: (i) inadequacies in necessary institutions for comprehensive water allocation, planning and management, particularly at the state and basin levels where they are frequently absent; (ii) lack of coordination between institutions, duplication of responsibility and accountability gaps; (iii) inadequate fostering of grass-roots institutions; and (iv) lack of involvement of civil society, i.e., local communities, NGOs, the business sector and academia.

The mechanism for **conflict resolutions** in matters of the sharing of water resources and their utilization is weak and needs to be looked into and strengthened at various levels.

In the matters of water resources management the civil society has a crucial role to play, but unfortunately its contribution, and the contribution of the business sector, have been greatly neglected. A substantial reason for their limited involvement to date is the limited efforts of government to inform the public on issues pertaining to water resources. In particular, outreach to women has been neglected, yet women are the most interested and involved in rural water supply, domestic urban water consumption, and health and sanitation issues, and are at least as concerned as men in matters of agricultural production.

6. Water Sector Investment

Being a vital resource for the lives and livelihoods of all Indian citizens, and having contributed significantly to India's economic growth since independence, water sector investments have rightly been accorded a high priority in India's development plans.

With a massive resource commitment for irrigation since independence of Rs. 576 billion, the gross irrigated area has increased four-fold from 23 million hectares in 1951 to about 90 million ha in 1997, substantially increasing and stabilizing the incomes of millions of farmers throughout the country. Significant achievements in drinking water coverage have also been realized. About 85 percent of India's urban population have access to public water supplies and over 75 percent of the rural population are now provided with public water supplies. It should be mentioned here that more than 1,000 million people in India, about 70 percent, live in the rural areas.

In all the sectors, however, there is considerable scope for conserving water resources. Such conservation can be a reality if the subsidies in water pricing are gradually removed, particularly in the agricultural sector.

7. *Reforms in the Water Sector*

Various reforms in the management of water resources are necessary, but by its nature water is multidimensional. It involves users from different sectors with widely different needs. India's task is made all the more difficult by its enormous population and its federal administrative structure.

The role of government needs to be more that of a facilitator than a provider and financier of services, and an enabling environment to be put in place for the different stakeholders to play their role, with necessary incentive framework.

As the reform program is implemented, a long-term vision needs to be conceived through a public debate and participatory process.

VI. COMMUNITY-LEVEL CASE STUDIES ON VULNERABILITY AND ADAPTATION TO GLOBAL WARMING

A. Community-Level Case Studies on Water Harvesting to Cope with Extreme Climate Events like Drought in Various Drought Prone Areas in India

In India, community-level water harvesting efforts in regions vulnerable to droughts/severe droughts due to a lack of adequate rainfall and infrastructure for the storage of rainwater during the rainy season have made the water harvesting process a very powerful technology for an effective adaptation at the community level to cope with such natural disasters that may be exacerbated due to human-induced climate change. Though adequacy of rainfall is a very important factor to consider in discussing impacts of droughts, it is important to remember that it does not matter how much rain a place gets, if there is no infrastructure to capture the rain water, the place will still be short of water. It is unbelievable that Cherrapunji, which gets 11,000 mm annual rainfalls, still has serious drinking water shortages. The CSE Report titled "Making Water Everybody's Business" asserts that every village in India can meet its basic drinking and cooking needs through community-level activities, including rain water harvesting. The community-based case studies that have been reported in this chapter are primarily based on material taken from the published literature ("Making Water Everybody's Business" - edited by Anil Agarwal et al.) and media reports.

B. Community-Level Case Studies : Western Coastal Plains

Out of the total of about 18,500 villages in Gujarat, at least 12,000 - 18,000 villages can be categorized as 'no source' villages. 'No source' villages are those which do not have a dependable source of drinking water. A number of problems like salinity, sea water incursion, high fluoride content and depletion of groundwater sources lead to a severe drinking water shortage. The State Government's response has been to introduce conventional solutions, such as utilizing groundwater sources, constructing large irrigation dams, and introducing piped water supply and tanker services during the dry season when water availability is under stress. These solutions, however, did not take into account specific problems of individual areas, and therefore were not very successful.

Large areas along the coastal parts of Dhandhuka block (in Ahmedabad district) used to be thickly covered with mangroves and piloo trees until about 30 - 40 years ago. With increasing water scarcity and

environmental degradation, local people have been forced to migrate. The introduction of a piped water supply raised hopes about quality water becoming easily available and in sufficient quantity, but both the quality and the quantity of water fell short of the expectations of the community.

Local communities took initiatives to find better solutions to the chronic drinking water shortages. Local communities in the villages of Rajpur, Mingalpur, Mahadevpura and Khun in the Dhandhulka block were quite divided among men and women on the foremost reason for migration of people from the area. Men cited the 'unproductive saline wasteland' as the main reason, while women insisted that the severe drinking water problem was the foremost reason for all difficulties in the area. The local communities were of the view that the water resources must be augmented at common property by desilting existing ponds and building new ones for drinking purposes to benefit the whole village. Villagers suggested the use of some sort of lining material on the bed and inner walls of new ponds to prevent salinity seepage from below and to the harvested rainwater in the pond.

Villagers contributed both in terms of labor and other resources. The success of the project inspired villagers to put forth new proposals to the Gujarat Water Supply and Sewerage Board (GWSSB) for obtaining support for such ponds, sowing the seeds of a long battle. The demonstration of lined ponds in these villages has resulted in the setting up of a Samiti, a people's organization comprising villagers from various organizations who help in promoting such ponds. Some 50 percent of the 94 members were women.

C. Community-Level Case Study : In Alwar district of Rajasthan

Communities from 650 villages took the initiative to rejuvenate about 3,000 traditional water harvesting structures (TWHS) called 'Johads'. Johads are small earthen check dams that capture and conserve rainwater, improving percolation and groundwater recharge. The results have been spectacular, raising the groundwater level by six meters and increasing forest cover by 33 percent. The most spectacular effect has been on the five rivers that used to go dry immediately following the monsoon. They have now become perennial.

For every Rs. 100 invested in Johads, the agricultural production has risen by Rs. 400 per capita per annum, income of the rural population has increased, annual migration of the male population to cities in search of livelihood practically stopped, and the people are in a position to address issues like health and education. At the core of this success lies the emergence and proper functioning of popular and local institutions like the gram sabha at village levels.

This is another example how a community-level effort can tackle problems like water scarcity/drought and ecological degradation, to bring back water in the rivers and forest cover that had completely disappeared.

These community-level activities were inspired by an Alwar-based organization called Tarun Bharat Sangh (TBS).

In rejuvenating about 8,000 traditional water harvesting structures, no qualified engineers were involved.

All the construction work—from planning to site selection, design and execution of about 3000 Johads—was undertaken by the villagers themselves, and the most reassuring fact is that all the structures are working fine, and none have collapsed.

D. Community-Level Case Study : In the Central Highlands of the Bundelkhand Region

The Bundelkhand region is comprised of seven districts of Lalitpur, Jhansi, Jalaun, Hamirpur, Mahoba, Banda, Shahiinagar in Uttar Pradesh and six districts of Datiya, Tikamgarh, Chattarpur, Panna, Sagar and Damoh in Madhya Pradesh. Poverty, illiteracy, unproductive agriculture and an acute lack of infrastructure are the main issues that the development processes in the region must address on a priority basis. Environmental degradation is increasing with soil erosion and widespread deforestation.

This region receives an average rainfall of only 750 mm annually. Traditionally, groundwater resources in Bundelkhand are meager due to the presence of hardrocks like gneiss and granite. The availability of water in the Bundelkhand region varies from season to season. In this region, agriculture is highly dependent on rainfall and only 20% of the total area under agricultural activity is irrigated.

Against this backdrop, Development Alternatives (DA)—with the active participation of the local communities, and in close consultation with the district administration of Tikamgarh—has surveyed villages of Niwari Block which were facing acute drinking water problems. Five villages were selected for interventions. The main objectives of the intervention were[12, 13] :

- to provide an adequate quantity of drinking water for these villages
- to increase availability of ground and surface irrigation in the area by constructing innovative water harvesting structures such as Check Dams

[Note: **Check Dams.** These are small barriers built across the direction of water flow on shallow rivers and streams for the purpose of water harvesting. The small dams retain excess water flow during monsoon rains].

- To upgrade wells and handpumps to minimize/eliminate stagnant water in close proximity to wells and hand pumps
- to increase drinking water availability in these villages

With these objectives, two check dams were constructed across the Gurari river in the area. These water harvesting structures created opportunities for the community to raise their income through increased agricultural outputs, and the awareness of the community on the benefits of safe drinking water and sanitation around the wells and handpumps.

The project resulted in improvements to the quality of life of the villagers by providing them with the scarce resource - water. The check dams on the Gurari river have contributed to the recharge of the groundwater supply within a radius of 2-3 km around the structures, with the result that farmers can now take up at least two crops a year, from only one crop earlier. The water reservoir also made available adequate water for lift irrigation to cater to 300-400 ha of cropland.

[12] Water Management Practices for Bundelkhand : Water for life : Air Vice Marshal S. Sahni (Retd.), DA N.L. March 1997.
[13] Check Dam - A Tool for Sustainable Development : Sanjay Vashist, DA N.L. April 2001.

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E. Community-Level Case Study in Decan Plateau : Anantapur District, Rayala Seema Region, Andhra Pradesh[14]

Out of the eight districts declared as drought - prone in Andhra Pradesh, the four districts of Kurnool, Ananthapur, Cuddapah and Chittor, with a population 110 lakh, comprise the Rayalseema region. Located in the rain shadowzone, Rayalseema has been facing droughts almost every alternate year for nearly a century. About 50 percent of the average rainfall of 550 mm is received over only 5-7 days and the number of rainy days with 25mm and above is less than 10. Nearly 75 percent of the population is engaged in agriculture despite the inadequacy of rainfall coupled with infertile land and the poor moisture retention capacity of the soil. The only rivers are Pennar, originating in the Nandi Hills of Karnataka, and Chitravathi. The rainfall in the district is meager, untimely and erratic and the entire area is drought prone.

To deal with the situation, local communities in the district had devised traditional water harvesting systems to meet drinking water needs, and to a certain extent irrigation needs. These include water harvesting systems in the district community tanks (1,091), spring channels (1,221), river channels (243) and wells (58,483) in the district as **collective property**. These community activities have greatly improved the water availability in the region and thus improved their economic level.

F. Community-Level Case Study in the Eastern Ghat Region: Saora Hills of Orissa

Saoras, one of the oldest tribes in India, harvest rainwater to turn stream beds into paddy fields and thus an inhospitable environment into a habitable one. The Saoras who live in the Saora hills of Orissa practice terraced paddy cultivation. Conservation of rainwater and improvement of the water regime in hill slopes are the main objectives of terracing. Using stone-packed contour bunding, saoras lay out small terraced fields on the hilly slopes and paddies. By means of water channels they regulate water flow from natural hill streams and irrigate the terraced fields. As flow irrigation is not possible in an undulating topography, the runoff water is stopped at different levels and allowed to soak deep into the soil. This results in the availability of adequate moisture at root levels, which helps in better crop production.

G. Community-Level Case Studies in the Central Highlands : Jhabua District, Madhya Pradesh

Jhabua is an upland region of western Madhya Pradesh. Once a heavily forested area, Jhabua has lost its natural wealth over the last 45-50 years. Almost 80 percent of its forest is severely degraded. The reasons are all man-made: unauthorized clearing of forests by contractors for agricultural activities and population pressure. As the uplands were used for cultivation without terracing, the humus and fertile layer of soil was lost and soil erosion accelerated. Free grazing further accelerated the loss of vegetative cover. The district was dotted with exposed rock hillocks. The intensive cultivation on uplands led to an ecological disaster, resulting in loss of land productivity, decline in employment opportunities and distress and out-migration of people.

The situation changed in the mid - 1990s, when the Madhya Pradesh government launched the Rajiv Gandhi watershed Development project (RGMWD) in October 1994. A decentralized and time-bound mission, it started with the objective of improving 1.2 million hectares (mha) of land and several watersheds by the year 2000. It envisaged greening more than 2.9 mha—approximately one percent of the country's total land area—spanning 6,691 villages through 5,024 watersheds.

[14] In Harmony with Nature : Koda Ramakrishna Reddy, Srikrishnadeva Ray University, Ananthapur in "Making Water Everybody's Business", Eds : Anil Agarwal, Sunita Narain and Indira Khurana, March 2001.

The Madhya Pradesh government is now looking at a mid-course strategy shift. The strategy is to build a community-based water security system that would be controlled and monitored by the village level Paani Roko Samities. Under the system as conceived, it is envisaged to create 8-10 lakh water harvesting structures and at least 25,000 water tanks in the villages. In the Kallipara Panchayat of Jhabua block, the village community, through its initiative, constructed 613 check dams. They have also completed the task of recharging a large number of handpumps by constructing the recharging pits. The residents of most of the villages are now very happy that hand-pumps installed in their villages after March 2001 are in working condition. In most of the villages the water table has gone up.[15]

Combining the principles of Joint Forest Management (JFM) and watershed treatment was a new approach that was adopted in Jhabua, and helped in the formation of 20 village forest committees, the executive bodies that used JFM to protect forests with the help of the forest department. Of Jhabua's total forest area, 60 percent (100,950 ha) is now under JFM and the 344 village committees cover 420 villages.

1. Management of Watershed Development Finances in Jhabua District

The total government expenditure until mid-1998 for watershed development was 16.48 crore. Of the Rs. 16.48 crore, Rs. 4.53 crore (about 30 percent) was spent by the project implementation agencies, out of which a substantial amount was spent (about 60 percent) to build up the credibility of the community organization, for their training and capacity building to create institutions and develop social mobilization at the village level.

A saving scheme program encourages villagers to save a part of their wages as a Watershed Development Fund (WDF), for future use for the management of the watershed. This is a mandatory fund, developed through contribution from all the users' groups who are land-owning people. Self-help groups (groups of landless people) do not normally contribute to this fund. The fund is entirely controlled by the community, and neither the panchayat nor the officials of the rural development have any control over it. Savings are also encouraged through a village fund for use to support collective activities of the communities and a women's thrifts and credit fund which women can use to help each other with soft loans. The watershed management program thus not only helped in improving the local ecology, but also in the improvement of the collective and individual financial security of the local communities, along with their coping capacity with drought and other natural calamities.

H. Community-Level Case Study in Western Coastal Plains: Saurastra

Gujarat faces a severe water shortage every year. The potential for surface irrigation being particularly low in the Saurastra region of Gujarat, harvesting rainwater through recharge wells is providing welcome relief. Over the years, ground water has been excessively extracted, leading to large-scale salinization of the coastline due to the incursion of sea water. A drop in groundwater in North Gujarat is also increasing fluoride concentrations, a serious health hazard. About 78 percent of the total irrigated area in Gujarat is served by wells alone, which has caused severe groundwater depletion. In view of this, harvesting of rainwater becomes a necessity.

The farmers in the region felt the need for more check dams to store river water during rainfall, and felt that the existing but unused/failed wells could be utilized for staring rainwater. Further, the farmers suggested that village level committees be formed to develop programs for recharging both private and public wells and handpumps and to construct check dams and percolation wells on riverbeds. An effective information center to assist farmers in water harvesting and management techniques in coordination with government and non-governmental organizations was also envisaged.

[15] *M.P. Focus on Water Conservation : Lalit Shastri, The Hindu, June 19, 2001*

The case study made it clear that well recharging activity is becoming popular in Saurastra, and per capita and household water consumption are increasing with better availability of water resources.

Farmers are already optimizing yields by using stored water during poor monsoon seasons or failure of monsoons. This has increased their per capita income, as evinced by increased use of fertilizers and pesticides.

I. Conclusion

a) The present study and analysis have clearly shown that developing countries like India are most vulnerable to the impacts of climate change due to resource constraints, lack of capacity and inadequate funds. This vulnerability is further exacerbated due to large-scale poverty in these countries.

b) The case studies bring out the efficacy of community-level responses to acute water scarcity. The community-level responses can be channelized and further strengthened, by creating an enabling environment in the country/society through the development of sustainable livelihood practices and entrepreneurships among the people and society. Such practices will not only increase the capacity of the community to cope with, and increase their resilience to. such natural calamities as droughts, floods, cyclones etc., but will check the migration of people to other states/regions.

c) The traditional community-level practices to cope with situations like droughts in water-scarcity/drought-prone areas/regions can be integrated into Government Policies and Responses to cope with such calamities and for adaptation to hydrological resources in India.

d) Community-level efforts must be encouraged by governments to start activities like Grameen Bank/Co-operative Banks on a co-operative basis by all the stakeholders. Such mechanisms can provide small loans to the affected communities to enable them to cope with the adverse situations. Such mechanisms will also help in community-based adaptations to water resources in water-scarce areas. The Co-operative Banks initiated from small contributions from communities increase the community resilience to face such climatic vagaries and extreme weather events.

e) Technological responses to adapt to climate change are most suitable for rich countries. Such adaptations in developing countries, however, may face technology transfer barriers, financial barriers, and capacity-building barriers. Solutions to such barriers must be put in place in developing countries before adopting technological options to adapt to climate change. Such solutions must be found from a participatory process among the communities and not transplanted from other countries / regions.

VII. Summary, Conclusion and Policy Recommendations

The consensus of the scientific community is that the available observational evidence indicates that regional changes in climate, particularly increases in temperature, have already affected a diverse set of physical and biological systems in many parts of the world. Many human systems are sensitive to climate change. The impact of climate change on these systems can have a severe adverse impact on human well-being in India. Thus it is important to assess India's vulnerability.

India may be particularly vulnerable to climate change as a poor and tropical sub-tropical country, highly dependent on weather for its agricultural output. For India, its freshwater systems, rainfall, rivers and groundwater are critical for its agriculture and food security. Disruptions, droughts and floods induced by climate change can cause great hardship and impose large costs. Similarly, given the large coastline of

India, millions who live near the sea and depend on coastal ecosystems for their livelihood may also be highly vulnerable to climate change.

A review of climate variability in India over nearly 120 years shows that there were 19 flood and 21 drought years. Excepting extreme events like earthquakes or cyclones, floods are the most important cause of mortality. Any increase in the frequency of floods thus increases vulnerability.

The economic costs of damage due to flood is rising steeply, mainly due to greater exposure. In the future, because of the much higher population with India's land scarcity, the damages could be much larger. Vulnerability would be high.

It is also noticed that mortality due to heat spells is increasing. This, however, depends on the nutritional status of the population.

It is expected that annual average surface air temperature will increase by 2050 by 2.7°C. The increase in winter would be higher, at 3.25°C. Annual average precipitation will increase by 6.6 percent. When the effects of sulphate aerosols are accounted for, the annual average temperature increase will be lower by 1.9°C but rainfall would be reduced by 2.4 percent. Thus, significant warming is expected over the Indian subcontinent.

Indian agriculture and food security are highly vulnerable. Agriculture generates 28 percent of GDP, employs 60 percent of the work force, and the poor spend 2/3rd of their income on food. Any disruption can thus cause much misery.

Analysis using a crop production model, the EPIC model, whose parameters were calibrated to reproduce Indian data on wheat and rice, shows that with a temperature increase of 2.3°C to 4.8°C, rice yields would decrease on the average by 32 percent to 40 percent. For wheat yields, the fall would be 41 percent to 52 percent. Even when the carbon fertilization effect is accounted for, rice and wheat yields will fall by 13 percent to 25 percent and 15 percent to 33 percent, respectively.

These yield changes would lead to changes in the structure of production, prices, incomes and consumption. When these are analyzed in a consistent general equilibrium model, depending on the climate change scenario under consideration, the expected decline in agricultural GDP ranged from 26 to 33 percent. The overall effect of climate change has resulted in a loss in GDP under all scenarios, with the decline ranging from 1.8 to 3.4 percent.

The welfare impacts are also very serious. Climate change increases the number of rural poor from 18.3 percent to as much as 31.1 percent. The abject poor increase by 10 percentage points in rural areas. The number of urban poor increases from 3.4 percent to 8 percent and abject poor by 1.0 percentage point. Even with the carbon fertilization effect, the number of rural and urban poor increases by as much as 6 and 2 percentage points, respectively.

This means that climate change could increase the number of poor in India by more than 130 million persons in 2060. Indian agriculture and India's food security are highly vulnerable to climate change.

These estimates have not fully accounted for many other threats to agriculture from climate change. Thus, the damage due to land loss, irrigation capacity loss and higher incidence of droughts and floods have not been factored in.

Sea level rise due to climate change can cause land loss, population displacement, increased flooding, salinity infusion, loss of agricultural yields, impact on aquacultures, tourism and beach erosion and property loss.

It is estimated that a 1-meter rise could lead to a land loss of 6,000 sq. km and displace over 7 million people. An increased frequency of tropical cyclones could lead to that much more loss. Moreover, it is estimated by one study that they will be more intense than the worst storms experienced under present day climate conditions.

Other impacts on the coastal system are not assessed.

India's freshwater resources are limited and scarce even today. With population growth the scarcity will increase. It is projected that under current trends only 6 percent of water would be left for environmental and other uses by as early as 2025. The impact on climate change could aggravate the problem. Salinity ingress with sea level rise could affect groundwater supply. Increased frequency and intensity of flooding would mean more runoff and less water for use, apart from the damage due to flood. The possible increase in rainfall may not compensate for this; it will depend upon its geographical and spatial distribution.

In India, community-level water harvesting efforts in regions vulnerable to droughts/severe droughts due to lack of adequate rainfall and infrastructure for storage of rainwater during the rainy season has made the water harvesting process a very powerful technology for an effective adaptation at the community level to cope with such natural disasters which may be exacerbated due to human-induced climate change. Though adequacy of rainfall is a very important factor to consider in discussing impacts of droughts, it is important to remember that it does not matter how much rain a place gets. If there is no infrastructure to capture rain water, the place will still be too short of water. It is unbelievable that Cherrapunji, which gets 11,000 mm annual rainfall, still has serious drinking water shortages, but it occurs.

A number of case studies of community-based approaches show the vast scope and effectiveness of dealing with issues of water and making it go further.

What kind of policy conclusions can one draw from theses?

(a) Even when India is not responsible for the threat of climate change it is quite vulnerable. India has the right to seek adequate compensation.
(b) It would be in India's interest to work to reduce the threat of climate change.
(c) Meanwhile, India should consider taking certain adapative steps. It may not want to initiate steps that involve additional costs, until it is compensated for them by those responsible. Yet there may be many no regret options which are worth pursuing even in absence of climate change.
(d) Like any good developmental project, such measures should have adequate benefit-cost ratios and be consistent with the needs of various stakeholders, not cause socio-cultural disruption, and the losers should be adequately compensated.
(e) Such measures, just as in the case of other developmental measures, are more likely to be successful if community-based, bottom-up processes are used in planning and implementation. This requires consultative and participative processes which are transparent.
(f) To ensure food security, India should promote research to develop more climate-tolerant crop varieties.
(g) Water conservation and use techniques should be followed.
(h) Development in flood plains and coastal regions may be controlled.
(i) Groundwater recharge through community participation should be encouraged and be a national program, as it also has many short-run benefits.
(j) India should step up its economic growth to reduce its dependence on agriculture and acquire the ability to import as much food as needed.

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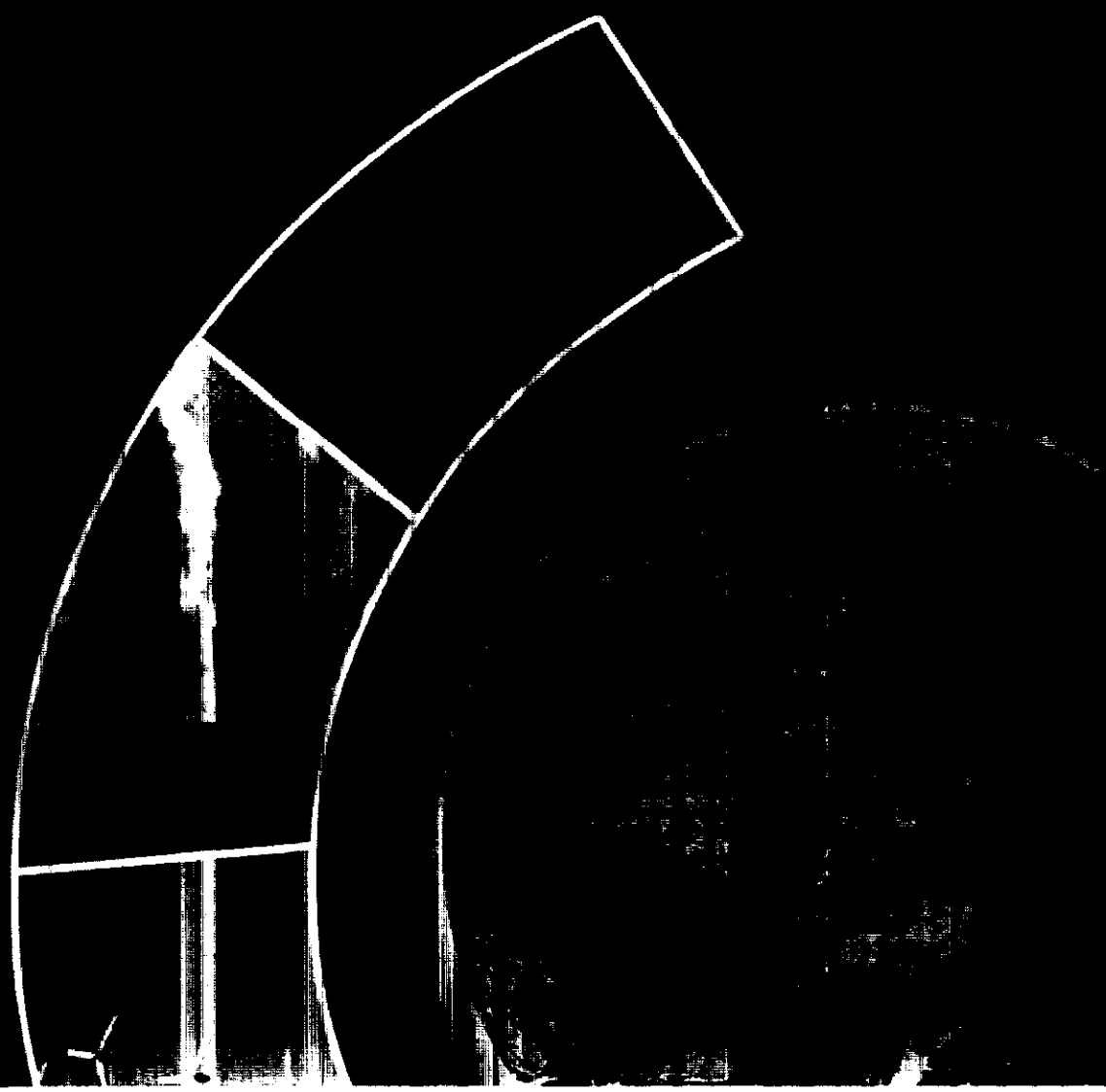
Economic Growth, Poverty and CO_2 Emissions in India



ECONOMIC GROWTH, POVERTY AND CO_2 EMISSION IN INDIA

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I. INTRODUCTION

In recent years, there has been a worldwide concern about climate change due to concentration of green house gases (GHGs) that block radiation of sunlight. It is believed that emissions of GHGs caused by anthropogenic factors associated with human activities are mainly responsible for the climate change problem that faces mankind. Attention has been directed particularly to carbon dioxide (CO_2) emissions from the burning of fossil fuels, the largest source of anthropogenic GHGs. While the scientific community continues to debate about climate change and the risks involved in it, there has been a broad consensus among the community of nations for exploration of possible measures to reduce carbon dioxide (CO_2) emissions. This is reflected in the United Nations Framework Convention on Climate Change (UNFCC) in 1992, where signatory nations agreed to prevent 'dangerous anthropogenic interference with the climate system'. The convention required all nations, developed and developing, to maintain accounting and reporting of emissions and encourage environmentally friendly activities. At the same time, it recognized the concept of 'common but differentiated responsibilities', depending on the development levels of the nations. The Kyoto Protocol signed in 1997 took further steps in this direction and required industrialized 'Annex I' countries to reduce their total emissions of CO_2 and other GHGs to 5% below the 1990 level by 2008-12. It excluded developing countries from any binding commitment to reduce GHGs emissions.

CO_2 emission takes place when we use fossil fuels like coal, oil and gas, which are essential and critical raw materials in the production processes of various goods and services. Hence, economic growth usually involves CO_2 emissions, whose reduction would mean an additional constraint on growth. Such a constraint might imply a lower economic growth and/or adoption of better techniques of production. Before deciding upon an appropriate policy for dealing with CO_2 emissions, a policy maker would like to know, if a particular policy were followed, how much growth would be affected or how much additional investment would be needed to adopt better technology. In the context of developing countries, prevalence of mass poverty is a basic issue that figures high on their agenda, and we need to examine the effects of environmental constraints on the incidence of poverty. On the whole, we need to know the strategic tradeoffs between development and environment.

Table 1 shows some basic economic and social indicators for India in relation to the world as well as to developed countries. India's per capita income, at about $450, is less than one-tenth of the world average and one-fiftieth of that of the high income countries. Given such a low income level, poverty persists at a high level. India has about 40% of its people living below the poverty line defined as an income level of $1 per capita per day. Large differences could be observed between India and the developed countries in the performance indicators of social sectors like health and education, too. India has a long way to go in reducing infant mortality and illiteracy. It must continue to have high economic growth to take care of poverty and to provide better health and other social services to its people.

The developing countries have not contributed in a large scale to the accumulation of GHGs. In fact, about a quarter of the world's population, living in the developed countries, has released about three-quarters of the accumulated CO_2 emissions. While developing countries need not have a fixed commitment to reduce CO_2 emissions, as recognized in the Kyoto Protocol, it is also felt that attention needs to be given to emissions taking place in some of the large developing countries. The obvious examples that come up in this context are China and India, which respectively account for about 14

Table 2: CO_2 Emissions in India, China and World

CO_2 emission (mt)				India/World	China/World
Year	India	China	World		
1980	305.97	1491.34	18658.1	0.0164	0.0799
1981	338.22	1474.86	18337.2	0.0184	0.0804
1982	349.88	1537.74	18202.8	0.0192	0.0845
1983	374.01	1618.53	18334.6	0.0204	0.0883
1984	386.63	1757.34	18891.4	0.0205	0.0930
1985	424.75	1888.28	19391.8	0.0219	0.0974
1986	460.75	2003.98	19761.8	0.0233	0.1014
1987	494.42	2136.52	20443.0	0.0242	0.1045
1988	533.28	2274.54	21095.9	0.0253	0.1078
1989	568.62	2364.21	21426.4	0.0265	0.1103
1990	599.78	2398.29	21245.9	0.0282	0.1129
1991	635.28	2485.86	21446.9	0.0296	0.1159
1992	672.57	2552.70	21391.7	0.0314	0.1193
1993	705.22	2699.37	21534.2	0.0327	0.1254
1994	750.05	2844.21	21607.2	0.0347	0.1316
1995	817.32	3035.00	22073.4	0.0370	0.1375
1996	863.19	3179.72	22784.4	0.0379	0.1396
1997	880.71	3161.95	22981.1	0.0383	0.1376

Source: International Energy Agency (1999): "CO_2 Emissions from Fuel Combustion"

Table 3: Per Capita CO_2 Emissions

(Tonnes CO_2)

Year	India	China	World	OECD
1980	0.45	1.51	4.23	11.42
1981	0.48	1.48	4.09	10.94
1982	0.49	1.52	3.99	10.51
1983	0.51	1.57	3.95	10.36
1984	0.52	1.69	4	10.57
1985	0.56	1.79	4.04	10.65
1986	0.59	1.87	4.05	10.57
1987	0.62	1.96	4.12	10.76
1988	0.65	2.05	4.17	10.93
1989	0.68	2.1	4.17	11.02
1990	0.71	2.1	4.07	10.77
1991	0.73	2.15	4.04	10.71
1992	0.76	2.18	3.97	10.68
1993	0.79	2.28	3.94	10.75
1994	0.82	2.38	3.89	10.8
1995	0.88	2.51	3.92	10.85
1996	0.91	2.6	3.99	11.14
1997	0.92	2.56	3.97	11.18

Source: International Energy Agency (1999):
"CO_2 Emissions from Fuel Combustion"

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which use reduced form equations without structural details and the implied policies behind them remain unclear. Another approach of top-down modeling is the computable general equilibrium (CGE) approach, where equilibrium prices and quantities are computed for one period and repeated sequentially for several periods. The main choice of the economic agents is essentially of static nature confined to events occurring in a single period, with a few linking equations for capital or labor stock from one period to another. Both econometric and CGE models often assume a high substitution elasticity, which makes it easy and relatively costless to adjust to CO_2 constraints. The activity analysis approach we have adopted here permits the easy incorporation of a simultaneous choice of economic variables for several periods in a dynamic setting. It provides macroeconomic consistency and incorporates specific technological options with limited substitution possibilities. This method can be viewed as one that integrates both the top-down and the bottom-up approaches[2].

In this paper, we use an activity analysis framework to examine the effects of CO_2 emission reduction on the national economy. This model, reported in Murthy, Panda and Parikh (2000), permits exploration of alternative technologies to meet CO_2 constraints from a long-term dynamic perspective. With alternative activities representing different technologies, one can permit substitution of various kinds and incorporate non-linearities in such models. The model maximizes a social welfare function specified as the present discounted value of utility streams corresponding to the per capita consumption of an average consumer, given the resources available to it and the various technological possibilities for using them. In principle, the time horizon of the model must extend to infinity. Empirical models, however, work with a finite time horizon of length, say, T time periods only (taken to be 35 years in our case), as it is computationally impossible to work with an infinite number of time periods. Instead, they account for the post-terminal period in other ways.

Murthy, Panda and Parikh, J. (1997a) estimate the carbon emission coefficients for the Indian economy and carry out various experiments using the input-output framework to identify the major emitting sectors, both directly, through a sector's own production process, and indirectly, through the demand for various inputs. In another paper, Murthy, Panda and Parikh J(1997b) calculate the carbon emission coefficients for six different income classes in rural and urban areas and find out how much emission takes place in the production of goods and services consumed by different income classes. While the carbon emission coefficients estimated in these papers have been used here with suitable aggregation of sectors, the model structure extends from consistency analysis of the input-output models to considerations of optimality in a general equilibrium framework.

We represent the whole economy with seven commodities/goods, some of which can be produced in more than one way. In particular, electricity can be produced by coal, oil, gas (combined cycle gas turbine, CCGT) and others (hydro and nuclear). We focus on specific options for the power sector, as a large part of India's CO_2 emissions occur in this sector and policy options here need to be clearly understood. Industrial output can be produced by two alternative activities that use coal-boiler and oil-boiler technologies. Technical progress and energy efficiency gains over time are prescribed exogenously. These remain the same across all scenarios.

Income distribution is endogenous and depends on the total consumption, exogenously projected total population and specified Lorenz ratio. The portion of the population belonging to each consumption expenditure class is determined in the model. Thus, the composition of aggregate consumption changes nonlinearly as the economy grows and people move from one income class to another. Fifteen alternative consumption bundles are provided for each class to represent approximately the indifference curve of the class. This permits substitution across commodities when relative prices change. The class boundary of

[2] The model used here 'integrates' top-down and bottom-up economic models with proper environmental accounting. In this sense, the term "integrates" differs here from in a section of the climate change literature where it is used to refer to integration of population, economic and climate change modules.

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the bottommost class corresponds to the poverty line and persons belonging to this class are classified as poor.

Ideally, income distribution should be linked to production structure and techniques used in the production process. Unfortunately, adequate data on income generated by such activities and how they are distributed to different income classes are not available. However, empirically, income distribution as reflected in consumption expenditure has remained very stable, with slow and miniscule changes in the Lorenz ratio. National Sample Survey (NSS) data show that it varied with minor fluctuations between 0.3417 in 1956-57 and 0.3202 in 1992 [see Panda (1999)]. Thus, an assumption of a constant Lorenz ratio over a long period of time is justified for India.

The constraints in the model include the following:

a) Commodity balance to ensure that demand does not exceed availability;
b) Production requires fixed capital, which, once allocated to an activity, cannot be shifted. Capacity constraints ensure that production does not exceed the capacity created by investment in each activity;
c) Capital accumulation constraints that restrict capital stock in each activity to increase by net investment in each activity;
d) Domestic production of oil is restricted to reflect the small oil reserves in India.

On the trade side, we impose a balance of payment constraint. There is also a wedge between export price and import price to reflect international trade and transport margins. Some restrictions are imposed on exports and import growth rates by sectors to keep the model realistic. Thus, import of agriculture is restricted to reflect a self-sufficiency requirement for a large country which is considered necessary for food security. We also restrict import of services, as not all services can be imported. Export bounds are introduced to account for fall-offs in export price and profitability consequent to large exports by India.

A savings constraint is imposed to restrict the marginal savings rate to 30 percent. Programming models often give high investments and implied savings rates. Such rates are not realistic, as governments in a democratic developing poor country are not able to force the savings rate beyond a limit. Finally, though the model is run for a period of 35 years, the post-terminal future has to be taken care of. This is done by assuming that a stationary state would prevail in the future with the composition of output, consumption, investment etc. fixed and growing at a prescribed rate. This translates into a larger weight for the terminal year consumption in the objective function.

A. Emissions Inventory

CO_2 is emitted when fossil fuels such as coal and oil are burnt in production and household activities. For a given fuel, the amount of emission is directly proportional to the quantity of fuel burnt. The CO_2 emission coefficient of a fuel depends upon its carbon content. We account for these emissions in two different ways: flows and stocks. The emissions from the production sectors are computed by considering the scalar product of the activity vector and the emission coefficient vector that indicates the amount of emissions per unit level of activity. The emission coefficient for an activity is derived by considering the fuel-specific emission coefficient and the fuel input coefficient. Apart from the production activities, emissions are also caused by the private and public consumption of fuels like kerosene, LPG and motor gasoline. We account for these by considering emission coefficients attached to each consumption activity.

The cumulative emission of CO_2 at the end of any period is computed by adding the emission flows during the current period to the cumulative emissions carried over from the previous period. CO_2 emissions are known to accumulate and reside for long durations in the atmosphere, leading to an increase in CO_2 concentrations.

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B. Carbon Reduction Options

In the model, CO_2 emissions can be reduced in a number of ways. First, they can be reduced by reducing the levels of different activities. This has the direct effect of reducing income and consumption and hence a loss in the social welfare. The second method is to change the composition of production in the economy in favor of less CO_2-intensive activities. This can be done either by changing the structure of trade so that the more CO_2-intensive products are imported, or the structure of consumption and other final demand may be changed by reducing the budget share of CO_2-intensive goods in the total final demand. This leads to an indirect loss of current welfare as the investor and consumer choices get distorted.

In addition, technological options are also available for reducing the CO_2 intensity of activity levels. These have the virtue of reducing emissions without any significant loss of output. There are essentially two such options: (a) Reduce the amount of CO_2-emitting energy inputs required by different activities; additional investment may be required to install equipment that can operate these processes at higher energy efficiency; and (b) switch to less carbon-intensive fuels. For example, instead of a coal based power plant, we may install a CCGT power plant, or instead of running industrial boilers on coal, we may use oil. The CO_2 emission coefficient varies across the fuels, being highest for coal (26 tC/GJ), followed by oil (21 tC/GJ) and lowest for natural gas (14.7 tC/GJ). Thus, oil or natural gas can substitute for coal and lower CO_2 emissions.

To sum up, the model used here belongs to the dynamic optimization category in a multisectoral and intertemporal framework with particular options for technology. It maximizes an objective function which is the discounted sum of utilities from consumption. The dynamic framework permits examination of optimal intertemporal choices. There are some specific features we might wish to highlight in this model for the Indian economy. First, the model incorporates specific technological options with a choice of alternative activities (or a combination of them) for producing a commodity. Second, it traces welfare effects for the low-income groups by examining the incidence of absolute poverty in the population. Third, there are large differences in consumption patterns among different income classes in a developing country, which are represented in our model. In this context, we also specify several alternative consumption bundles for each income class, from which the respective representative consumers can choose. Thus, we permit consumer purchases to be sensitive to the relative shadow prices of commodities in our programming model. Endogenous income distribution is important because it will have considerable impact on the structure of consumption demand in the economy, as population in a lower income class today will move to a higher income class in the future as income growth takes place. Finally, we impose terminal conditions on stock variables in our model. With the inclusion of natural resources among the stock variables, the terminal conditions can be interpreted as sustainability constraints.

C. Data

We have empirically implemented the model by using recent data for India to estimate the various parameters and initial values of different variables included in the model structure discussed in the previous section. Input-output coefficients and capital-output ratios for various activities form the core of the model. This data is available from published sources for most sectors.[3] In some cases, like the capital-output ratios for the generation of electricity using alternative technologies, we have based our estimates on statistics published by the Centre for Monitoring Indian Economy (1995) on the ongoing and proposed power projects in India. Future projections of government consumption levels and of the upper and lower bounds for exports and imports (where relevant) are specified in terms of growth rates. The database for operating the model is listed in the Appendix Tables. The model is solved using the GAMS programming tool developed by Brooke et al. (1988). For endogenous income distribution consistency, we iterate over optimal solutions, changing distribution parameters between iterations till they converge.

[3] Details are available in Parikh et al. (1995)

III. SCENARIOS

We use the model described in the earlier section to evaluate the impact on economic growth and other related variables corresponding to several alternative CO_2 reduction scenarios over a reference scenario during a period of 35 years from 1990 to 2025.

Reference scenario: The reference scenario is a **'business-as-usual' (BAU)** scenario in which the pattern of growth of various variables is determined by the model *in the absence of any emission constraints.*

Emission Reduction Scenarios: We then develop scenarios in which there are restrictions on the amount of CO_2 emissions. These restrictions are applied in two different forms:

(a) reduction of 10%, 20% and 30% in *cumulative* CO_2 emissions (CEM_T) over 35 years (these three scenarios are labeled **C10, C20** and **C30** respectively);
(b) annual reduction of 10%, 20% and 30% in CO_2 emissions (EM_t) in *each year* of the 35-year time horizon (these three scenarios are labeled **A10, A20** and **A30** respectively).

Thus, we have six different scenarios of emission restrictions for comparison with the BAU scenario.

IV. IMPACT OF CARBON DIOXIDE EMISSION REDUCTION

We now discuss the results of our experiments as designed above. Tables 4-6 show the values of some important macroeconomic variables and alternative activity levels for selected years for the BAU scenario, as well as various scenarios involving cumulative and annual emission reduction. Some characteristics of the BAU scenario are as follows: The economy grows at an average annual rate of 6.3% over 35 years. This growth rate is about the same as the average of above 6% achieved since 1991, when India started a series of major economic reform measures to liberalize trade and industry. It is more than the average growth rate of the 1980s (5.5%), but lower than the government's target of 7-8% average growth over the next 10-15 years. The BAU Scenario thus is not overly optimistic, and it reflects the acceleration noticed in the Indian economy in the 1990s. The number of poor in the BAU scenario in the year 2000, at around 26 percent, is also close to the 1999 estimate from the National Sample Survey data. It falls considerably over the next 20 years as a result of sustained economic growth. Poor households are defined as those whose per capita income falls below an absolute income level; it is only natural that the number of 'poor' would decline in a growing economy if the distribution factor remains stable. Such a BAU scenario is again consistent with the past experience of India, insofar as a fast decline in poverty has been observed in periods of high per capita income growth[4]. The carbon emissions grow from 157 mtc in 1990 to 1421 mtc in 2025. Of these emissions, 61 mtc are from electricity generation and 53 mtc from industrial production in 1990, and 659 mtc and 397 mtc, respectively, in 2025. The annual emissions are plotted in Figure 1. The cumulative emissions over the 35-year period amount to 20353 mtc.

Table 4 gives the effects of CO_2 reduction on aggregate GDP and per capita consumption. Enforcing a 10%, or even a 20%, cut on cumulative CO_2 emissions has virtually no impact in the short run (3rd or 5th year) or medium run (10th year), as can be seen from column C10 or C20 of Table 4. The GDP and consumption levels fall only marginally. In the long run (30th year), however, the effects of emission restriction are more visible. In the 30th year under the C20 scenario, for example, GDP and consumption per capita fall by 1.36% and 1.85%, respectively, compared to the BAU scenario. Hence, the number of people below the poverty line increases by 5.94% (Table 5).

[4] With an average population growth of 1.8% per annum, 6.3% GDP growth translates to 4.5% per capita income growth.

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Figure 1: Annual Emission in Million tC

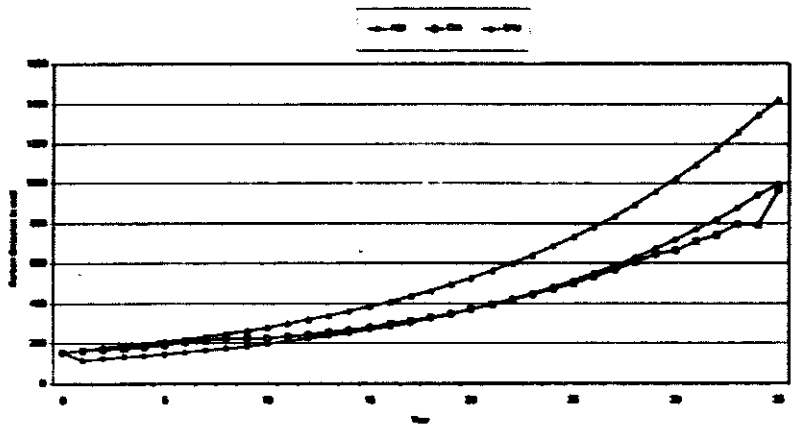

Table 4: Income and Consumption Effects of Carbon Emission Reduction in India

	BAU	C10	C20	C30	A10	A20	A30
		Percentage Change from BAU					
Gross Domestic Product (Rs. Billion)							
Year 3	4850	-0.02	-0.02	-0.19	-0.47	-3.79	-11.86
Year 5	5301	-0.02	-0.02	-0.17	-0.47	-2.83	-10.45
Year 10	6801	-0.03	-0.03	-0.62	-0.59	-2.93	-9.07
Tear 20	12307	-0.02	-0.30	-1.45	-0.59	-3.30	-10.17
Year 30	24595	-0.53	-1.36	-4.06	-0.69	-3.66	-10.70
Per Capita Consumption (Rs.)							
Year 3	3758	0.00	0.00	-0.21	-0.48	-4.18	-12.43
Year 5	3902	0.00	0.00	-0.21	-0.44	-3.13	-11.05
Year 10	4431	-0.02	-0.02	-0.74	-0.59	-3.14	-9.86
Tear 20	6520	-0.02	-0.41	-2.42	-0.71	-3.74	-11.86
Year 30	10888	-0.63	-1.85	-4.95	-0.81	-4.14	-12.03
Cumulative Emissions (mtc)	20353	-10.00	-20.00	-30.00	-10.00	-20.00	-30.00
BAU: Business as usual							
A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU							
C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU							

Source: IGIDR Model results

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As the emission restriction level is tightened from 10% to 20% and further to 30%, the effects on long run GDP and welfare become increasingly adverse. Thus, GDP falls by 0.53%, 1.36% and 4.06% and the number of poor increases by 2.1%, 5.9% and 17.5%, in the 30th year for 10%, 20% and 30% cumulative carbon emission restrictions, respectively (Tables 4 and 5). The flexibility of the economic system gets reduced, as emission restriction becomes tighter. Also, note that the loss in GDP and consumption is nonlinear, i.e., loss rises at an increasingly faster rate than emission restriction. For the case of a 30% restriction, even the short run effects (up to 5 years) are noticeable: GDP and per capita consumption loss is about 0.2% and incidence of poverty is higher by 0.3% compared to the BAU scenario. Furthermore, the losses are more severe toward the end of the target period (30th year) than near the beginning of the restriction period. The model tries to postpone the economic losses due to two reasons: it discounts the future consumption flows and it also enjoys the facility of attaining an emissions reduction target over a 35-year period rather than in just one or two years. Consequently, emission reduction also gets postponed to the last years of the time horizon in the cumulative reduction scenarios (such a flexibility does not exist in the case of annual reductions). Figure 1 very clearly reveals this for the C30 scenario.

Table 5: Poverty Effects of Carbon Emission Reduction in India

	BAU	C10	C20	C30	A10	A20	A30
		Percentage Change from BAU					
Number of Poor (Million)							
Year 3	298.80	0.03	0.03	0.34	0.77	6.58	20.67
Year 5	292.35	0.03	0.03	0.33	0.72	5.04	18.90
Year 10	258.83	0.04	0.04	1.34	1.04	5.70	19.02
Tear 20	139.58	0.08	0.99	5.95	1.65	9.42	33.22
Year 30	39.43	2.10	5.94	17.48	2.45	14.34	49.65
BAU: Business as usual							
A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU							
C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU							

Source: IGIDR Model results

Next, we consider the impacts of imposing annual reduction targets for CO_2 emissions. A 10% annual reduction target over each year of the 35-year period (scenario A10) achieves the same reduction over the period as the 10% cumulative reduction scenario (C10). But the economic losses are larger under the annual reduction scenario than the cumulative reduction of the same order. The impact differences between annual and cumulative emission reduction scenarios turn out to be particularly large with a higher order of reduction. For example, in the 20% restriction case, annual constraints lead to a GDP fall of 3.66% in the 30th year as compared to 1.36% for cumulative constraint. The GDP is lower by a whopping 10.7% for the 30% annual reduction case (Table 4). A large annual reduction in carbon emission becomes possible by diverting substantial resources for this purpose, and growth is adversely affected given the constraint on total resource availability. Annual constraints are more restrictive than cumulative constraints because they deprive the economic system of its freedom to choose an adjustment path over time, though the terminal period carbon stock level is the same under both types of constraints.

The short-run effects are also large for the case of annual constraints. GDP losses in the 3rd year vary from 0.47% in the case of 10% annual emission restriction to 11.86% for the 30% restriction. The increase in the number of poor is a large 20.67 percent increase, even in the short run, and in the 30th year the number of poor increase by nearly 50 percent, for a 30% annual reduction, which indicates a significant short run burden on the lower income segment of the population (Table 5).

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The model results for alternative activity levels for the 5th and 30th years are presented in Table 6. These results clearly illustrate that, when a CO_2 emission constraint is active, India would shift away from coal-based electricity to oil- and gas-based electricity and from coal-boiler based manufacturing to oil-boiler based manufacturing. There is, however, no change-over to a new technology in the short run, when a cumulative restriction of 20% or less is affected.

Table 6: Effects of Carbon Emission Reduction on Selected Activities in India

	BAU	C10	C20	C30	A10	A20	A30
	Absolute Levels in Rs. Billion						
Selected Activity Levels in Year 5							
Electricity-coal	216	216	216	173	162	142	129
Elecctricity-others	41	41	41	41	52	64	58
Electricity-oil	16	16	16	16	16	10	0
Electricity-CCGT	0	0	0	37	37	42	47
Industry-coal	3962	3961	3961	3895	3734	2330	2074
Industry-oil	0	0	0	0	164	1454	1350
Selected Activity Levels in Year 30							
Electricity-coal	1190	664	635	616	901	704	575
Elecctricity-others	10	269	289	280	36	197	251
Electricity-oil	4	4	4	0	4	4	4
Electricity-CCGT	0	229	227	224	230	221	202
Industry-coal	17526	17421	4879	1172	17362	16320	14317
Industry-oil	0	0	12689	16193	41	403	801
BAU: Business as usual							
A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU							
C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU							

Source: IGIDR Model results

V. CONCLUSIONS

The climate change problem due to carbon dioxide emission from anthropogenic sources in the industrial age has attracted the attention of many nations. Even as the world community is moving toward reduction of such emissions on an urgent basis, it also understands the need for the low income developing countries to attain a decent standard of living. Hence, it is recognized, as in the Kyoto Protocol, that a global CO_2 emission reduction strategy must safeguard the developmental objectives of the developing countries. It is for this reason that India has rightly been excluded from undertaking any binding commitment to CO_2 emission reduction.

However, the two largest countries—China and India—might contribute significantly to incremental carbon emission in the coming decades. They need to explore whatever possible emission reduction measures they can take without compromising their income growth and poverty reduction objectives. In this paper, we have attempted to examine the impact of alternative levels of carbon dioxide reduction measures from a 'business as usual' scenario on growth and poverty in India.

The results from the scenarios suggest that annual emission reductions impose costs, in terms of reduced GDP and higher poverty, both in the short and the long run, through distortions in the choice of

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techniques in electricity generation as well as in energy use in industry. The quantitative dimension of the GDP fall could vary from about 0.5 - 0.7% in the case of a 10% reduction in emission to as high as 12% in case of a 30% annual emission reduction. Cumulative emission reduction targets are preferable to annual reduction targets and a dynamically optimum strategy can help reduce the burden of emission reductions. Even cumulative reduction targets increase poverty by a larger percentage, in the range of 2.1-17.5% as compared to GDP reduction of 0.5 - 4.1%, in the 30th year. GDP loss of this order is not negligible in the long run.

Thus, emission reduction imposes costs in terms of lower GDP and higher poverty. India cannot have any obligation to reduce its carbon emissions for quite some time without sacrificing its basic development objectives of GDP growth and poverty removal. If India were to reduce its carbon emissions for the sake of the global good, it should have sufficient built-in compensation or incentives for such an action. The 'flexible mechanisms' of the Kyoto Protocol, like international emission trading and clean development mechanisms (CDM), could provide such incentives to developing countries[5].

At the end, we might turn to some major limitations of the present exercise and indicate a scope for further work. First, we have not considered uncertainties in this exercise. We note that the model used here is a policy model and not a prediction model. We have adopted the BAU scenario as the most likely future path as per our judgment and considered "if-then" type comparative static exercises. It is possible that the economy would take a different path than the one depicted in the BAU scenario, even in the absence of any policy action on carbon reduction. This is the reason why we have put emphasis on deviations from the BAU scenario. As long as the BAU scenario broadly represents the path the economy would take, both the BAU and the policy scenarios would change in a similar manner and 'deviations' would be more or less representative. Even then, big uncertainties cannot be ruled out in the context of the long time horizon. In such a situation even the policy responses may differ. Given the limited time and resources available for this study, experiments with alternative BAU scenarios were not possible.

Second, we have experimented with known and feasible technological options. It is possible that new technological opportunities in the coming decades would help to significantly increase reduction of carbon emissions. In particular, low cost and large scale solar and wind energy generation, if and when these become available, would open up non-carbon energy options and carbon reduction could be feasible at a lower cost than what is estimated here.

[5] See several interesting papers in Toman (2001) in this regard.

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APPENDIX 1: MODEL EQUATIONS[6]

The model's objective is to maximize a social welfare function W given as the present discounted value of utility streams $\{U_t\}$ corresponding to the per capita consumption (PC_t) of an average consumer over the time horizon 1,2,....,T. The social discount rate chosen is ρ.

$$\text{Maximize} \quad W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} \qquad \text{where} \quad U_t = \log(PC_t) \tag{1}$$

The maximization is subject to several constraints. In the description below, we have omitted what is obvious, that constraints have to be specified for each commodity or each activity and for each period. The first constraint refers to material balance. The total supply of each commodity i, domestic production (Y) plus imports (M), must be no less than the total demand which is the sum of intermediate demand, private consumption (H), public consumption (G), investment (N) and exports (E). All these are real variables evaluated at base year's prices.

$$Y_{i,t} + M_{i,t} \geq \sum_{j=1}^{m} a_{i,j} X_{j,t} + H_{i,t} + g_i G_t + N_{i,t} + E_{i,t} \tag{2}$$

where $[a]$ is the input-output matrix with i commodities and m activities, X is a vector of activity levels and $\{g\}$ is the vector of public consumption budget shares. G_t is specified exogenously while determination of $H_{i,t}$ in relation to the per capita consumption (PC_t) is discussed below later. The input-output matrix need not be square as we distinguish between the set of commodities and the set of activities that produce them. In general, more than one activity is capable of producing a given commodity. A make matrix $[u]$ links each production activity to the commodities they produce. Additionally, this allows the possibility of joint production: an activity may produce more than one output. There is one column vector corresponding to each activity in this matrix and it represents numerically the commodity-wise composition of its gross output.

$$Y_{i,t} = \sum_{j=1}^{m} u_{i,j} X_{j,t} \tag{3}$$

The income generated by each production activity is proportional to their respective level (X) and is equal to the value of the output less the cost of the inputs. Aggregation over all activities (j) gives the gross domestic product (GDP) at market prices.

$$GDP_t = \sum_{j=1}^{m} \sum_{i=1}^{n} (u_{i,j} - a_{i,j}) X_{j,t} \tag{4}$$

The constraints in equations 5 to 9 describe the capacity and investment relations in the economy. All activities must operate within the available domestic capacity.

$$b_j X_{j,t} \leq K_{j,t} \tag{5}$$

where $K_{j,t}$ is the capital stock available for activity j in period t and b_j is the incremental capital output ratio ($ICOR$) for activity j. The production capacities available in different sectors at the beginning of the first period are specified as a part of the initial conditions.

[6] Taken from Murthy N. Satyanarayana, Manoj Panda and Kirit Parikh (2000): "CO_2 Emissions Reduction Strategies and Economic Development of India", IGIDR, Mumbai. An earlier version of the model appears in Parikh, Panda and Murthy (1995).

Typically, in the literature, a two-parameter standard lognormal probability density function (*SLN*) underlies the distribution function *f*. The two parameters are the Lorenz ratio (*LR*) and the per capita expenditure (*PC*). We calculate the proportion, $pop_{p,t}$, of people in the *p*-th class using the value of PC_t chosen optimally by the model and the class expenditure boundaries (e^{p-1} and e^p) for the *p*-th class and the value of the Lorenz Ratio (*LR*), each specified exogenously. The magnitude of population in the *p*-th class is given as

$$POP_{p,t} = POP_t \cdot pop_{p,t} \qquad \text{where} \quad pop_{p,t} = f(PC_t; LR, e^p) - f(PC_t; LR, e^{p-1}) \tag{17}$$

$$f(PC_t; LR, e^p) = SLN\left(\frac{1}{LR}\ln\left(\frac{e^p}{PC_t}\right) + \frac{LR}{2}\right) \qquad \text{where} \quad SLN(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{s^2}{2}} ds \tag{18}$$

Note that $e^0 = 0$ and $e^3 = \infty$ which yields $f(PC_t; LR, 0) = 0$ and $f(PC_t; LR, \infty) = 1$.

The average consumption expenditure $PCC_{p,t}$ of class *p* can be computed as:

$$PCC_{p,t} = \frac{PC_t \cdot SLN\left(\frac{1}{LR}\ln\left(\frac{e^p}{PC_t}\right) - \frac{LR}{2}\right)}{f(PC_t; LR, e^p)} \tag{19}$$

A representative consumer of the *p*-th class is allowed to choose a linear combination of *R* different types of commodity bundles. Her consumption expenditure budget ($PCC_{p,t}$) is allocated across the *R* bundles in each time period *t* so that the following identity holds.

$$PCC_{p,t} = \sum_{r=1}^{R} PCB_{r,p,t} \tag{20}$$

Each commodity bundle is composed of different commodities in fixed proportions. For example, $\mu_{i,r,p}$ is the expenditure share of commodity *i* in the *r*-th bundle available to a consumer of class *p* and this value remains fixed in the model. Nevertheless, the consumer achieves a degree of substitution between different commodities by choosing the combination of different bundles and the amounts she spends on each of them. The consumption vector (*C*) of each class as the aggregate over the set of *R* consumption bundles.

$$C_{p,i,t} = POP_{p,t} \cdot \sum_{r=1}^{R} \mu_{i,r,p}\, PCB_{r,p,t} \tag{21}$$

The economy-wide consumption vector {*H*} is then represented by the sum of consumption vectors corresponding to the individual classes.

$$H_{i,t} = \sum_{p=1}^{P} C_{p,i,t} \tag{22}$$

Since the distribution parameter (*LR*) is fixed in our model, poverty alleviation requires growth in consumption, which is chosen optimally in the model subject to the constraints.

Another point to note in this connection is that we have used the GAMS program to solve the model. GAMS, however, does not permit equations with standard lognormal functions, SLN(.) above. It, however, permits a loop where the SLN function could be computed before obtaining the optimization

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solution and iterations could be carried out within the loop such that the value of the SLN function converges. We have taken advantage of this facility.

Emissions Inventory

The emissions from the production sectors are computed by considering the scalar product of the two vectors: the activity levels $\{X\}$ and an emission coefficient vector $\{e^X\}$. Apart from the production activities, emissions are also caused by the private and public consumption of fuels like kerosene, LPG and motor gasoline. We account for these by considering two other emission coefficient vectors, $\{e^C\}$ and $\{e^G\}$. The total emissions in period t is therefore given as:

$$EM_t = e^X X_t + e^C H_t + e^G G_t \tag{23}$$

The cumulative stock of CO_2 emissions CEM_t at the end of any period t is computed by adding the emission flows EM_t during the current period to the stock CEM_{t-1} carried over from the previous period.

$$CEM_t = EM_t + CEM_{t-1} \tag{24}$$

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Table A1
Model Parameters Related to Activities

Activities	Agri	Coal	Oil	Electricity produced from				Industry		Trans	Service
				Coal	Other	Oil	CCGT	Coal	Oil		
Commodities											
Base Year Input-Output Coefficients : [a]											
Agricult.	0.199		0.000		0.003			0.092	0.092	0.002	0.019
Coal	0.000	0.011	0.000	0.184				0.011	0.004	0.006	0.001
Oil	0.010	0.027	0.469			0.157	0.132	0.016	0.040	0.097	0.008
Electricity	0.007	0.096	0.005	0.248	0.248	0.248	0.186	0.031	0.031	0.015	0.007
Industrial	0.075	0.196	0.042	0.076	0.076	0.076	0.076	0.342	0.342	0.171	0.063
Transport	0.012	0.044	0.012	0.045	0.045	0.045	0.045	0.035	0.024	0.068	0.034
Service	0.038	0.074	0.064	0.045	0.045	0.045	0.045	0.119	0.119	0.079	0.058
Make matrix: [u]											
Agricult.	1	0	0	0	0	0	0	0	0	0	0
Coal	0	1	0	0	0	0	0	0	0	0	0
Oil	0	0	1	0	0	0	0	0	0	0	0
Electricity	0	0	0	1	1	1	1	0	0	0	0
Industrial	0	0	0	0	0	0	0	1	1	0	0
Transport	0	0	0	0	0	0	0	0	0	1	0
Service	0	0	0	0	0	0	0	0	0	0	1
Capital composition matrix: [k]											
Capital goods											
Agricult.	0.15	0	0	0	0	0	0	0	0	0	0
Industrial	0.8	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958
Transport	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Service	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
Base Year Output (10^{12} rupees)											
	1.810	0.064	0.219	0.140	0.054	0.022	0.000	3.028	0.000	0.418	1.832
Incremental capital output ratio: diagonal elements of [b]											
	2.046	1.483	1.500	5.348	6.750	6.750	6.270	0.828	0.845	3.286	1.110
Initial capital stock (10^{12} rupees)											
	3.704	0.095	0.329	0.749	0.365	0.149	0.000	2.508	0.000	1.374	2.034
Emision coefficient: [e] in grams/rupee											
CO2	0.55	39.36	13.98	399.52	0.00	221.40	85.00	17.46	12.04	47.92	1.11

1) I-O table [a] is aggregated from a 60x60 absorption matrix obtained from Planning Commission (1991).
2) Capital Coeff. matrix is obtained by taking the composition of investment demand from 1989-90 I-O matrix and assuming that the investment goods from agriculture sector are entirely used by agriculture sector itself.
3) Base Year capital stock is the product of ICOR and base year output.

Table A2
Model Parameters Related to Commodities

Commodities	Agriculture	Coal	Oil	Electricity	Industry	Transport	Service
Budget shares of different goods in private consumption expenditure of households							
Bottom class: {c1}	0.5594	0.0011	0.0075	0.002	0.23	0.03	0.17
Middle class: {c2}	0.4213	0.0009	0.0135	0.0052	0.2803	0.0457	0.2331
Top class: {c3}	0.2915	0	0.0196	0.01	0.3139	0.075	0.29
Budget shares of different goods in government consumption expenditure							
{g}	0.0027	0.0001	0.0195	0.0253	0.1716	0.0257	0.755
Upper bounds on annual growth rate of Imports							
g^{MU}	0.05			0.02		0.05	
Upper bounds on annual growth rate of Exports							
G^{EU}	0.05				0.12		0.12
Base year values (10^{12} rupees)							
Private consumption: C_0	1.077	0.002	0.042	0.017	0.781	0.172	0.741
Govt. consumption: G_0	0.001	0	0.01	0.013	0.088	0.013	0.386
Export demand: E_0	0.029	0	0.005	0	0.204	0.031	0.099
Import demand: M_0	0.016	0.006	0.056	0	0.345	0.039	0.027

1) Budget shares in private consumption classes are from Parikh, Panda and Murthy (1994).
Variations in budget shares are permitted around these base values as discussed in the text.
2) Government budget shares are from 1989-90 I-O matrix.
3)Imports and exports bounds appear only for some sectors indicated above.

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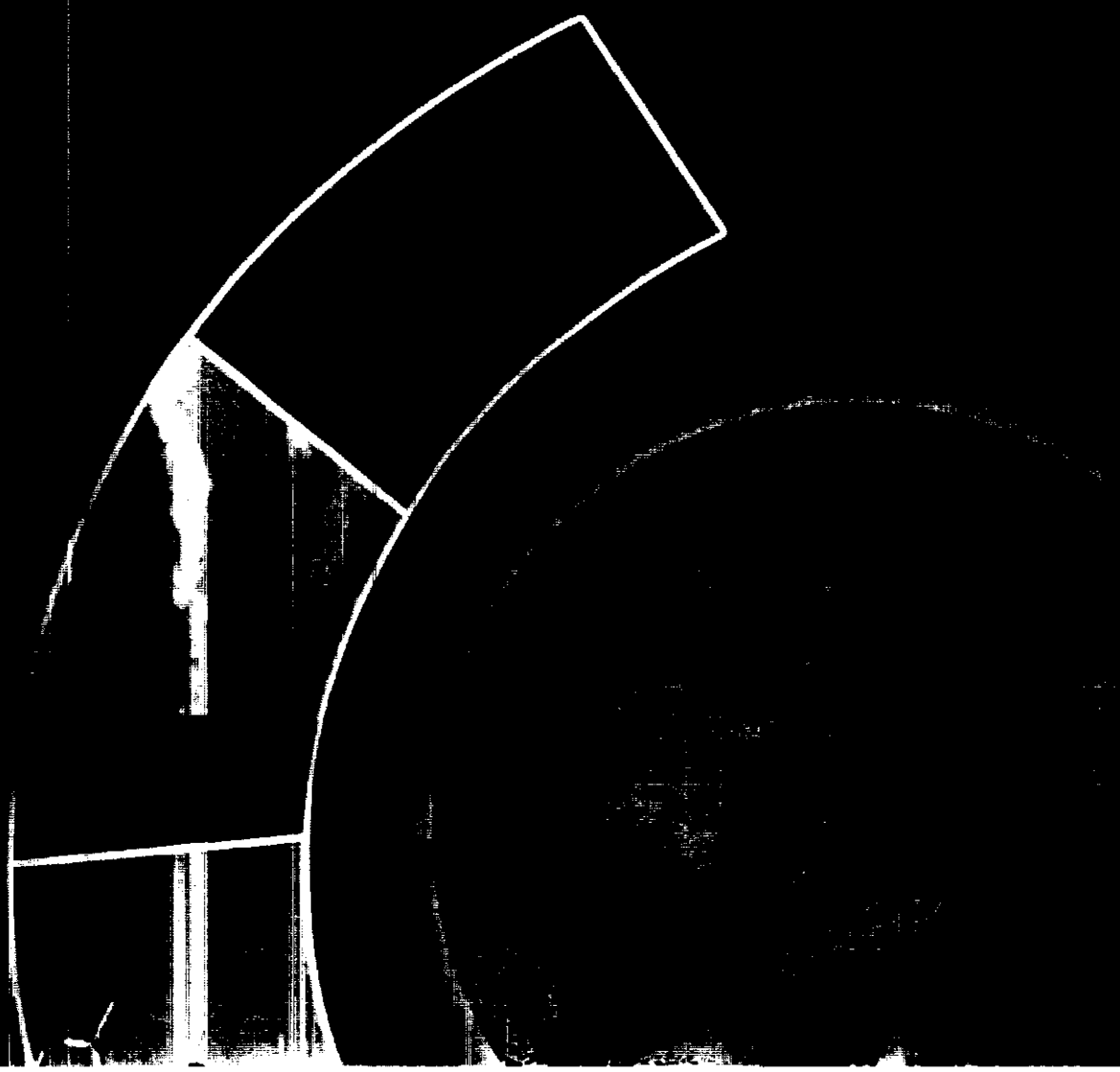
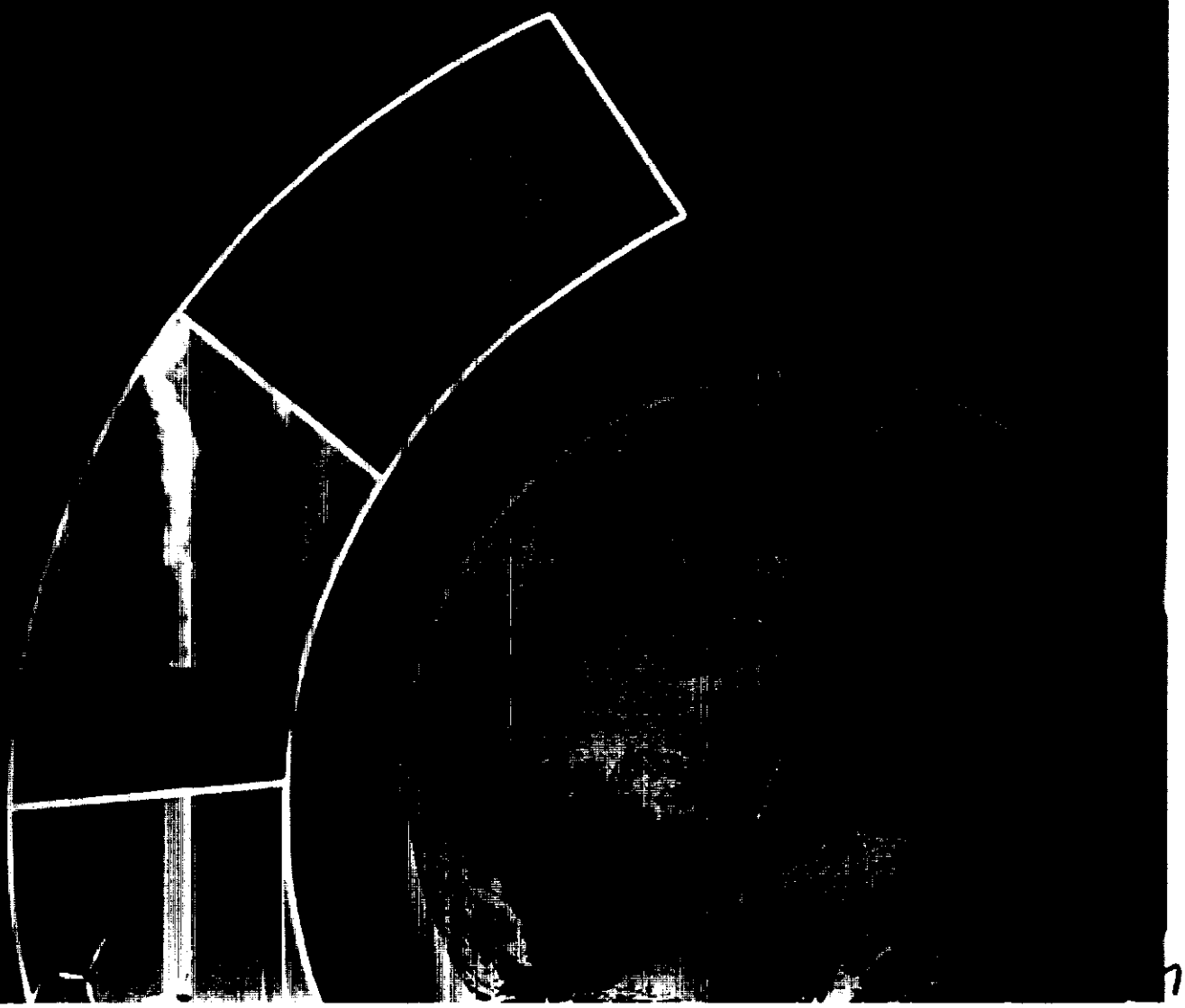
	Table A3	
	Other Model Parameters	
1	Total investment in base year in 10^{12} rupees	0.991
2	Maximum domestic incremental savings rate	0.300
3	Annual growth rate of government consumption	0.050
4	Annual foreign borrowings in the dynamics-as-usual scenario (in 10^{12} rupees): Ft	0.120
5	Annual social discount rate:	0.100
6	Post-terminal annual growth rate	0.055
7	Population in base year in 10^6	821.9
8	Annual growth rate of population (%)	1.8
9	Lorenz ratio of private consumption expenditure distribution: LR	0.38
10	Upper cut-off level of expenditure for bottom class: (rupees)	2250
11	Upper cut-off level of expenditure for middle class: (rupees)	4000

Mitigation Measures and Opportunities for the Future



Assessment of the Role of Renewable Energy Technologies



ASSESSMENT OF THE ROLE OF RENEWABLE ENERGY TECHNOLOGIES

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I. INTRODUCTION

The per-capita electricity consumption in India is about 400 kWh/year, which is significantly lower than the world average (2100 kWh/year/capita) [1]. The level of development and the quality of life in a country correlates with the per capita energy consumption. Any future development path for India will result in an increased per capita consumption of electricity. The power planning strategy in India has been to build large fossil fuel fired power plants and supply electricity through a centralized grid. Despite rapid increases in the supply system, energy shortages and peak scarcity persist in most parts of the country. A large number of villages are yet to be electrified (estimated to be about 80,000). Even in electrified villages, a significant proportion of households do not have access to electricity (40% or more).

The limited fossil fuel reserves have made it imperative to explore alternatives. Table 1 shows a summary of the fossil fuel reserves available in India and the reserves/production ratio. It is clear that the oil and gas reserves of India can sustain consumption for only a decade or two. Though India's coal reserves are likely to last longer, a fossil fuel-based electricity sector is clearly not sustainable in the long run. Adverse local environmental impacts (SO_x, NO_x, SPM) and global environmental impacts (greenhouse gas emissions mainly due to CO_2) associated with fossil fuel combustion have also intensified the search for clean energy sources. Nuclear can be a significant solution to India's energy problem only if breeder reactors are commercialized and the extensive thorium reserves are tapped. Issues related to decommissioning and nuclear safety need to be resolved for nuclear to play a greater role in India's energy scenario.

Future energy systems in India are likely to have a greater share of renewables.

Table 1. Summary of Fossil fuel reserves of India

Fuel	Reserves	Production (1998)	
Coal Million tonnes	60000	296	~200+
Oil Million tonnes	660	33.86	19 (9)
Natural Gas Billion m^3	692	26.4	26
Nuclear Natural Uranium	——	——	50

Data source TEDDY [2]

This paper assesses the role of renewable energy technologies (RETs) in the Indian power sector, quantifies the role they can play in the next 20 years and reviews the barriers to RETs and policies required for accelerated diffusion.

II. STATUS OF RENEWABLE ENERGY TECHNOLOGIES

Figure 1 shows the share of the installed capacity of different sources in the Indian power sector. It is seen that wind energy accounted for about 1% of the country's installed power capacity in 1998 [3,4]. The aggregate data does not include some of the renewables, viz. biomass and dispersed options. Small hydro is also not separately accounted for. If these are included, the share of renewable energy was about 2% in 1998.

The renewable energy installed capacity was 205.5 MW in 1993 (104.6 MW small hydro, 39.9 MW Wind). This increased to 2978 MW in 2001 (as on 31st March 2001) and accounted for almost 3% of India's installed power capacity. The growth rate of installed renewable power capacity during the period 1993-2001 was 39% per year. During (January 1) 2000-2001(March 31st), the installed capacity increased from 1,600 MW to 2,978 MW (an annual growth rate of 49%).

Figure 2 shows the installed capacity of different renewable energy technologies [5]. The major contributors are small hydro (< 25 MW), which accounts for 1,341 MW (45%), and wind, which accounts for 1,267 MW (42%). The installed capacity in biomass-based power generation is 308 MW (10.3%), with most of it coming from bagasse-based cogeneration.

Both wind and small hydro are technologies that are commercially available. Potential sites have been mapped and there is likely to be a steady growth in the capacity. However, these are only applicable at some sites where there is sufficient wind or water flows and heads. Figure 3 shows a listing of the options for power generation from renewables. The solar energy route has a variety of configurations possible, based on either solar thermal or solar photovoltaic technologies. These will be assessed in detail in this report. Wind and small hydro are commercially available technologies that will also be covered in this report.

III. TIDAL, OTEC AND WAVE ENERGY

The remaining process routes are restricted to only a few regions near the coast. This report will not cover tidal, Ocean Thermal Energy Conversion (OTEC) and wave energy in detail. Of these technologies, power generation from OTEC is only at a prototype stage. There have been experiments at the Natural Energy Laboratory of Hawaii (NELHA, USA). Power generation is based on utilization of the temperature differences existing in the ocean. Since the temperature differences are small (20°C), the cycle efficiencies are poor (approx 3%). A mini OTEC closed cycle (ammonia working fluid in a Rankine cycle) of 50 kW was installed in 1979 in NELHA with a 10 kW net power output. A 210 kW gross output open cycle plant (working fluid – sea water) was operated between 1992-98 with a net output of 40 kW. These technologies are in the prototype/development phase and are not yet commercialized. A 1 MW demonstration unit is being planned off the coast of Tamil Nadu. This is being funded by the Department of Ocean Development and implemented by the National Institute of Ocean Technology with a consortium of private companies.

India has experimented with a 150 kW wave energy system at Thiruvananthpuram (Kerala) . This is based on an oscillating water column with a Wells turbine and an electrical generator [7]. The system's average output was 25 kW during December-March and 75 kW during April–November. The average wave energy available is 10 kW per m of the oceanfront. The estimated cost of electricity is 9-10 c/kWh (Rs. 4-4.50/kWh). However, though prototypes have been built and some operating experience obtained, this is not yet a commercially available technology.

Figure 1 Share of Power Installed Capacity (1998)

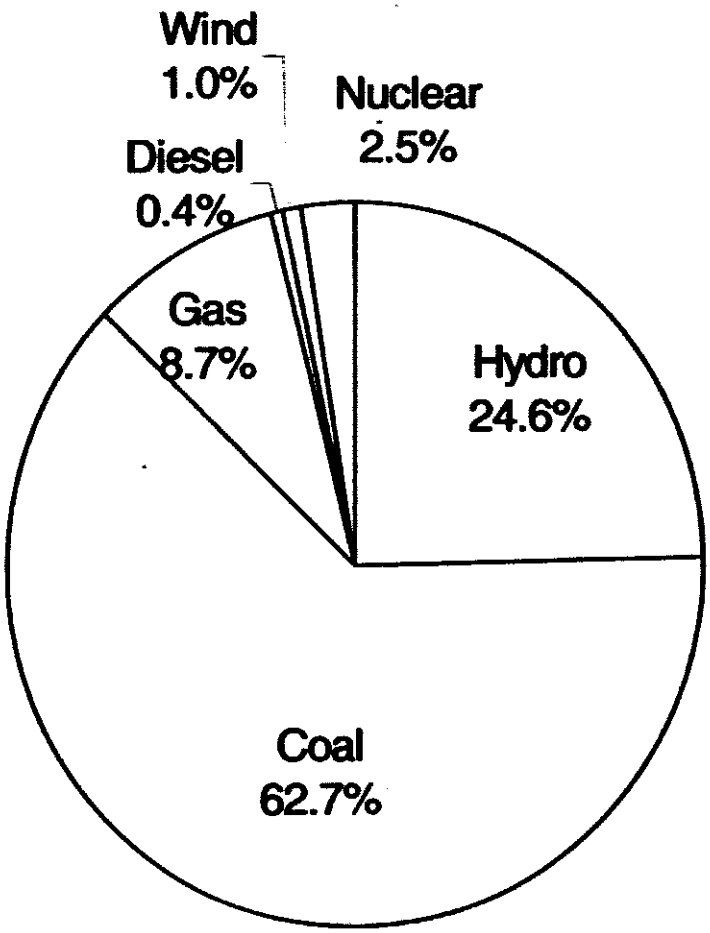

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Figure 2.Installed Capacity of Renewables in India

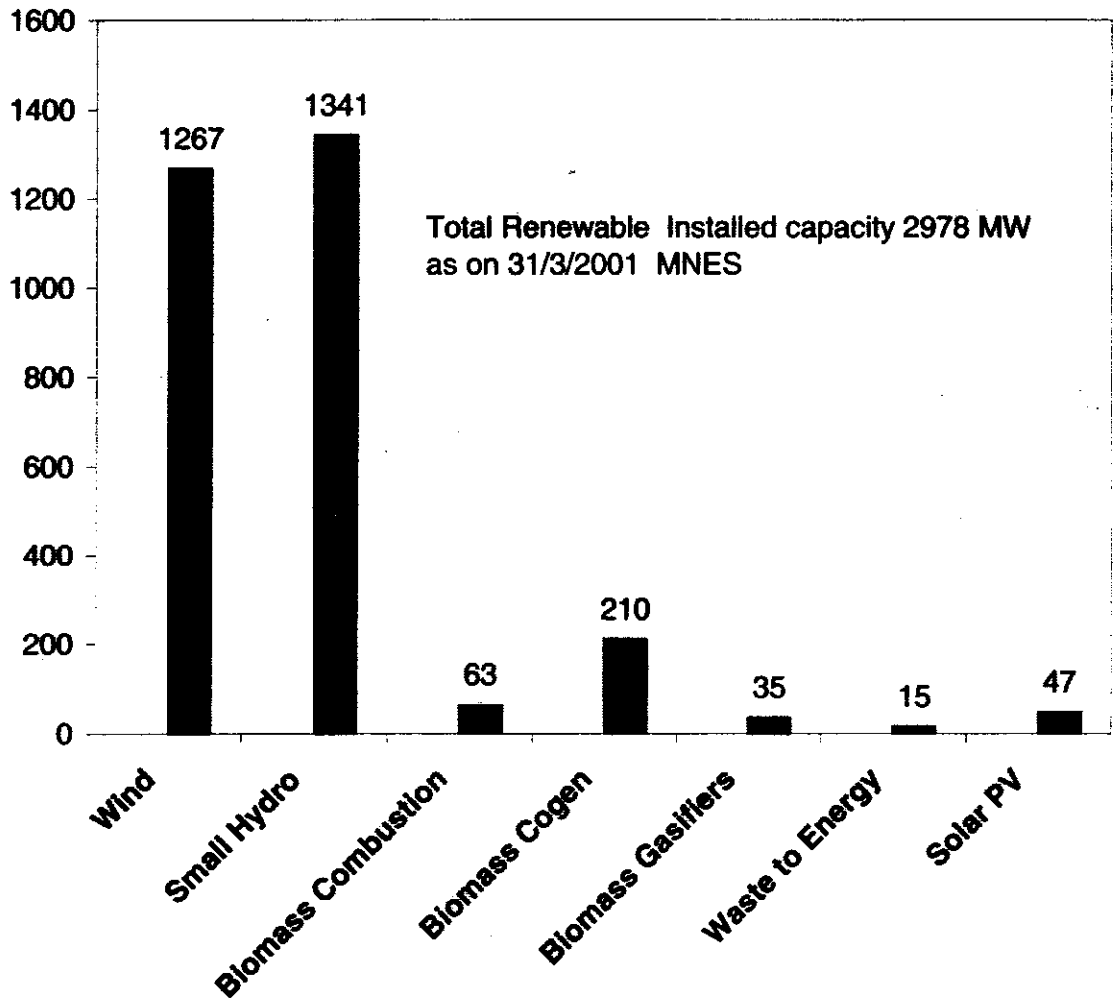

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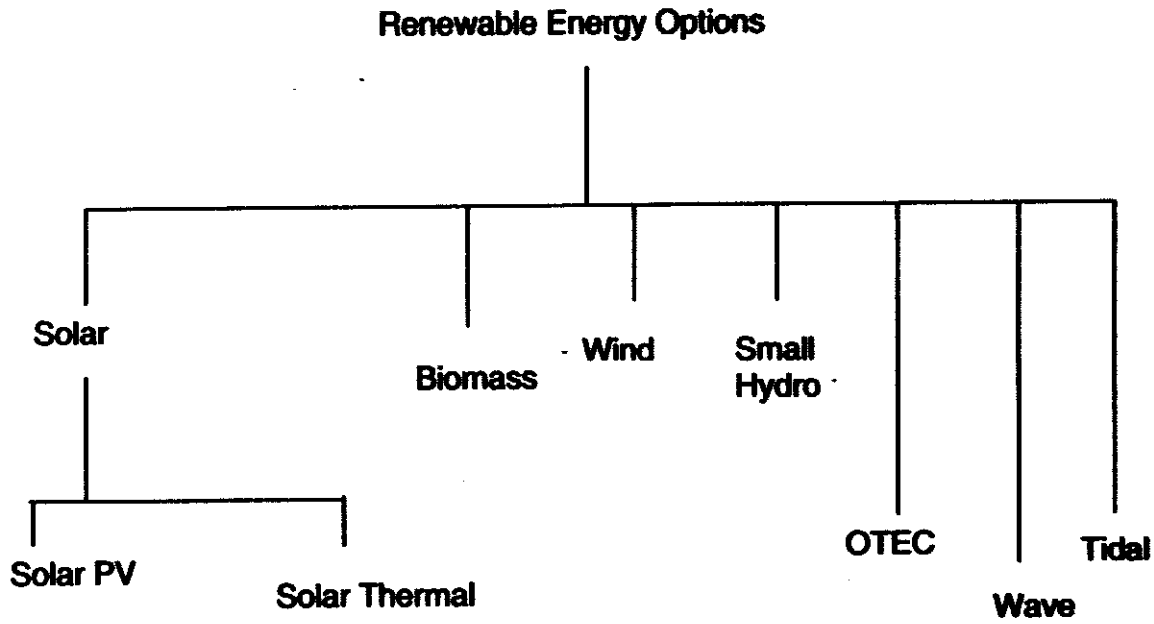
Figure 3. Renewable Energy Options for Power Generation



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Tides are caused due to the gravitational attraction of the moon. The difference in levels between the high tide and low tide can be utilized. This is done by creating an artificial basin, trapping the high tide and releasing the water during the low tide. The difference in head (water height) is used to run a water turbine and generate power. A 240 MW tidal power plant in France (La Rance) has been operating for the last two decades. In India, the potential sites are the Gulf of Kutch (with estimated potential of 900 MW), Gulf of Cambay (with estimated potential of 7,000 MW) and the Durgaduani Creek in the Sundarbans Delta (with estimated potential of 1,000 MW). There is at present no tidal power station in India. A 3 MW tidal plant is being planned in the Durgaduani Creek . A detailed project report has been prepared and is likely to be implemented by the West Bengal Renewable Energy Development Agency. The capital cost for a 100 MW installation is expected to range between $1,200-$1,500 /kW (Rs 60,000-75,000 /kW). Also, the capacity factor will be low as the power will be available only during low tide.

IV. RENEWABLE ENERGY POLICIES

The Government of India established the Department of Non-Conventional Energy Sources (DNES) in 1982 to support new and renewable sources of energy in India. In 1987, DNES proposed a plan of 15,425 MW by 2000/ 2001 through renewables [8]. The actual realization is significantly lower. A review of the renewable energy program by Sinha[9] in 1990 indicated that this target was unlikely to be met. In the initial years of the renewable program, the emphasis was on biogas that received more than 50% of the total funding. The funding emphasis shifted in the 1990s, with the wind, small hydro and biomass programs getting a larger share of the budget.

The DNES upgraded to the Ministry of Non-Conventional Energy Sources (MNES) in July 1992. A separate agency – the Indian Renewable Energy Development (IREDA)-was set up to provide financing for renewables. IREDA has attracted significant multi-lateral funding (GEF, World Bank) in addition to the Government funding. There has also been a shift in the approach of MNES/ IREDA from direct subsidies to a greater emphasis on fiscal incentives and funds for concessional financing of renewables.

MNES is structured with divisions based on technology areas – solar thermal, biomass, solar PV, small hydro. The divisions are also clubbed together into groups based on end-use areas like the Power group and the Rural Energy group. MNES has also set up a Solar Energy Centre, a Centre for Wind Energy Technology and a National Institute for Renewable Energy. In addition to the central government ministry, different states have set up their energy development agencies like the Maharashtra Energy Development Agency (MEDA), Gujarat Energy Development Agency, West Bengal Renewable Energy Development Agency. Each state nodal agency is responsible to promote and support renewable energy in its state. Another development has been the creation of 26 Aditya Solar Shops with seed funding from IREDA to market and sell renewable energy products in the region.

The MNES recently formulated a renewable energy policy which targets 10% of the additional generation capacity to be realized through renewables by 2012. The power generation potential from renewables, as per MNES estimates [10], is shown in Table 2. The potential estimates are uncertain. It is clear that the renewable energy potential is significant. The key factor is to determine the economically viable potential. This point will be discussed after we examine some of the renewable energy technologies in more detail.

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Table 2. Renewable Energy Power Generation Potential [10]

Source	Potential (MW)	Harnessed (MW)
Wind	45000	1267
Biomass/ Bagasse	19500	292
Small Hydro	15000	1341
Waste-to-Energy	1700	16.2
Solar PV	20 MW/km^2	1.67

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CHAPTER 2 ASSESSMENT OF RENEWABLE ENERGY TECHNOLOGIES

I. INTRODUCTION

This chapter reviews some of the important renewable energy technologies for power generation. For each technology there is a brief description of the technology and its current status in India. The technologies considered are wind, small hydro, solar photovoltaic, solar thermal, biomass combustion, cofiring, cogeneration, gasification and biogas. Typical values of costs are indicated for each of the technologies.

II. WIND ENERGY

Among the different renewable energy sources, wind energy has made a significant contribution to the installed capacity and has emerged as a viable and cost effective renewable option for grid quality electricity. This is due to the multidimensional initiatives under the Wind Power Programme taken up by the Ministry of Non-conventional Energy Sources. This program involved research & development, survey and assessment of wind resources, implementation of demonstration and commercial projects, capacity building for manufacturing, installation, operation and maintenance, promotional policies and institutional and infrastructure development.

A. Status

India is the fifth largest wind power producer in the world, with a wind power generating capacity of 1,267 MW. Table 3 shows the installed wind power capacity in India as of December 2000. Some 26 project sites have been developed in the high-potential states under the demonstration program, resulting in a capacity of 57 MW. 1,210 MW of power has come through commercial projects. About 6.5 billion units of electricity have been fed to various state grids from wind power projects.

Table 3: Wind Power Installed Capacity (MW)
(as of December 31, 2000)

Andhra Pradesh	3.1	86.5	89.5
Gujarat	17.3	149.6	166.9
Karnataka	2.6	35.3	37.8
Kerala	2.0	-	2.0
Madhya Pradesh	0.6	22.0	22.6
Maharashtra	6.4	149.0	155.4
Rajasthan	4.3	-	4.3
Tamil Nadu	19.4	767.7	787.1
Others	1.6	-	1.6
Total	**57.2**	**1210.0**	**1267.2**

Source : MNES Annual Report 2000-2001

B. Resources Assessment

The Wind Resources Assessment Programme (WRAP) carried out in India to reassess the wind potential was one of the largest programs of this kind in the world, covering about 900 wind monitoring stations and mapping stations in 24 states and union territories. WRAP has so far identified 192 potential sites in 13 states. States with high wind potential are Tamil Nadu, Andhra Pradesh, Karnataka, Kerala, Madhya Pradesh and Maharashtra.

Wind energy potential in India has been estimated at 45,000 MW (at 50-m hub height), however, the technical potential is estimated at about 10,000 MW assuming 20% grid penetration. This is expected to increase with the augmentation of grid capacity in the potential states. State gross and technical wind power potential is shown in Table 4.

Table 4 : Wind Power Potential

Andhra Pradesh	8275	1290
Gujarat	9675	1450
Karnataka	6620	900
Kerala	875	400
Madhya Pradesh	5500	875
Maharashtra	3650	2500
Orissa	1700	400
Rajasthan	5400	500
Tamil Nadu	3050	1220
West Bengal	450	450
Total	**45195**	**9985**

Source : MNES Annual Report 2000-2001

C. Technology

Wind electric generators ranging from 55 to 750 kW in rating have been developed and manufactured in the country. State-of-the-art wind power technologies are now indigenously available in India. Wind turbines in the megawatt scale are envisaged to enter the Indian market in the near future. An annual production capacity of 500 MW has been established. Wind electricity generators of up to 750 KW unit capacity are now being manufactured. The rotor blade, a crucial component of wind turbines, is manufactured in India. Nearly 80 percent indigenization has been achieved.

1. Research & Development Efforts

- State-of-the-art wind R&D centers and field-test stations have been established
- Electronic Research and Development Centre (ERDC), Thiruananthpuram has fabricated an Intelligent Power Controller for wind electric generators to maximize generation and to reduce reactive power requirements. The Controller is under field-testing.
- Electronic Research and Development Centre (ERDC), Thiruananthpuram is also preparing guidelines for integration of wind turbines with weak grids.

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D. Economics and Policies

- Capital cost of wind power projects ranges from Rs. 4.0-4.5 crore per MW
- Cost of generation is estimated to be Rs. 2.0-2.5 per kWh (depending upon the site)
- These costs compare favorably with new conventional power projects
- Gestation period for wind energy projects is short and it also allows modularity
- Cost can be brought down and profitability increased with technology improvements, increased size of turbines and optimal planning and site selection

Aims and Targets: The wind power program in India aims at catalysing commercialization of wind power generation in the country through:

- a country wide wind resources assessment
- R&D support
- implementation of demonstration projects to create awareness and opening up of new sites
- close involvement of utilities and industry
- development of infrastructure capability and capacity for manufacture, installation, operation and maintenance of wind electric generators
- adaptation of technologies for improved performance of turbines at low to medium wind speeds and improved capacity utilization, cost reduction and high reliability and increased life of turbines
- policy support

Target achievements of wind energy in the Eighth Five Year Plan period are shown in Table 5. Targeted capacity for the next five years is about 1,000 MW. This will require an investment of Rs. 40,000 million.

Table 5 : Target Achievements of Wind Energy in the Eighth Five-Year Plan Period

Wind power (MW)	12.68	61.09	235	10	382.11	100
Wind pumps (No.)	93	41	200	200	29	200
Wind battery chargers (No.)	4	6	15	35	1	35
Urjagram (No.)	29	25	25	-	-	-

Source : Tata Energy Data Directory & Yearbook 2000-2001

Policy Measures and Incentives: The policy framework and incentives for wind energy projects are:

- Fiscal and financial incentives
- Wheeling, Banking, Third Party Sale and Buy-back facility by State Electricity Boards (SEBs)
- Capital subsidies and sales tax incentives in certain states

Soft loans from the India Renewable Energy Development Agency Ltd. (IREDA)

Fiscal and Promotional Incentives: The Indian Renewable Energy Development Agency (IREDA) has been playing a significant role in promoting renewable energy projects in general and wind energy projects in particular. It has attracted bilateral and multilateral financial assistance from the World Bank, the GEF, the ADB, etc. Major national financial institutions have also been financing wind power projects. Another major development has been the entry of central and state power generating entities, such as the National Thermal Power Corporation and the State Power Corporation, into the wind sector.

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Other public sector undertakings are also in the process of diversifying into the wind sector, and a few have already initiated developing large wind farms. The following fiscal and promotional incentives are available from the Central Government:

- Concessional import duty on specified wind turbine parts
- 100 percent accelerated depreciation in the first year
- Sales Tax, Excise Duty relief
- Loans through IREDA
- Five-year Income Tax holiday
- Sales Tax incentives in certain states

Fourteen states have introduced policies based on MNES guidelines:

- 2 per cent Wheeling charges
- Banking up to one year
- Third Party Sales at remunerative prices
- Buy-back facility at minimum price of Rs. 2.25 per kWh
- 5 percent annual escalation in tariff

In the case of state government projects, 60 percent of the wind turbine equipment, maintenance spares and erection and commissioning costs (subject to a benchmark cost of Rs. 3.2 crore/MW) would be borne by the Central Government. All other costs will be met by the state government.

IREDA loans for wind power projects are available under different schemes, as follows:

- Project financing
- Equipment financing (up to 1 MW per party per financial year for grid-connected projects)
- Manufacturing equipment.

Financing norms of IREDA have been given in Table 6.

III. SMALL HYDROPOWER

Small hydro projects (SHP) are an environmentally benign and economically viable source of energy and are very useful for remote and hilly areas where extension of the grid is not possible or is uneconomical. The environmental and social constraints involved in large hydro projects are not concerns in small hydro projects. These projects have a short gestation period. Small hydro projects have received sharp focus in recent years. Due to preferential policies and incentives given to this sector by the Ministry of Non-conventional Energy Sources, it has grown four-fold from 63 MW to 226 MW in the last 10 years. Small hydro power projects of up to 25 MW capacity have now been brought under the purview of MNES.

There is a renewed interest among many state governments to exploit their SHP potential and 13 states have announced their policies to encourage private sector participation in commercial SHP projects.

These are Himachal Pradesh, Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Karnataka, Kerala, Andhra Pradesh, Tamil Nadu, Orissa, West Bengal, Maharashtra and Rajasthan.

Table 6 : IREDA'S Financing Norms for 2000-2001

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A. PROJECT FINANCING							
	Wind Energy						
	(i)Development of Wind Farms on lease basis	13.75	10	1	25	Up to 75% of total project cost	
	(ii)Development of Wind Farms on ownership basis	13.50	10	1	25	100% of eligible equipment cost limited to a maximum of 75% of total project cost in case on project sanctioned from international funds	
	(iii)Development of Wind Farms by Machine suppliers/manufacturers upto 5 MW/Party per year on built, operate, own lease, transfer basis	13.00	10	1	25	Up to 75% of project total cost	
	(iv) Development of Wind Farm/estate with minimum station capacity of 10 MW by Co-operative Sector /Public Sector/Joint Sector/Private Sector Companies on built, own, operate, lease, transfer basis subject to following conditions: - Applicant having minimum net worth of Rs. 100 crores - Applicant having AAA (or equivalent) rating	12.75	10	1	25	Up to 75% of project total cost	• Existing Companies to get preference • Loan to be provided lines of credit • Co-operative Societies, if sanctioned loan should be profit making
	(v) New Technology above 750 kW machines	12.50	10	1	25	Up to 75% of project total cost	Loan to be provided only under international line of credit

Source : IREDA News

A. Resource Assessment

The Central Electricity Authority (CEA) has conducted a study for potential sites for small hydro power of up to 15 MW in all states. MNES has a database of 4,096 potential sites with an aggregate capacity of

about 10,071 MW for projects up to 25 MW. There lies a potential of about 15,000 MW of small hydro power in India.

B. Status

The number of projects set up / ongoing in different states and their capacity has been given in Table 7. So far, India has set up 387 small hydro power plants of up to 25 MW capacity totalling 1,341.05 MW. 170 projects of 25 MW with a total capacity of nearly 498.28 MW are under implementation. Most SHPs are grid connected. However, there are a few projects being managed by local community organizations or NGOs. MNES has recently started a program of development and upgrade of water mills to enable the direct use of mechanical power for different uses. MNES has also launched a demonstration project to study the performance of portable micro-hydel sets under field conditions. Fifty portable micro-hydel sets of 5-15 kW capacity have been provided to local bodies / communities in seven states.

C. Research & Development

India has a well-established manufacturing base for a full range and type of SHP equipment. However, R & D is required to improve the efficiency and reduce costs of equipment. The main objectives of R & D efforts are:

- simplification and optimization of the system and equipment designs and engineering practices
- reduction in the cost of different elements
- improvement in equipment reliability
- development of techniques for speedy construction in order to reduce gestation period

New concepts such as rubber dams, COANDA systems, the SCADA system for computerized project monitoring etc. are being tried out in various demonstration projects.

D. Economics and Policies

Aims and Targets: The Government of India is encouraging private sector participation for setting up SHP projects. All the states have suitable policies in this direction, to be achieved through:

- a nationwide SHP resource assessment
- Encouragement to commercial SHPs
- Special incentives to northeastern states to exploit Small Hydro Power potential
- Projects aggregating 65 MW under the renovation and modernization program
- Demonstration projects based on commercially viable and environmentally sound technologies
- Upgrading of 100 existing water mills to multi-purpose units

Cost Economics

- Engineering, procurement and construction cost of a small hydro project is US$ 1,000/kW
- Evacuation cost is about US$ 4,000 / Km
- Total project cost

Fiscal and Promotional Incentives: The facilities available in the states include wheeling, banking, attractive buy-back rate and facility for Third Party Sale, among others. In order to accelerate development of SHP power in the country, MNES is providing incentives for:

- Detailed survey and investigation
- Detailed project report preparation

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Table 7 : State-wise Details of Small Hydro Power Projects Set-Up/Ongoing

Haryana	4	48.20	1	0.10
Himachal Pradesh	36	87.28	9	21.73
Jammu & Kashmir	25	85.14	11	29.81
Punjab	15	100.90	3	3.30
Rajasthan	10	23.85		
Uttar Pradesh & Uttaranchal	72	73.40	27	67.28
Goa	1	0.05		
Gujarat	2	7.00		
Madhya Pradesh & Chattisgarh	8	39.16	3	22.60
Maharashtra	23	195.33	6	14.00
Andhra Pradesh	36	128.21	20	44.81
Karnataka	27	138.35	11	28.20
Kerala	10	69.52	11	75.50
Tamil Nadu	10	73.85	3	10.40
Bihar & Jharkhand	10	48.95	9	35.85
Orissa	4	1.30	7	9.93
West Bengal	15	87.94	5	8.42
Sikkim	9	30.50	2	3.20
Arunachal Pradesh	36	33.07	12	20.61
Assam	1	2.00	10	51.11
Manipur	7	4.70	4	3.50
Meghalaya	3	30.71	7	0.28
Mizoram	14	11.76	3	15.50
Nagaland	6	3.87	4	26.80
Tripura	3	16.01	1	0.10
A & N Island			1	5.25
Total	**387**	**1341.05**	**170**	**498.28**

Source : Tata Energy Data Directory & Yearbook 2000-2001

- Interest subsidy for commercial projects - up to 7.5 percent in the hilly regions and up to 5 percent in the plains
- Under special incentives for the northeastern region and Sikkim, a capital grant of Rs. 7.5 crore per MW is available for SHP projects in the region
- Financial support for renovation and modernization and capacity uprating of old SHP stations
- Financial support for development / upgrading of water mills
- IREDA provides soft loans for setting up of SHP projects up to 25 MW. The financing norms of IREDA have been given in Table 8.

IV. SOLAR PHOTOVOLTAICS

Solar Photovoltaic (PV) technology based on solar cells provides one of the most environmentally friendly sources of electricity generation. PV can be used both in stand-alone and in grid-connected

applications. It is useful for rural remote areas, urban domestic and commercial establishments as well as for specialized applications such as in railways and telecommunications.

Solar cells are semiconductor devices, which convert sunlight into electricity directly without involving any moving parts. Wafers sawn from mono- or multi-crystalline ingots of high-grade silicon are the most-used semiconductor materials for making solar cells today. Thin film solar cells are being regarded as the technology for the future. A complete PV power system has a PV array, an energy storage system and necessary electronic, electrical and mechanical subsystems.

India receives about 300 clear sunny days in a year. This is equal to over 5,000 trillion kWh. year, which is far more than the total energy consumption of the country in a year. The daily average solar energy incident over India varies from 4-7 kWh/m^2, depending upon location. Table 9 shows the potential of PV in different states on a scale of 1 to 4.

Table 8 : IREDA'S Financing Norms for Small Hydro (2000-2001)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
A. PROJECT FINANCING						
	Hydro Energy *(upto 25 MW Station Capacity)*					
	Mini Hydro					
	(i) Upto 1 MW Capacity	13.50	10	3	20	Up to 80% of total project cost. 100% of eligible equipment cost and 90% of civil cost limited to a maximum of 80% of total project cost in case of project sanctioned from international funds
	Small Hydro					
	(i) Above 1 MW and upto 3 MW Capacity	13.75	10	3	25	Up to 75% of total project cost. 100% of eligible equipment cost and 90% of civil cost limited to a maximum of 80% of total project cost in case of project sanctioned from international funds
	(ii) Above 3 MW and upto 25 MW Capacity	14.00	10	3	25	Up to 75% of total project cost. 100% of eligible equipment cost and 90% of civil cost limited to a maximum of 80% of total project cost in case of project sanctioned from international funds

Source : IREDA News

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Table 9 : Index of PV Potential by State

Maharashtra	3.8	Bihar	2.8	Jammu & Kashmir	2.3	Sikkim	1.9
Karnataka	3.5	Madhya Pradesh	2.8	Meghalaya	2.2	Pondicherry	1.7
Gujarat	3.4	Delhi	2.8	Tripura	2.2	Lakshadweep	1.5
West Bengal	3.3	Assam	2.8	Himachal Pradesh	2.1	Daman & Diu	1.5
Goa	3.3	Manipur	2.7	Arunachal Pradesh	2.1	Andaman	1.5
Andhra Pradesh	3.3	Orissa	2.6			Dadra & Nagar	1.0
Tamil Nadu	3.3	Rajasthan	2.6				
Punjab	3.2	Nagaland	2.5				
Uttar Pradesh	3.2	Chandigarh	2.4				
Kerala	3.2	Mizoram	2.4				
Haryana	3.1						

Source : Indian Solar PV Market Assessment and Publicity Campaign Development Study 1994

A. Market Base in India

India has both the need and the opportunity to use solar energy on a large scale. Annual production volumes are of the order of 10 MWp. India is one of the largest markets and manufacturers of PV modules in the world after the US, Japan and the European Union.

In India, where more than 70% of its one billion population live in the rural sector, water pumping (especially for irrigation) presents one of the biggest markets for PV. India today has about 13 million electrical pump sets in operation with a potential for six million more. Of these, open wells total about two million. Even if 10% of these open wells are energized (i.e. 200,000 open wells), this would translate to a demand for PV of the order of 200 MW, assuming 1 kW stand-alone PV systems. There are 100 million kerosene lanterns in use in the remote villages of India. This represents a market for 1 GW of PV (assuming replacement by 10Wp solar lanterns).

Assuming 25% of India's population live in the urban sector (i.e. 0.25 billion or 250 million) and an average family consists of 5 members, this would represent 50 million households. Even if 2% of this figure, i.e. one million-households / houses, opt for 500 Wp PV stations, on an average, the demand for PV would be 500 MW. We have not talked about commercial complexes, corporate buildings and farmhouses. It is expected that increased volumes of PV module production will result in a significant reduction in the module costs.

B. Status

About 65 MW aggregate capacity (about 8,000,000 systems) stand-alone PV systems have been installed for various applications. 7,500,000 systems, aggregating to about 58 MW, have been installed under MNES's PV program. This includes 3,600,000 solar lanterns, 1,600,000 homelighting systems, 43,000 street lighting systems and 3,575 water pumping systems.

MNES is implementing two major schemes for the deployment of stand-alone PV systems in the country:

- Lighting systems, stand-alone power plants and other specialized systems
- Water pumping systems for agriculture and related uses

Prominent regions where SPV homelighting systems and power plants are in demand are West Bengal, Rajasthan, the hilly regions of Uttar Pradesh, Laddakh, Lakshdweep, Andaman and the Nicobar Islands. Eleven power plants of 250 kWp aggregate capacity have been installed in Sagar Island in West Bengal.

Target achievements of SPV in the Eighth Five Year Plan period are shown in Table 10. In the last two decades, the cost of PV has gone down by more than 10 times, increasing accessibility for dispersed rural applications.

Table 10: Target Achievements of SPV in the Eighth Five-Year Plan Period

Power units (kWp)	143.36	122	100	30	89	50
Community lights (No.)	-	-	-	-	-	-
Domestic lights (No.)	3,043	6,399	500	1000	-	-
SPV Lanterns (No.)	-	-	-	-	-	-
SPV Street lights (No.)	-	-	-	-	-	-
SPV Water pump (No.)	106	1894	1000	-	738	1000

Source : Tata Energy Data Directory & Yearbook 2000-2001

Aims and Targets: An all-India SPV program to develop cost-effective PV technology and its application for large scale diffusion in different sectors, especially in rural and remote areas, is under implementation by MNES. Major components of the PV program include:

- Research and development
- Demonstration and utilization
- Testing and standardization
- Industrial and promotional activities

C. Promising PV Technologies for Terrestrial Use

Monocrystalline silicon technology is the oldest and most enduring workhorse of all PV technologies. While laboratory efficiencies have reached 25%, manufactured efficiency is in the range of 15.3 to 17.5% (14-16% module level). PV module efficiencies which are close to 15% at present are expected to increase to 22% by 2010. The prices are also expected to come down to $2/Wp by 2010. The basic raw material is sand (quartzite or silicon dioxide), which is reduced to metallurgical grade silicon and then purified to semiconductor grade (99.9999% pure). Mono-crystalline Si technology is of the 'indirect band gap' type with very poor absorptivity. The minimum thickness of silicon material required for absorption would be on the order of 100 microns or so. Today, single crystal wafers of 250 microns thickness are available. Ingot pulling is energy-intensive and wafer slicing wastes material (Kerf loss) up to 40-50%. Optical enhancement of incident light entering the solar cell is achieved by various techniques including anti reflection coating, texturing of the surface and laser grooved buried contact design and PERL (passivated emitter rear locally diffused) structure.

Silicon Film: Today, quite a few companies like Astropower are growing silicon film epitaxially on low cost surfaces (like ceramic). The thickness of material would be on the order of 50 microns or less. The

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active layer (#50 micro-meters) is supported by a substrate consisting of non-silicon material or low grade Si. Efficiencies of cells exceeding 16% have been achieved. PV module efficiency of 8-10% was achieved in 1998 and is expected to reach 12% this year. The price of silicon film on a low-cost substrate is expected to come down to $2/Wp shortly and is predicted to come down to $1.25/Wp by 2010.

Polycrystalline Si technology is gradually overtaking single crystal silicon technology in terms of production capacity and shipments. Polycrystalline Si ingots are cast (and not pulled with the help of a seed crystal) in square or rectangular shapes, as opposed to the round and pseudo-square shapes of single crystal Si cells. In 1998, polycrystalline Si PV modules recorded efficiencies of 13-15%, which are predicted to increase to 20% by 2010, while prices are expected to fall to $ 2/Wp.

EFG (Edge defined film fed growth) technology, patented by ASE Americas, involves the pulling of crystalline silicon tubes from growth furnaces. Si pellets are melted in furnaces at 1,410°C. From the molten material, hollow octagonal tubes are grown to a height exceeding 16 feet before being removed from the furnace and laser-cut to 100 mm squares that are processed to make electrically-active thinner cells. Wire sawing & consequent kerf losses etc. are avoided. Cells are then sealed in a clear encapsulant material, specially developed by ASE Americas, and then assembled into modules. Glass is used as substrate and also as superstrate. 14% module efficiencies were reported in 1998. The efficiency is expected to increase to 17% this year and to 25% by 2010, and the price per watt is expected to come down to $ 1.25/Wp by 2010.

Concentrator technology: Concentrator technology which involves the concentration of sunlight to a point or line focus through an optical interface got its impetus through liberal funding in the U.S. during the oil crises of the early and late '70s. The PV concentrator companies still active include Amonix (cell type m-Si, concentrator factor 260), BP Solarex (m-Si, 30), Daystar (m-Si/Cis, 45), Entech (m-Si, 20), Hitachi (BI, mono facial Si, 2), PVI (m-Si, 9) and Solar Systems (Si, GaAs, 300-500). Amonix is well known for its huge concentrator systems based on a point focus fresnel lens system and on high efficiency silicon cells (26.5% efficiency). Currently 300 kWp of Amonix systems are installed in Arizona (PHOTON International, Jan 2000). It is believed that a niche market for concentrators in the future could arise from the BIPV (Building Integrated PV) sector in countries with higher diffused solar radiation.

Amorphous Silicon (a-Si) is using a p-I-n structure ('p' layer, undoped intrinsic layer and a 'n' layer). This is perhaps one of the oldest of all these film technologies, initially finding use in consumer (including non-PV) applications. The major advantage of a-Si technology is its high absorptivity (40 times more than mono-crystalline Si) and hence the requirement of much less material (one micron or so). A-Si can be deposited on any substrate, such as glass (window glass), stainless steel (4 to 8 mm thickness) or plastics (kapton, polyimides). The biggest disadvantage of a-Si technology is its light-induced degradation (in the first 12 to 16 weeks of its exposure to the sun), called the Staebler - Wronski effect. This 'effect' has been partially overcome by stacking cells (tandem cells) and using very thin 'p' layers or window layers or using micro crystalline 'p/n' layers in the top junction.

Due to the use of less material and the ease of the manufacturing process (deposition is by PECVD generally), a-Si holds the promise of the prices of modules coming down to $1.25/Wp by 2010. Today prices are about $3/Wp. Module efficiencies are expected to increase to 14% by 2010.

Cd-Te Cadmium Telluride offers the best match to the solar spectrum with its band-gap of 1.43eV. It uses a CdS (Cadmium Sulfide) window layer and Cd-Te 'p' layer.
The advantages of the Cd-Te technology are :

a) High absorptivity.
b) Cd-Te sublimes congruently upon heating, liberating Cd & Te in equal amounts (1:1 ratio), the residue remaining stoichiometric Cd-Te. Cd-Te condenses stoichiometrically as long as the

substrate is heated to about 400° Centigrade. Films deposited at lower temperatures (not in stoichiometric ratio) can be heated to create the single phase stoichiometric compound.

c) Because of b) above, it is amenable to many deposition technologies such as closed space sublimation, chemical spraying, screen printing, sputtering, spray pyrolysis, galvanic deposition, CVD, atomic layer epitaxy etc.

d) Module efficiencies which are 6-8% today are expected to increase to 14% by 2010. Prices are expected to come down to $1.25/Wp by 2010.

Copper Indium Diselenide CIS or CIGS, i.e. copper indium gallium diselenide, is another promising thin film technology that uses CdS as a window layer. Sometimes gallium or sulfhur are also added. CIGS cells are self-repairing. They are stable and long-lived. The material probably tends to repair itself because of the natural tendency of copper atoms to distribute themselves evenly and at great speed. They spread into damaged spots and carry out the repair.

Gratzel cell or Dye-sensitized Tio2 cells The Gratzel cell (also referred to as dye-sensitized mono-crystalline TiO_2 or photo-chemical solar cell) is a new type of PV cell, a photochemical device that is based on dye-sensitization of thin (10-20 micro-meter) nano-crystalline films of TiO_2 nano-particles in contact with a non-aqueous liquid electrolyte.

1. Research & Development

Materials and Devices

- Development of crystalline silicon thin film layers and low-cost substrates for deposition of films
- Development of large size solar cells / modules based on crystalline silicon thin films
- Development of multi-junction amorphous silicon solar cells / modules, pilot plant demonstration
- Development of devices based on new materials such as TiO_2, carbon cells etc.
- Improvement in solar cell efficiency to 14-15 percent at commercial level and >20 percent at research level
- Improvement in PV module technology, higher packing density, suitability for solar roofs etc.
- Development of light-weight modules for use in solar lanterns and similar applications

Applications:

- Improvements in system design for PV lighting systems, including development of a new design of electronics used in solar lanterns
- Development of high efficiency invertors, charge controllers and power conditioning units
- Development of spill-proof tabular plate lead acid batteries
- Development of maximum power point trackers
- Development of high efficiency water pumps and motor pumps and water pumping systems
- Development of integrated power conditioning units
- Development of new PV systems
- Reliability and performance studies of technologies and instruments
- Development of solar roof systems and electronics used in solar roof systems

PV Products: Solar lanterns, home lighting systems / solar home systems, street lighting systems, stand alone PV power plants, refrigerators for medicines and vaccines, solar PV water pumping systems for agriculture and related uses, and other applications of PV technology, including new applications.

2. *Investment Opportunities*

- Opportunities exist in all major thrust areas
- Grid interactive SPV power projects of 500 KW capacity: manufacturers of solar cells and modules, industry and private sector, can set up these projects by entering into a suitable power purchase agreement with the SEBs
- Joint ventures with global PV manufacturers
- Setting up manufacturing plants as 100 percent export-oriented units
- Technology transfer for PV module, especially for PV models based on thin film materials

3. *Incentives & Duties*

- 100% accelerated depreciation available in the first year.
- 5 years tax holiday on power projects.

4. *Concessions to Entrepreneurs Belonging to SC/ST, Women, Ex-Servicemen and Handicapped Categories*

i) Exemption from payment of following:
   - Initial Processing and Documentation charges
   - Inspection Fees
   - Legal Charges
   - Expenditure incurred on Nominee Director(s)
   - Front-end Fee @ 1.00%

ii) Concession of 5% in Promoter's contribution

iii) Rebate of 0.50% in Interest Rate for all NRSE schemes of IREDA for projects involving project costs upto Rs. 25.00 lakhs.

5. *Concessions in IREDA'S Lending Norms to Entrepreneurs for Setting Up Projects in North Eastern States, Hilly Areas, Islands Including Estuaries and Desert Areas*

- Concessions in the interest rate @ 2% per annum on all sectors of Renewable Energy Projects (other than Grid connected Projects). Entrepreneurs belonging to the SC/ST/Women/Ex-Servicemen/Handicapped category will be eligible for concessions. Concessions would, however, be subject to the condition that a minimum interest rate @1% p.a. would be chargeable.
- The definition of hilly areas, desert areas, islands etc. would be as notified/announced/declared by way of Gazette/Government Order/Circular/Executive Order/Specific Clarification letter by competent authorities of Central/State Governments/Local Authorities in the prescribed form of IREDA.

V. SOLAR THERMAL

Apart from the solar photovoltaic route, discussed in the previous section, which has been commercially exploited in the low power range, it is possible to obtain power from the solar thermal route. Figure 4 lists the technology options for power generation from solar. Solar thermal options involve using solar radiation to heat water or a heat transfer fluid and then operate a power cycle with the fluid. Sukhatme [1,2] reviewed the options for solar thermal power generation and classified the thermodynamic cycles as low (about 100°C maximum temperature), medium (up to 400°C) and high temperature cycles (above 400°C). One option for the low temperature cycles is to install solar flat plate collectors and use an

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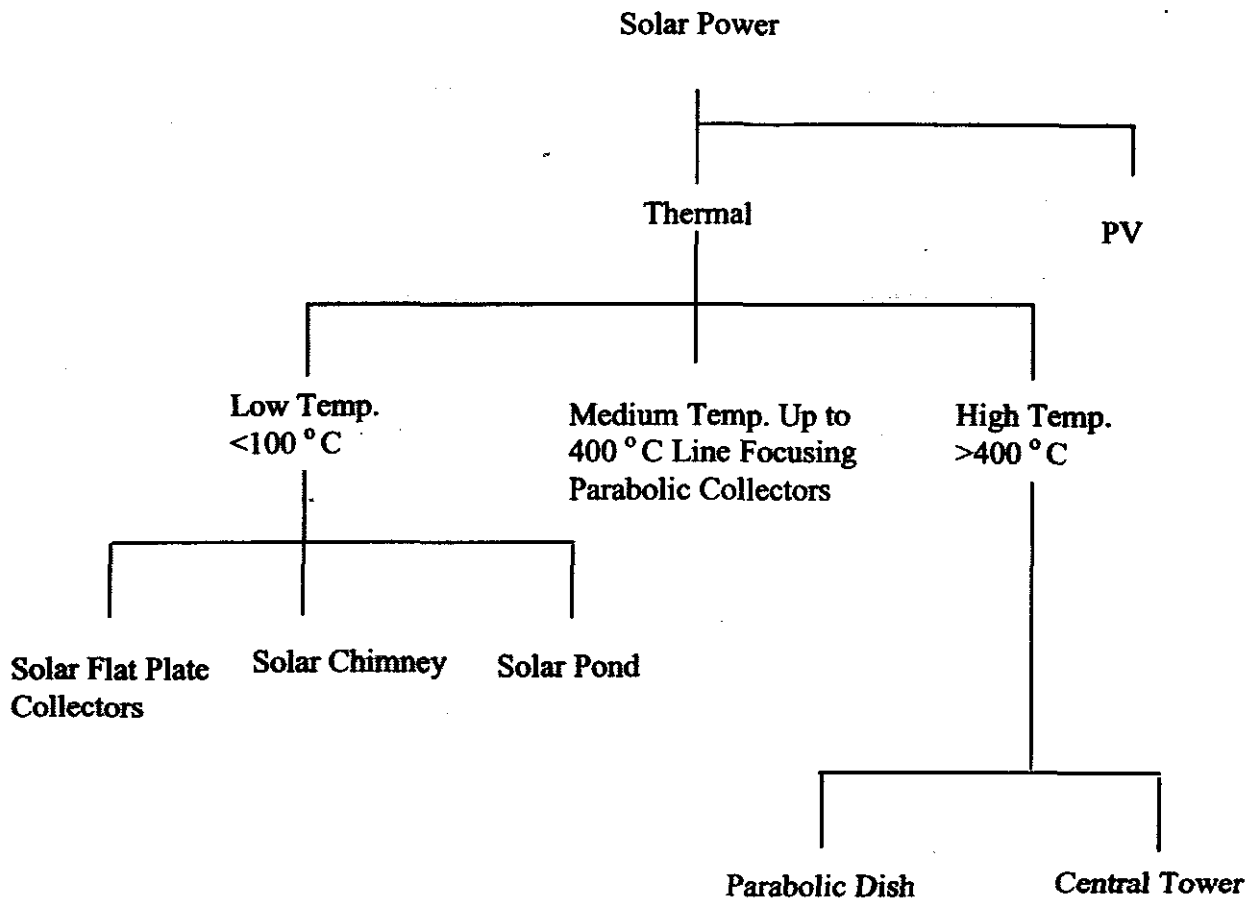
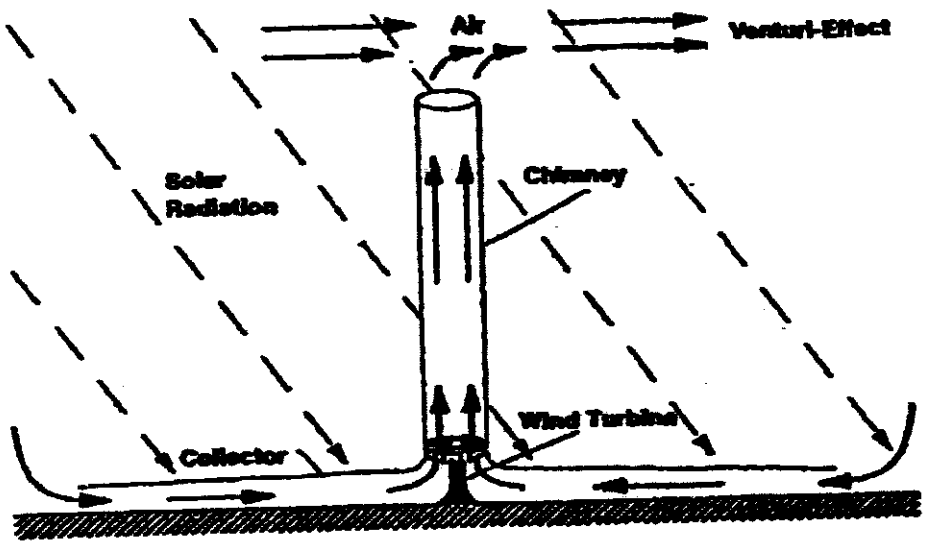
Fig. 4 Technology Options for Solar Power



organic ranking cycle with working fluids like methyl chloride, toluene or refrigerants like R-11. The overall cycle efficiency is low. The high capital cost ($6000 /kW) and the low capacity factor (25-30%) makes this unviable. Two concepts have been proposed in order to reduce the cost - solar ponds and a solar chimney. A 5 MW solar pond based power plant was set up in 1984 in Bet Ha Arava in Israel with an area of 250,000 m^2 (50,000 m^2/MW). Though this has been shown to be technically viable, it is not a commercial technology. In India there has been some experience with solar ponds for thermal applications (hot water for a dairy) operated by TERI in Bhuj, but there has been no attempt to use a solar pond for power generation.

An alternative concept that has been demonstrated is a solar chimney power plant [3,4]. In the solar chimney plant, a transparent cover glazing is provided over a circular area around a tall chimney (Figure 5). This glazing is maintained above the ground by a metal frame. The air trapped in the enclosed circular area gets heated and a natural convection system gets established with the hot air getting drawn up through the chimney. This hot air is replaced by fresh air from the edges of the circular glazing. A solar chimney plant of 50 kW capacity was built in Spain in 1983 with a 195m high, 10.3m diameter chimney and a glazing 2m above the ground covering a radius of 126m[1,2]. A solar chimney plant with a 1km

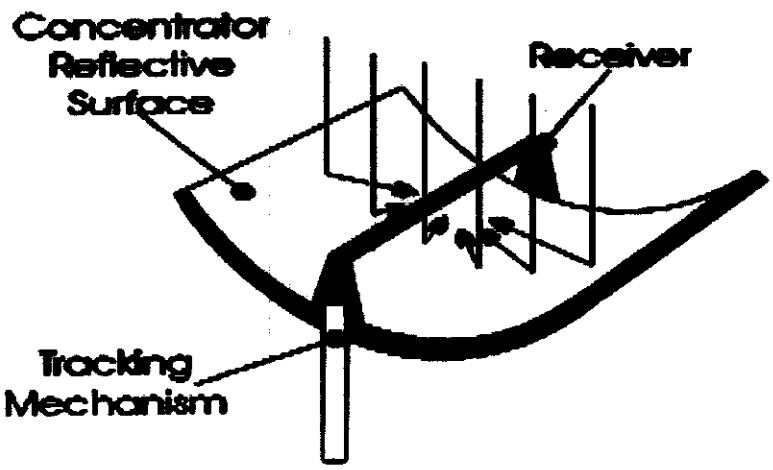
Fig.5 Schematic of Solar Chimney[4]



chimney and 100 million m^2 of collector area generating 200 MW was planned in Rajasthan [3]. However, the project idea has not been pursued. The cost is estimated at $4,600/kW. Though it has been estimated that this system might have the lowest life cycle energy cost [4], this is not yet commercially available. Since 1983, no new plants using the solar chimney concept have been set up in the world.

Of the solar thermal technologies, the maximum experience, globally, is with the line focussing parabolic trough technology. These are medium temperature systems. Figure 6 shows a schematic of a parabolic concentrator. The parabolic concentrators focus the solar energy on the working fluid (synthetic heat transfer oil) that is heated to a temperature of 400°C. This is used to generate superheated steam that drives a conventional Rankine cycle. This is the only solar thermal power technology that is commercially

Fig 6 Schematic of a Parabolic Concentrator



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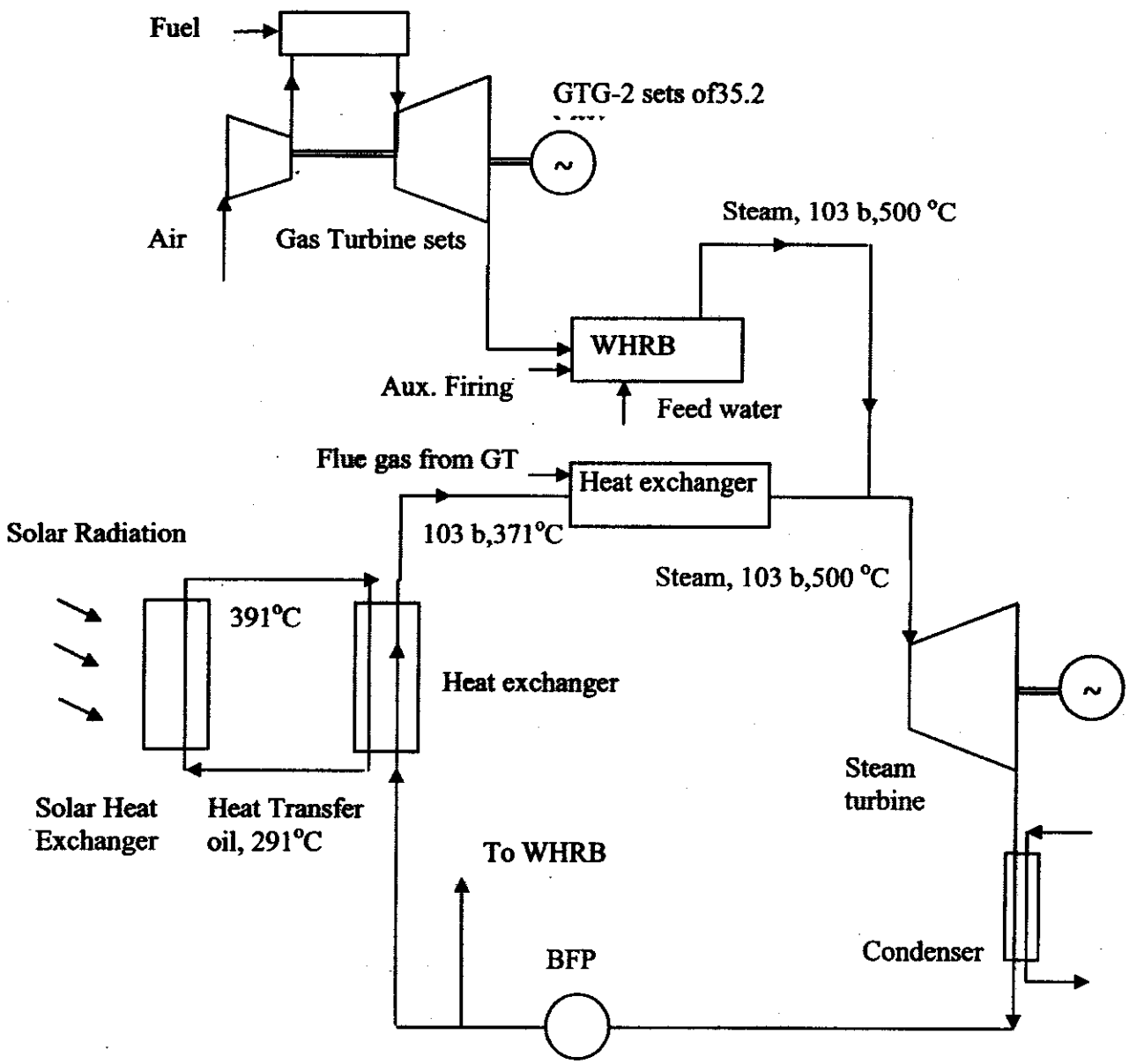
available with 354 MW (9 plants) of grid connected power plants in operation in California. The plant ratings vary from 4 to 80 MW. The collector area for the 80 MW plant is 464,340 m^2 (5,800 m^2 /MW). The cost for the 80 MW plant is estimated to be $2,900/kW.

A 50 kW solar power plant has been in operation in the Solar Energy Centre at Gurgaon. Due to maintenance problems, the unit has been derated.

A 35 MW solar power plant in an Integrated Solar Combined Cycle (ISCC) plant of 140 MW is planned in Mathania, Rajasthan with GEF funding. Figure 7 shows a schematic of the proposed ISCC plant. The total collector area is about 219,000 m^2 . The parabolic collectors heat a heat transfer fluid to 391°C. This fluid is used to generate steam (103 bar, 371° C) in a heat exchanger. This steam is superheated to 500°C

Fig.7 Schematic of the Proposed ISCC Plant



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using the heat available from the b- bar exhaust of a gas turbine. Two gas turbines of about 35 MW each will be operated with naphtha as fuel. The exhaust gases generate steam at 103 bar 500°C in waste heat recovery boilers that have an option for supplementary firing. The steam from the waste heat recovery boilers and the solar supplied steam are used to drive a condensing steam turbine of 75 MW rating. The total capital cost of the plant is Rs 872 crores ($245 million). The Global Environmental Facility is providing $45 million toward incremental costs. The total ISCC cost works out to Rs 62,000/kW. However the incremental cost for the solar component is likely to be about Rs 90,000/kW. The advantage of combining the solar power plant with the combined cycle gas turbine plant is the ability to function as a dispatchable power plant without any storage requirement.

The highest efficiencies possible for solar power plants are with concentration using the paraboloid dish or the solar tower concept. Figures 8a and 8b show schematics of the paraboloid dish and the central receiver plants. In the paraboloid dish the concentrator tracks the sun by rotating about two axes and the solar radiation is focused on the receiver (point focus). The heat absorbed in the receiver is used to drive a prime mover, normally a Stirling engine. The efficiencies are the highest obtained in the solar thermal route- around 29%. Systems of rating 8-50 kW have been developed internationally. A 20 kW experimental unit near Hyderabad has been installed and an additional demonstration 10 kW plant is being installed at Vellore. These are both based on imported technology.

In the central tower power plant the solar radiation is reflected from arrays of large mirrors (heliostats) and focussed on a receiver located at the top of a tower. A 10 MW solar tower plant (Solar One) was installed at Barstow, California and operated from 1992 to 1998. This had 1,818 heliostats of 39.3 m^2 reflective area each. Solar One was converted to a molten salt transfer system using a mixture of sodium and potassium nitrate. Since solar radiation is only available for 5-6 hours in a day, storage systems are also required. The central tower is a costly concept ($4,700/kW), but continues to be explored since the molten salt receiver acts as a storage facility and the system can have high capacity factors. Table 9 shows a comparison of Solar Thermal Power Generation Technologies.

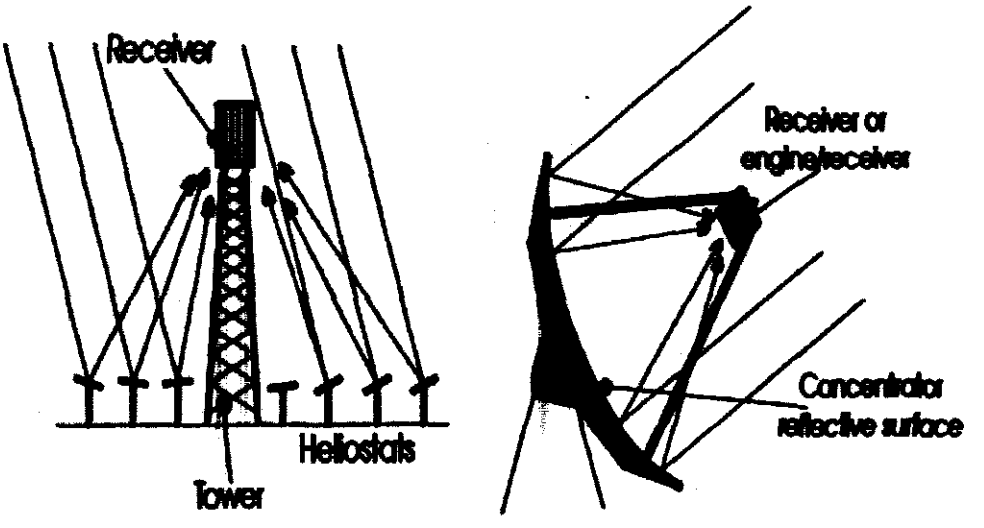

Fig. 8 (a) Central receiver (b) Paraboloid dish [7]

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Table 9. Comparison of Solar Thermal Power Generation Technologies

Solar Flat Plate Collectors	2%	10 kW exptl unit at IITM	D	Rs 300,000	———
Solar Chimney	1%	No experience 50 kW Spain	D	Rs 200,000 ($4600/kW)	———
Solar Pond	1-2%	Experience for hot water Bhuj (Israel 5 MW power)	D		
Line focussing Parabolic	Peak 20% Average 11-14%	50 kW system in SEC installed Planned 35MW solar in 140 MW ISCC at Mathania	C	Rs 140,000 ($3000/kW) ~ 390 MW of operating plants	15 c/kWh Rs 6/kWh
Paraboloid Dish	29% peak 12-18%	Demo unit 20 kW near Hyderabad 10 kW Vellore	D	Rs 150,000	
Central Tower	23% peak 7-14%	No experience	D	~Rs 200,000 ($4700/kW)	

D- Demonstration
C- Commercially available technology
Data Sources [2-6]

VI. BIOMASS

Fuelwood, agricultural residues (rice husk, sugarcane trash, coconut shells) and animal waste are the main biomass fuels. The advantage of biomass fuels is that they are available throughout the country. Different biomass sources are available in different regions. Biomass accounts for about 40% of India's primary energy use [8]– mainly fuelwood (about 20%), crop residues and cattle dung. The present biomass usage is mainly for cooking in chulhas (cookstoves) with poor efficiency.

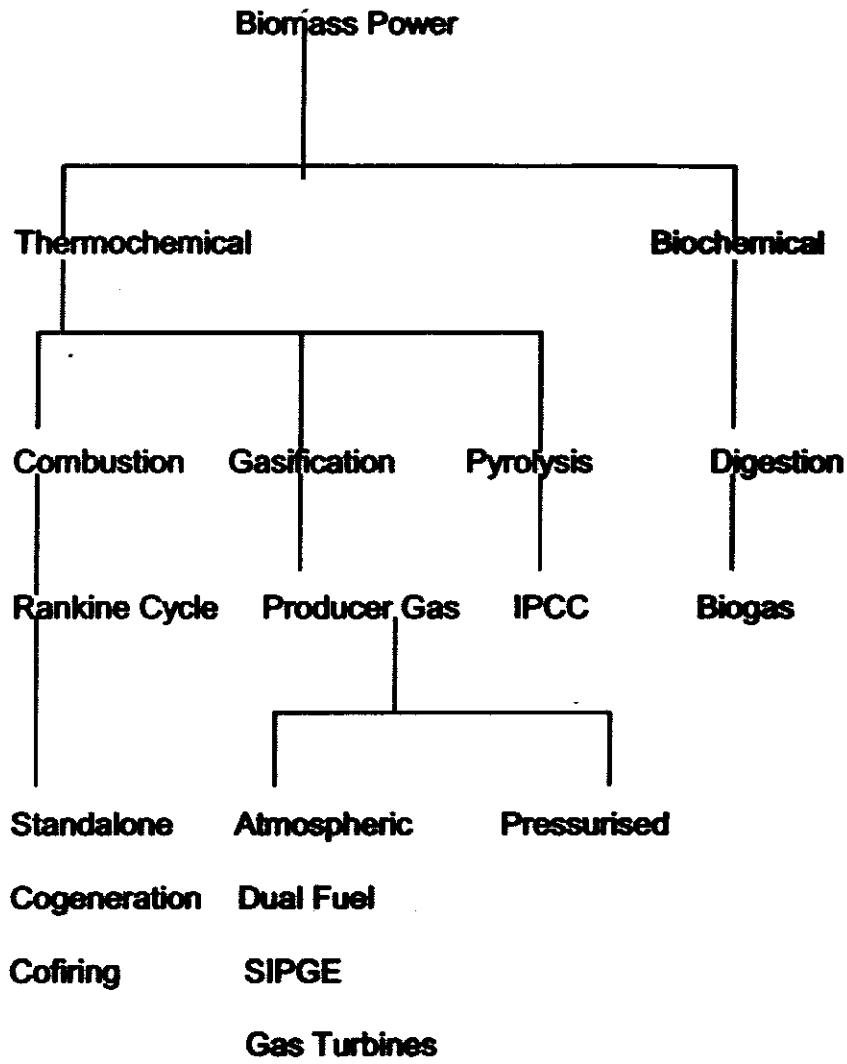
Aggregate estimates of biomass availability can be made from the crop production data and the residue to product ratio. Using this approach, Mukunda[9] estimated the biomass produced in India in 1997-8 to be 545 million tons. Of this, about 150 million tons is expected to be available for power generation. This is estimated to be made up of 23% rice straw, 18% wheat straw, 16% other straw, 15% bagasse and 12% plant stalks. These residues are estimated to have a generation capacity of 16,000 to 18,000 MW with a plant load factor of 68.5% (6,000 hours per year). The MNES estimates a potential of 3,500 MW from Bagasse-based power generation and an additional 16,000 MW from other biomass that is already available [10].

In addition to residues that are available, it is possible to have dedicated plantations on waste land or degraded lands that are not normally used for agriculture. In social forestry programs, sustainable yields of 7-8 tons/hectare/year have been achieved [11]. The waste land available in the country has been estimated to be from 66-130 million hectares [9]. Using an average productivity of 5 tons/hectare/year

and 100 million hectares of waste land the total biomass available annually is 500 million tons, which can fuel power generation of 60,000 MW at a PLF of 68.5% (6,000 hours/year).

Biomass-based power generation can have higher capacity factors than solar or wind. Figure 9 lists the different options for power generation from biomass. The conversion options are thermochemical or biochemical. The thermochemical processes involve combustion, gasification or pyrolysis. The calorific value of biomass (on a dry basis) typically ranges around 3,000-3,500 kcal/kg.

Fig 9. Technology Routes for Biomass Power



A. Combustion

The most commonly used route is combustion (thermochemical). The cycle used is the conventional Rankine cycle, with biomass being burnt in the boiler to generate steam which is expanded through turbines to generate work output. The biomass power plants account for 63 MW of existing capacity (15 projects). The average rating of the power plants is 4 MW. This includes a 6 MW rice husk based power plant in Andhra Pradesh. A 5 MW project in Madhya Pradesh with rice husk as the fuel uses an atmospheric fluidized boiler operating at 65 at 485° C. A 12 MW multi-fuel biomass power plant has

been set up in Tamil Nadu [10,12]. Five grid connected projects accounting for a total capacity of 24 MW were commissioned during 2000-2001. An additional 29 projects with a total capacity of 135 MW are under implementation (average project capacity of 4.6 MW).

The net power cycle efficiencies that can be achieved are about 23-25%[5]. Most of the boilers used are of the spreader stoker (moving grate) type. The boiler efficiency is expected to be around 70%. The use of a biomass dryer is likely to help improve the boiler efficiency. The advantage of the combustion route is that the technology used is similar to that of a thermal plant based on coal, except the boiler. In order for this technology to be economically viable, it is necessary to have larger plants (5 MW and higher). This will require biomass collection and transport over a larger geographical area. It is preferable to link these power plants with dedicated biomass plantations. A 5 MW power plant operating for 6,000 hours per year would require a biomass plantation spread over 7,500 hectares (with an average yield of 5 tons/hectare). The actual generation from these plants and their operating experience needs to be reported to help decide future policies. The capital cost is expected to be about 1,500$/kW (Rs 60,000 -70,000/kW).

Technologies are commercially available with Indian manufacturers like BHEL, Thermax, Triveni.

B. Biomass Cofiring

Cofiring of biomass along with coal in thermal power plants is another option which has been adopted in some European countries and the US. This has not been tried in Indian coal plants. This has been developed by utilities as a response to portfolio standards and developing markets for green power. Cofiring results in reduced greenhouse gas emissions (since biomass is almost carbon neutral) and reduced local NOx and SOx emissions. Reviews by Tillman [13] and Hughes [14] provide an overview of cofiring experience in the US, in terms of economics and policy.

Biomass cofiring tests have been carried out in the US in coal power plants of rating between 32 and 700 MW. Cofiring has been attempted for both pulverized coal and cyclone boilers. The biomass used in cofiring has been wood /sawdust. Tests show that cofiring at a level of 7-10% (by heat input) results in a drop in boiler efficiency by 0.3-1.0%. The Net Station Heat Rate (NSHR) increases with cofiring (by about 1%) for a 10% biomass contribution by heat input. The NSHR for the cofired biomass component [13] works out to 11,000 BTU/kWh (11.6 MJ/kWh), which is 10% higher than the NSHR of coal only operation [10000 BTU/kWh (10.5 MJ/kWh)] . Apart from the deterioration in the heat rate, there is a change in the properties of the ash. It must be ensured that the ash is acceptable as an input to the cement process.

Cofiring can be done by a) blending biomass with coal or b) firing biomass separately. The capital cost of modification is lower for blending ($50-$100/kW of biomass capacity) than for separate biomass firing ($175-$200/kW of biomass capacity). The cost is about Rs 9,000/kW of biomass capacity. This has been found to be the most cost-effective way to increase the biomass share in the power generation mix and reduce carbon dioxide emissions. Cofiring does not increase system capacity. Hence, the capital cost comparisons are not appropriate with new generation facilities. The economics depend on the differential between the coal price and biomass price and are unlikely to justify the incremental capital cost in the absence of any credits due to reduced local and global emissions. It is suggested that a few pilot cofiring experiments could be tried in India to evaluate the economics and gain operating experience.

C. Cogeneration

Cogeneration in sugar factories using bagasse is a viable option. Cogeneration is the simultaneous generation of power (electricity or motive power/shaft work) and process heat (steam). The process steam required in sugar factories is at low pressures - most of the steam is required at 2 ata, a small portion is required at 6 ata. Traditionally, sugar factories have been designed to meet most of their power

requirements during the crushing season from the bagasse itself. All sugar factories already have cogeneration of steam and power. However, the steam generation pressures are low (usually 21 atm absolute [ata]). Figure 10 shows the typical configuration for a 2,500 tons-crushed-per-day (tcd) sugar factory. The mill turbines and power turbines are old and inefficient.

If the steam generation pressures are increased by using a high pressure boiler, the sugar factories can export surplus power to the grid. A large number of options are possible. The following options have been proposed [15]:

a) Replace the milling turbines by efficient electric motors and the power turbine by an efficient back pressure turbine.
b) Increase the generation pressure to 43 ata and steam temperature to 480 °C (new boiler). The milling drives are retained and additional turbine generators are included.
c) Include an additional steam turbine and a high pressure boiler generating steam at 65 ata 480° C
d) In addition to c), replace the milling turbines by an efficient back pressure turbine
e) Similar to d) but with a condensing extraction turbine.

A schematic of the configuration for (e) is shown in Figure 11. The power output in each of the cases is given in Table 10. In case e), the power available for export is a maximum of 9.5 MW for a 2,500 tcd plant.

Other estimates [16] indicate that the power export potential ranges from 60-80 kWh/ton of cane crushed and can be increased to 100 kWh/ton of cane crushed with efficient condensing extraction turbines. This is similar to the range shown in Table 10. The average steam consumption per kWh is 10-12 kg, as compared to 7-9 kg of steam/kWh in sugar factories in Hawaii[16]. Energy efficiency options to reduce the steam requirement can increase the power export by an additional 20-30 kWh/ton crushed [16,17].

MNES estimates indicate a potential of 3,500 MW net (additional) exportable capacity from the Indian sugar factories. Thirty four bagasse - based cogeneration projects aggregating 210 MW have been commissioned until March 2001. The average export capacity of these plants is 6 MW per plant. The projects implemented have been with steam conditions of 60 ata (although some are lower). New cogeneration projects designed with steam conditions of 87 ata and 515 °C are being implemented [10]. There are proposals to have cogeneration plants with higher pressures of 105 ata in Maharashtra and Karnataka. The gross calorific value of bagasse (mill wet basis) is 2,300 kcal/kg [16]. None of the sugar factories in India have installed bagasse dryers. Bagasse dryers would improve the efficiency of the cogeneration plants.

Bagasse-based cogeneration has the problem that the mill operates only during the crushing season (7-9 months a year). Bagasse can be supplemented using other biomass fuels such as cane trash and rice hulls so that there is power export throughout the year. An Advanced Bagasse Cogeneration project component in an USAID-sponsored pilot phase of the Greenhouse Emissions Prevention project [16] focussed on the use of alternative fuels in sugar factories during the off-season.

There are about 430 sugar mills in India. In terms of equivalent 2,500 tpd mills, about 360 were in operation during 1996-97 [16]. Based on the option discussed earlier (case-e), this would result in an exportable power output of about 3,500 MW. Sugarcane production has been increasing at a rate of 3-5% per year. Hence, the cogeneration potential can be expected to increase at this rate. The capital cost of the plant is around $450/kW of output or $650/kW of exportable surplus. This works out to around Rs 30,000 per kW of surplus power, which is cheaper than setting up a new fossil fuel power plant. The incremental fuel cost is low and depends on the alternate use of the bagasse. The total cost of electricity supply is likely to be about Rs 2-3 /kWh .

Fig. 10 Schematic of a Typical existing Cogeneration Configuration in a 2500 tcd Sugar Factory [15]

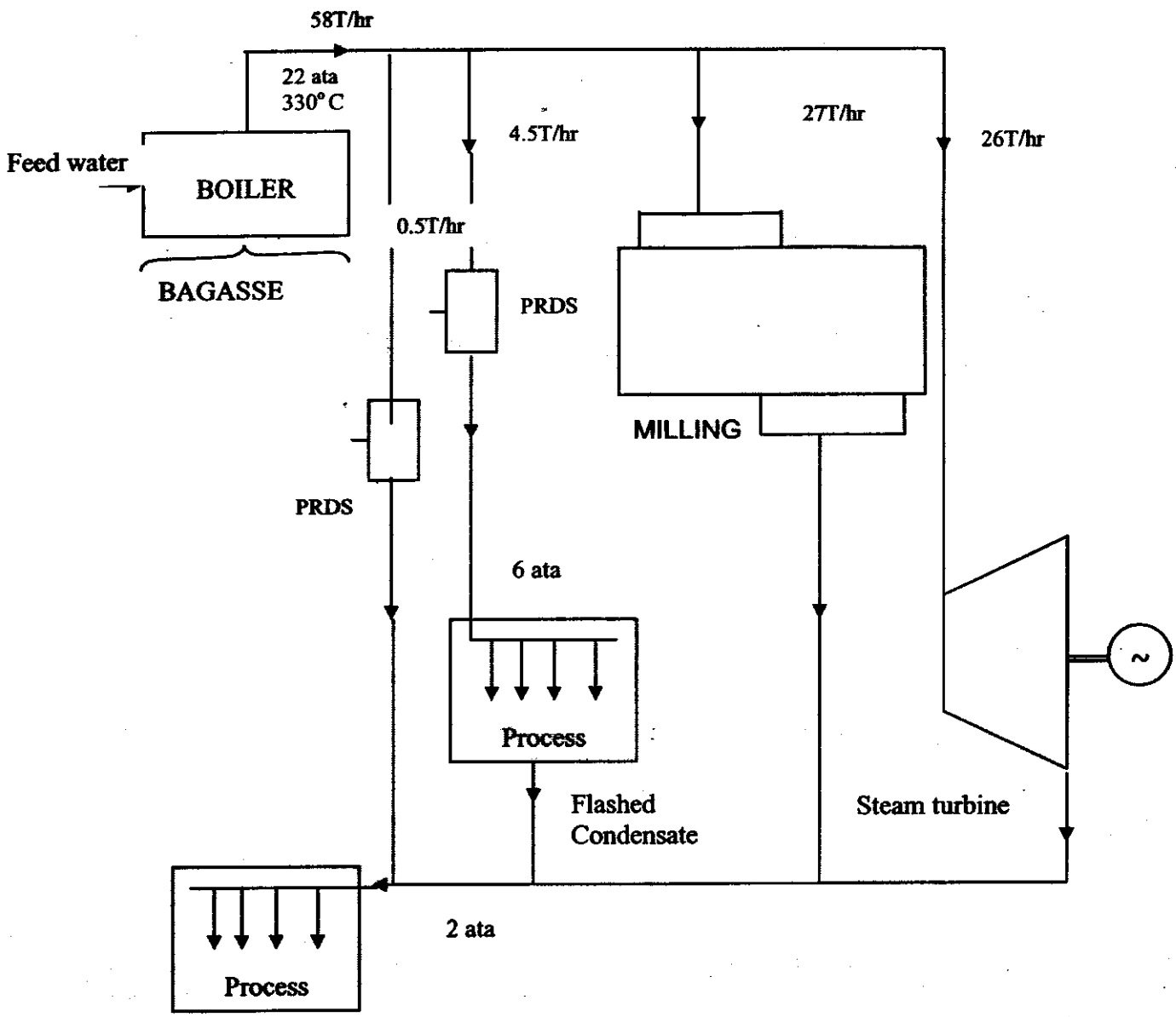


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Fig. 11 Schematic of Option (e) for a 2500 tcd Sugar Factory [15]

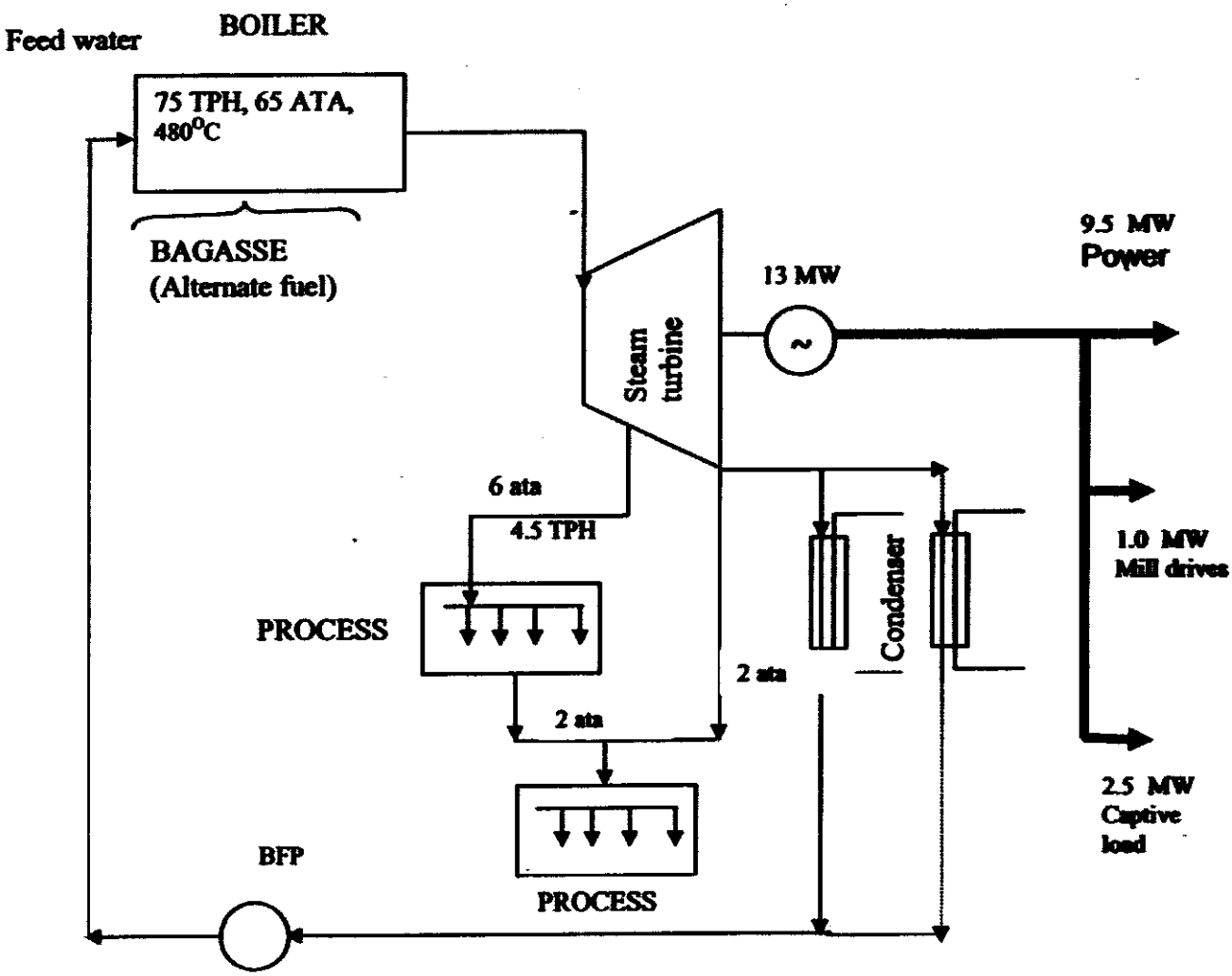

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Table 10 Comparison of Different Options for a 2500 tcd Plant.

A	5.4 MW	1.9 MW	18
B	7.5 MW + milling	5.0 MW	48
C	6.8 MW + milling	4.3 MW	41
D	10.7 MW	7.2 MW	69
E	13 MW	9.5 MW	91

Source [15]

MNES provides an interest subsidy on term loans for cogeneration in sugar. The interest rate reduction is 3% for 80 ata and above, 2% for 60-80 ata and 1% for 40-60 ata. Most state governments have announced policies that fix buy back rates, permit wheeling and banking [10]. To encourage co-generation in cooperative and public sector mills, a joint venture/ Independent Power Producer model has been proposed by MNES in the major sugar-producing states. Capital subsidies are available for the first projects of these types in each state.

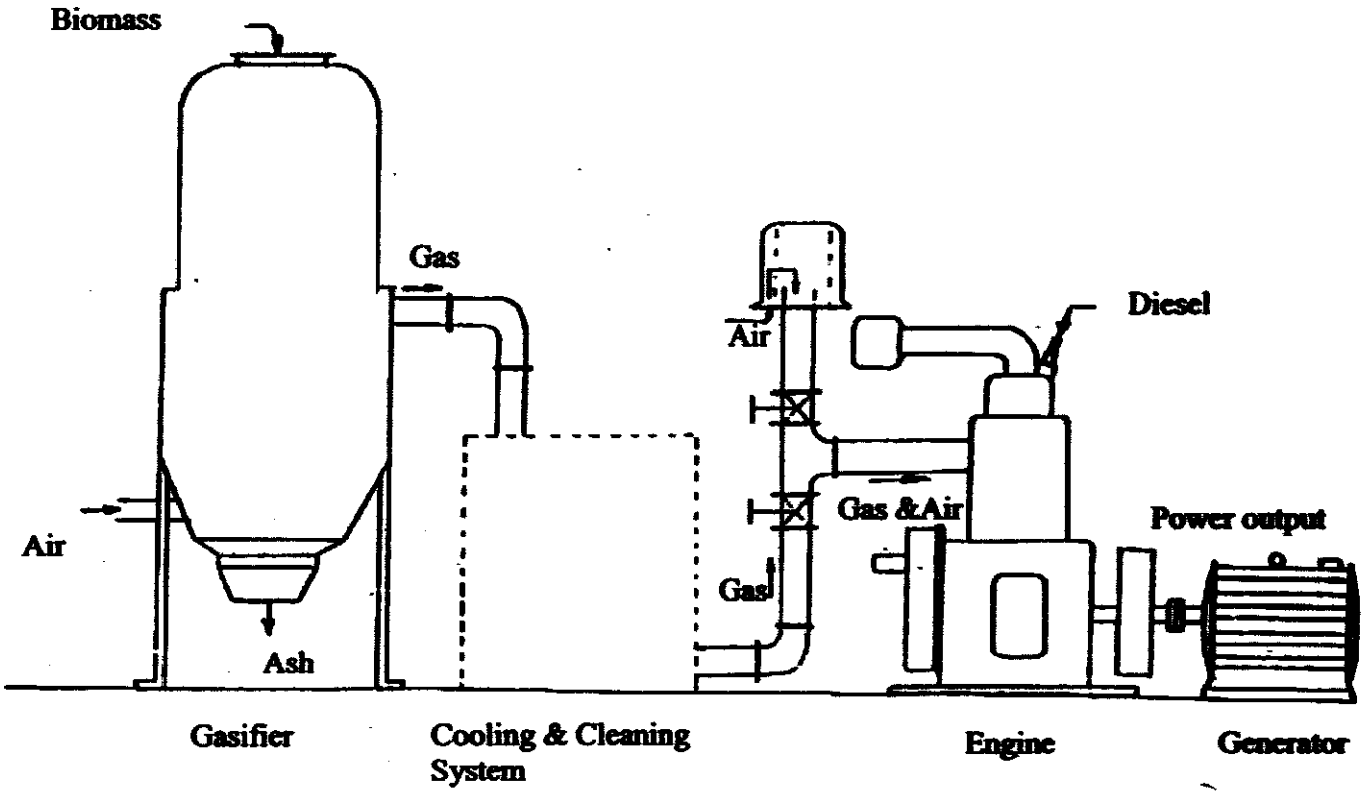
Many of the sugar factories are in the cooperative sector. They are traditional industries with limited technical capability. Often the sugar factory does not have the confidence to operate high-pressure steam-based power plants. The capital investments are significant, about Rs 300 million for a 2,500 tcd plant, and the sugar factories are hesitant to make these investments. At present boilers and turbines are available in India from suppliers like BHEL, Thermax, ISGEC, and Triveni. Grid interconnection and recovery of dues from the State Electricity Board is a problem. As an example, in Maharashtra, the Maharashtra State Electricity Board (MSEB) is reluctant to sign fresh Power Purchase agreements with sugar cogenerators in the context of the Dabhol Power Corporation controversy and the MSEB financial situation. There are also difficulties in obtaining off-season fuel that will permit all year operation.

D. Biomass Gasification

Instead of combustion, it is possible to convert the biomass into producer gas by gasification (partial combustion). Thermochemical gasification involves burning the biomass with insufficient air so that complete combustion doesn't occur but a gaseous product is obtained. Producer gas is a mixture of carbon monoxide and hydrogen. Gasifiers are classified as updraft or downdraft, depending on the direction of flow of the biomass and the producer gas. In a downdraft gasifier the biomass and the gases flow in the same direction (downwards). These are also known as co-current gasifiers. Updraft gasifiers have the product gas flow countercurrent to the biomass flow. Figure 12 shows a schematic of a downdraft gasifier [18]. Gasification can also be classified based on the medium used as air, oxygen or hydrogen gasification. These gasifiers are also known as fixed bed gasifiers and operate at atmospheric pressures. Moving bed and fluidized bed gasifiers are other technology options. The updraft gasifier is more efficient than the downdraft gasifier, but the producer gas has a greater amount of tar and particulates that might create problems in the engine operation. Updraft gasifiers are preferable for thermal applications.

In a typical downdraft gasifier, the biomass is fed from the top. It passes through the gasifier and undergoes the following sequence of processes: drying, pyrolysis, oxidation and reduction. These processes are controlled by the zone temperatures. A controlled amount of air is passed through the tuyeres at the oxidation zone. The gas formed is passed through a cooling and cleaning sub-system that usually consists of a cyclone for particulate removal and a scrubber for cooling and cleaning the gas (removing the tar). Some ash is formed from the oxidation reactions. The ash moves through the

Fig.12 Schematic Diagram of Gasifier –Engine System [18]



reduction zone and gets removed from the ash disposal system (grate and ash collection system). The typical composition of producer gas is 20-22% CO, 15-18% H_2, 2-4% CH_4, 9-11% CO_2 and 50-53% N_2 (by volume). This is a low calorific value fuel with a calorific value of 1000-1200 kcal/Nm^3. This is primarily due to the presence of (compression-ignition) in a duel fuel mode. The typical gasification efficiency obtained is about 70%. Diesel replacements of up to 70-75% have been reported.

India has significant experience in atmospheric fixed bed gasifiers. About 1,700 gasifiers have been installed, with a total installed capacity of 34 MW. The average gasifier size is 20 kW. Biomass gasifiers were initially developed for diesel replacement in agricultural pumpsets. Gasifier models were indigenously developed around 1986. During the initial years of the National Demonstration Programme (1986-1994), the emphasis was on agricultural pumpsets of 5 and 10 hp rating. A feature of this program was heavy subsidies on gasifiers, pump-sets and diesel engines. It is estimated that the majority of installations (80%) during this phase become inoperative within one to three years of the system installation[19]. Target beneficiaries took little interest in the program and reverted back to full diesel operation, after the initial few hundred hours of operation. Subsidies were misused to obtain a diesel engine pump-set at a cheaper rate. Despite this, there was important technology demonstration experience obtained in the installations that continued to operate with gasifiers.

Since 1994, the Government policy was changed, with subsidies being reduced. Subsidies were now restricted only to the gasifier. This initially resulted in a drop in the number of annual installations, but the program is now more market-oriented. A large proportion of installations are now from interested beneficiaries.

Biomass gasifiers typically have been developed either for wood or for rice-husk. Other fuels that have been used are cotton stalks, coconut shells, saw dust, palm shells, and corn cobs. Installations range from 3 - 500 kW capacity. The biomass input required ranges from 5-500kg/hour for electrical outputs ranging from 5-500 kW. The largest installation size is 500 kW in Gujarat that is being connected to the grid. A 500 kW (5×100 kW) rural electrification system has been installed at Gosaba in Sunderbans (West Bengal). A 100 kW rice husk based gasifier has been installed in a rice mill in Andhra Pradesh. Almost all gasifier systems installed are stand-alone. Most installations use diesel engines in the dual fuel mode. The economics of a gasifier power plant depend on the load factor, extent of diesel substitution, price of diesel and biomass. There are a number of manufacturers: Ankur Scientific (Ascent, Baroda), Netpro, Cosmos (Raipur), AEW and Tanaku. Four Gasifier Action Research Centers have been established at the Indian Institute of Technology (IIT) Bombay, Indian Institute of Science (IISc) Bangalore, Indian Institute of Technology (IIT) Delhi and Madurai Kamaraj University (Tamil Nadu) to provide technical support to the gasifier program. Decentralized Energy Systems India (DESI Power) has set up six projects as independent rural power producers (IRPP) in various parts of the country. The first installation was at Orchcha in Madhya Pradesh (100 kW rating – 2 units of 50 kW each). DESI power estimates that a 100 kW IRPP will directly employ 11 persons and create another 56 downstream jobs in new small-scale industries (because of the availability of electricity).

The cost of a biomass gasifier engine system is Rs 45,000- Rs 50,000 per kW of installed capacity. Using a consumer discount rate of 12%, the price of electricity ranges from Rs 3/kWh (at a load factor of 70%) to Rs 4.3/kWh (at a load factor of 30%) for 70% substitution and a diesel price of Rs 16 per liter and biomass price of Rs 1000/tonne. At the higher discount rates that are normally prevalent for companies (30%), the prices increase to Rs 3.7 –5.7/kWh at the respective load factors. The electricity supply price is sensitive to the diesel price and the substitution.

A more viable option is likely to be a dedicated producer gas engine, as there is no diesel cost. There is some experience in IISc Bangalore with a dedicated producer gas engines. There is an inter-university collaborative project funded by the UN foundation with Carnegie Mellon Univ, IISc Bangalore, IIT Bombay, National Aeronautical Laboratory and TERI that is planning to install a dedicated producer gas engine of 100 kW operated using biomass in a milk chilling plant in Karnataka.

The gas turbine route is potentially more efficient, but there is no experience with the Biomass Integrated Gas Turbine Combined Cycle (BIGCC) in India. International experience in BIGCC is limited and the technology is still in the demonstration phase. The BIGCC systems are in the MW range and have higher efficiencies, but are costly and not yet proven. Figure 13 shows a block diagram of the different components of a BIGCC plant. A BIGCC demonstration plant has been set up at Varnamo, Sweden [20] using a circulating fluidized bioler operating at 22 bar. The power plant cogenerates heat and power and is rated to produce 6 MW of electricity and 9 MW of heat. The plant cost was $39 million in 1993. The plant operates on wood powder from forest industry waste and has an electrical efficiency of 32%.

There is a wide variation in cost estimates of the different technological routes for power generation from biomass. Research on conversion of biomass into liquid products by pyrolysis is a relatively new technology which might be worth exploring especially with high biomass prices [21].

E. Biogas

Biogas plants,both family and community sizes, use biochemical digestion by anaerobic bacteria. Biogas has a higher calorific value than the producer and can be directly used in a diesel engine or a dedicated gas engine. Biogas consists of 45-70% methane (CH_4), with the remaining being carbon dioxide (CO_2). Figure 14 shows a schematic of a floating dome biogas plant. The digestor is a well containing the animal waste slurry. The dome floats on the slurry and acts as a gas holder. The spent slurry is sludge

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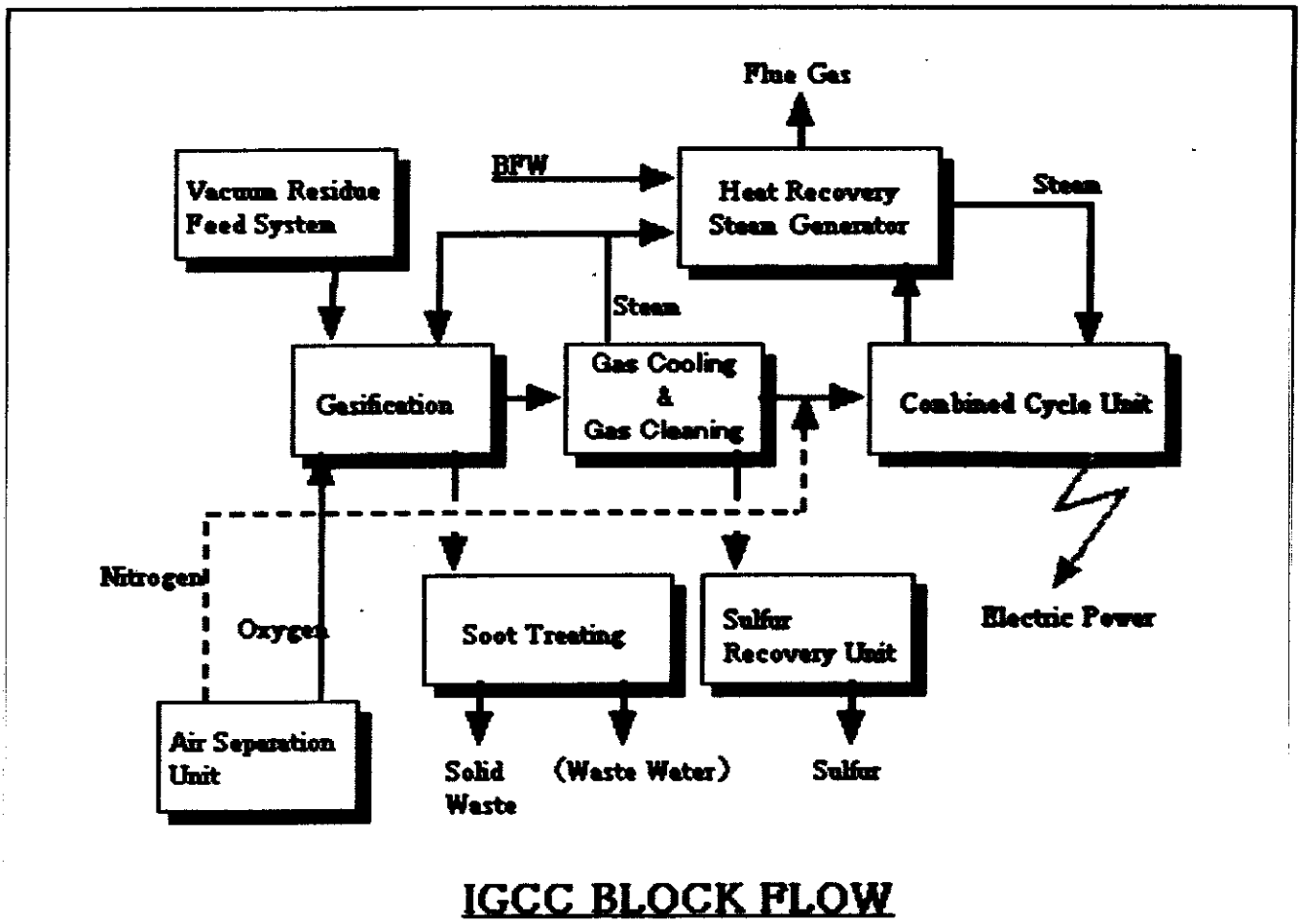
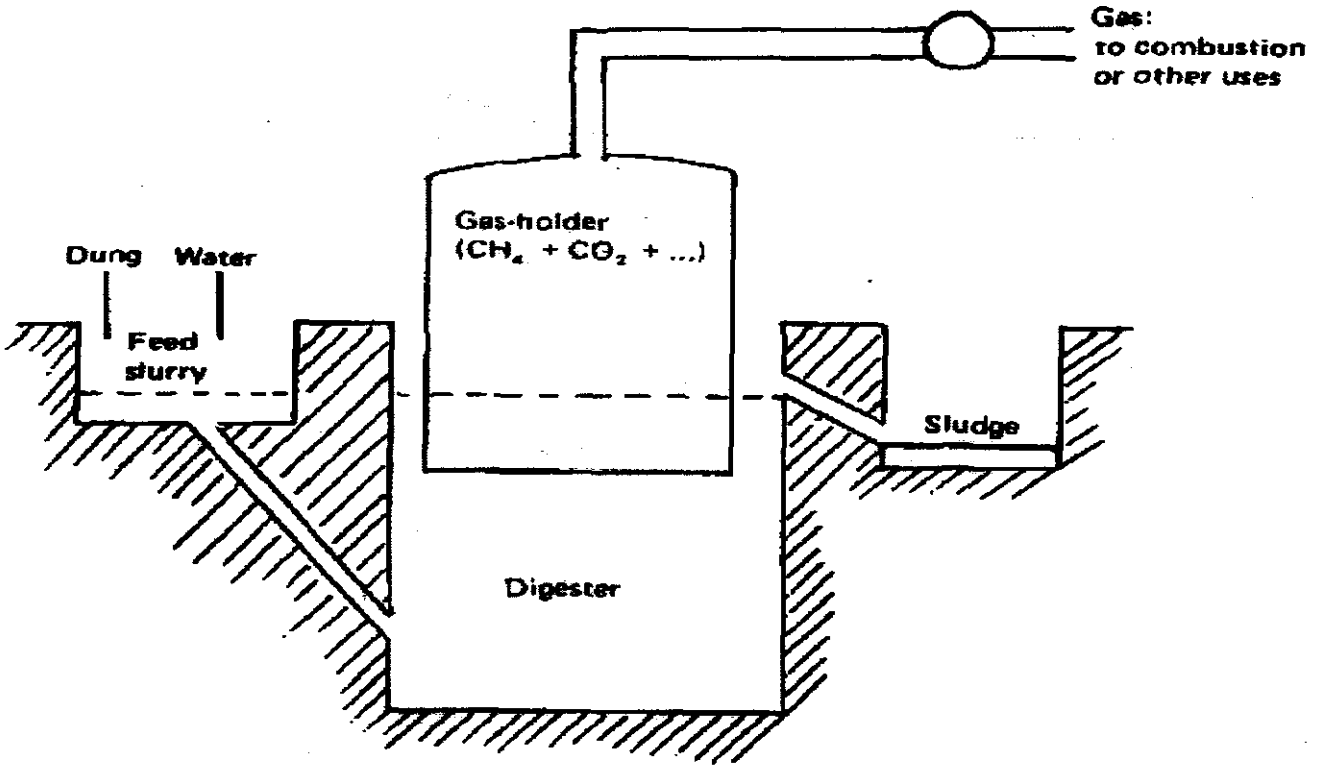
Fig. 13 Schematic of an IGCC Plant



that can be used as a fertiliser. The reaction is anaerobic (in the absence of air) digestion that occurs by bacterial action. Family size plants are typically rated at 2 m^3/day while community biogas plants have ratings of 12-150 m^3/day. A family sized unit needs to have 2-3 stall-fed cattle to supply it. The calorific value of biogas is 16-25 MJ/m^3. The biogas can be used for cooking or can be used as a fuel driving a diesel engine in the dual fuel mode. Indian designs typically have been the floating dome type (Khadi Village Industries Corporation KVIC design). Several modified Chinese designs of fixed gas storage dome design (Deenbandhu type) have also been manufactured because of their low cost. Most Indian biogas plants have been designed to operate on cattle waste (cow dung).

A successful biogas plant case study is the Pura [17, 22] community biogas system that was installed in 1987. The biogas plant is a KVIC type floating drum plant rated at 42 m^3/day. The capital cost of the installed capacity was Rs 31,400/kW (in 1992 prices). The biogas plant operates a 5 kW diesel engine that is connected to a 5 kVA, 440 V three-phase generator for electricity generation. The power generation system operates for 4 hours per day with 77% diesel substitution.

Fig. 14 Schematic of a Floating Drum Biogas Plant [17]



The current capital cost for a biogas plant connected to a diesel engine-generator is estimated to be Rs 50,000-60,000/kW. The cost of electricity depends on the load factor. It is estimated to be Rs 6.5/kWh for 5 hours a day operation. This can reduce to about Rs 4/kWh at load factors of about 70%. Capital subsidies are available for biogas plants from MNES and concessional loans are available from IREDA.

About 3.1 million biogas plants have been installed in India through March 2001. This is about 25% of the estimated potential of 12 million plants. About 3,000 community biogas plants have been installed. Most of these installations are only for heating and lighting.

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CHAPTER 3 CONCLUSIONS

I. RENEWABLE POWER PROJECTIONS

Since renewables are still in the initial stage of development, it is difficult to project future growth profiles accurately. The growth in the last 8 years (1993-2001) has been significant, with annual growth rates of 39%. If a similar growth trend persists for another decade, the 2011 renewable capacity would be 80,000 MW. Is this a realistic future growth rate? Consider the total installed capacity of India – approximately 100,000 MW. If this capacity grows at 7% per year, the total installed capacity in the Indian power sector in 2011 will be 196,700 MW (an increase of 96,700 MW or 9,600 MW capacity addition per year). The estimate for renewable capacity would account for 80% of the new generation capacity. This seems unrealistic since renewables currently account for only 3% of the total installed capacity.

By 2011, if it is planned to have a 10% renewable share, it would imply a total renewable capacity of 19,670 MW, or 20% of the new installed capacity from renewables. Is this feasible? Most of the renewable growth has been from wind and small hydro. The wind potential has been estimated at 45,000 MW. The MNES itself has assumed that the technical potential is about 10,000 MW. The wind capacity addition per year has been an average of 200 MW/year over the last few years. This could be increased to an average of 400 MW/year (annual manufacturing capacity of 500 MW already exists). Hence the final estimate for wind power in 2011 is likely to be between 3,000 and 5,000 MW, depending on the diffusion rate. The small hydro installed capacity is 1,341 MW and the projects under construction account for about 500 MW. The potential for small hydro is estimated at 15,000 MW. The estimate for small hydro in 2011 is 5,000-6,000 MW. These two technologies are currently market-driven, though government policies and incentives can affect the diffusion. The key to achieving the 10% renewable share depends on the growth of biomass-based power generation. The biomass-based cogeneration potential in 2011 would be about 4,700 MW (estimating a 3% growth in the sugar production annually). Since the economics are extremely attractive, it should be possible to tap 40-50% of this potential. This would require significant policy interventions. Hence, the biomass cogeneration target in 2011 is estimated as 1,700-2,300 MW. At present, about 135 MW of biomass combustion power plants are under construction, while 24 MW were added in 2000-2001. Biomass combustion based power plant capacity can be added at an average rate of 50-100 MW/year. This would result in a 2011 estimate ranging between 560 and 1,060 MW. Biomass gasifiers, biogas-based power generation and solar photovoltaic are expected to cater to the requirements for stand-alone dispersed power generation. Official statistics indicate that 18,000 un-electrified villages are remote and will not be feasible to connect to the grid. These are expected to be electrified using renewables. The average population of a village in India is 1,125 (around 200 households). Almost 50% of the total number of villages have a population of less than 500 households per village. The average number of households in the unelectrified villages is likely to be lower than the electrified villages. Assuming an average of 100 households, the installed capacity required would be about 30 kW per village. This would imply a total potential of 540 MW in decentralized power systems. Significant policy interventions and institutional changes would be required to meet this potential. A capacity of 19,700 MW corresponds to an annual growth of 20%, which is about half of the actual growth rate achieved during 1993-2001 (39%).

In addition to the technologies that are proven and available commercially, it is necessary to try out and obtain experience in some of the renewable energy technologies through a series of demonstration projects. A list of technology demonstrations that should be tried in India is provided in the next section.

II. TECHNOLOGY DEMONSTRATIONS

The following technology demonstration projects would be useful for deciding future alternatives:

a) Tidal power plant – 3-5 MW range
b) OTEC – already in progress – 1 MW
c) ISCC- 35 MW – In addition to this, there is a need to develop capability to manufacture parabolic concentrators for steam generation.
d) Biomass gasifier running a gas turbine of about 1 MW range
e) Cofiring of biomass in a coal-based power plant
f) Bagasse dryer installation in a sugar factory with a condensing extraction steam turbine
g) BIGCC for a sugar factory – This would result in a significant increase in the surplus power generation from bagasse. However, the technology needs to be tested at least at a pilot scale for a sugar factory.
h) Biomass gasifier/Biogas based micro-turbine operation
i) Power generation from a large scale municipal waste biogas plant
j) Hybrid Renewable Systems – A combination of one or more renewables with a diesel backup is likely to be a viable option for remote off-grid applications. Demonstration projects for wind-gasifier-diesel, wind-PV systems should provide useful inputs for future renewable systems.

III. POLICIES

A target of 10% renewables by 2011 is not going to happen in a business-as-usual scenario. Several policy changes are required to facilitate this. A few policy issues and directions are discussed here.

a) Externalities – Most renewables have the benefit of being clean, green fuels. They have significantly lower local and global emissions. Fossil fuel based power generation technologies have adverse health impacts due to local emissions of sulfhur dioxide, nitrogen oxides and particulate matter. Studies in Europe have shown that most of the external social costs of energy supply and use are due to the health impacts. There is a need to devise metrics and techniques for incorporating externalities in the social choice of deciding appropriate power generation technologies.

Life Cycle Assessment or fuel cycle analysis techniques can be used to determine the total emissions and impacts associated with a particular option. The need to stabilize and control greenhouse gas emissions globally is providing a new impetus for the development of clean fuels. Table 11 shows the carbon dioxide emissions per kWh of electricity generated by different technologies.

Table 11. Carbon Dioxide Emissions from Power Technologies in g/kWh [1]

960-1300	800-860	690-870	460-1230	9-100	37-166	30-150	2-410	11-75

A life cycle analysis of a biomass gasification combined cycle (BIGCC) plant [2] revealed net carbon dioxide emissions of 46 g/kWh. This consists of 28 g/ kWh associated with the feedstock production, 6 g/kWh with transportation and 12 g/kWh with power plant construction. The net carbon dioxide emissions from this biomass route is only 5% of the carbon dioxide emissions from a conventional coal-based power plant.

b) Monitoring and Verification – In the initial period a lot of the renewable development has been on upfront subsidies and incentives. It is necessary to evaluate the track record of different renewables for power generation in India. There is competition between renewables. Most technology developers and marketers try to overstate the benefits and conceal the problems. It is necessary to have independent monitoring and verification agencies that would do energy and financial audits of the facilities. The information regarding the performance of different renewable power plants needs to be collected and compiled and made publicly available. This is important to convince skeptics and also to get the true picture.

c) Cost Recovery- In the case of rural electrification, recovery of costs is a key issue. The price of electricity from dispersed renewables (isolated) is likely to be high if the load factors are low. The average price can be reduced only if this is linked with some rural industries like cold storages or oil mills. Different models for cost recovery need to be tried. Issues of metering and billing need to be addressed.

d) Utility Mindset- In the case of grid connected systems, the utility attitude toward renewables critically affects their adoption. Indian utilities are facing a crisis of payment. They are hesitant to enter into power purchase agreements with renewable power plants. Even rates regarding wheeling and banking have suddenly been revised in some states. The utility has traditionally been interested only in large power plants. Hence, there is a need to increase the awareness of utilities about renewable power generation and influence attitudes regarding dispersed generation.

e) Change Incentive Structure- It is necessary to devise incentives based on performance. This could be included in the tariff structure.

f) Strategy Think Tank- It is necessary to have a collaboration between the government (MNES, state govts.), industry and academics to evolve appropriate policy interventions, thrust areas and technology development and research plans for renewable power.

g) Manpower Training- The renewable installed capacity is similar to the nuclear capacity. The trained manpower, institutions and research facilities established for nuclear power are significantly better than the renewable field. There is a need to train quality manpower for the renewable power sector.

h) Institutions – A separate joint venture for biomass power generation on the lines of the National Thermal Power Corporation or the Nuclear Power Corporation is likely to help effectively plan and implement new biomass power capacity.

i) Policy Experiments- In the case of rural electrification, there is a need to try out alternative implementation strategies with private, co-operative ownership and different recovery mechanisms. The results from policy experiments in different states should be well documented and critically assessed before deciding on replication models.

India has the potential to tap significant renewable resources. This will need flexible and innovative approaches by policy makers.

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Carbon Mitigation for the Indian Power Sector

CARBON MITIGATION FOR THE INDIAN POWER SECTOR

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I. EXECUTIVE SUMMARY

Power sector mitigation in India covers a wide spectrum of economic, technological, environmental, institutional and socio-political issues. This research paper assesses policies and measures under alternate mitigation scenarios and provides an assessment for the future of the Indian power sector. Results show that power generation capacity increases by 1.5 times in the next 10 years, doubles in the next twenty years and reaches 395 GW in 2035. Some specific insights provided from the research are indicated below.

Coal dominates in the long-term future generation capacity mix, but its use becomes more sustainable with clean coal technology penetration. Gas technologies penetrate fast in the medium term (till 2020), mainly to meet peak load requirements. In this context, the building of a gas supply infrastructure is an important issue. In later periods (beyond 2020), its penetration slows down due to the buildup of large peak reserve capacity in the system. Expectations about improved performance of nuclear plants increase nuclear penetration, but its capacity is restricted due to socio-political and environmental considerations. Despite large hydro being competitive, socio-environmental constraints cause a decline in its capacity share. Among renewable energy options, small hydro, co-generation and biomass technologies are highly competitive and penetrate rapidly. For wind penetration, strengthening of local manufacturing capabilities and push policies to promote investment in wind power projects enhance technology competitiveness. Solar technologies penetrate in the medium-term due to capacity building through demonstration projects that enhance learning experiences, but long-term penetration will depend largely on international lowering of costs.

The Indian power sector has substantial potential for greenhouse gas (GHG) emission mitigation by changes in the energy and technology mix. In the short-term, demand side technologies make a large contribution to emission reduction due to low inertia of technological stock along with improvements in transmission and distribution efficiency. In the medium- and long-term, the supply side contribution increases due to significant shifts in technology mix. Gas and renewable technologies substitute for coal in the medium-term, while in the long-term, there is high penetration of carbon-free technologies like large hydro and nuclear. A hedging strategy, therefore, is to keep the energy and technology mix diverse and flexible.

Electricity supply cost declines due to autonomous technological advancements and better management practices (load management) that lower the peak to off-peak cost ratio from 2.5 to less than 1.5 in next 35 years. Carbon mitigation policies lead to a more substantial rise in electricity costs, especially in the long-term, as compared to local pollution mitigation policies. However, recycling of carbon revenue can bring down electricity costs. Therefore, climate change mitigation policies for the Indian power sector will have to be crafted for their own sake.

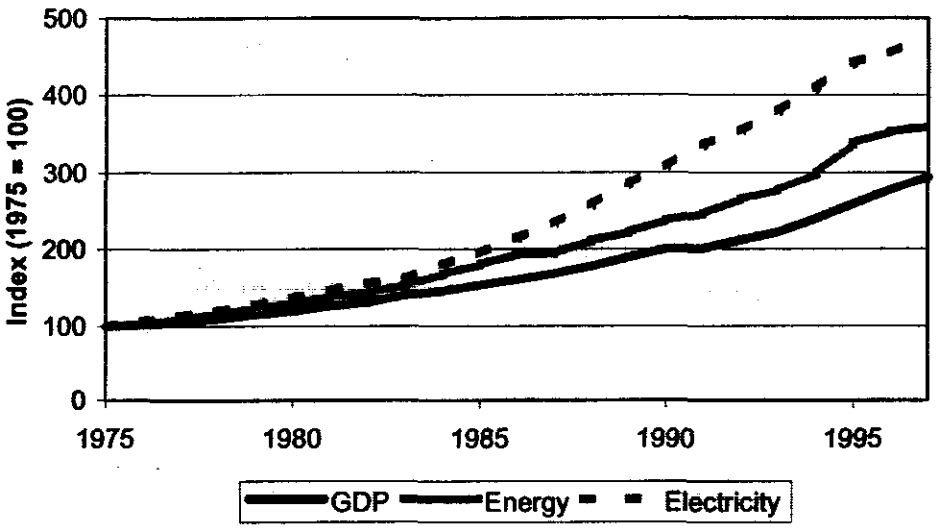
II. CARBON MITIGATION FOR THE INDIAN POWER SECTOR

A. Overview of the Indian Power Sector

The energy consumption in India is rapidly rising due to growing industrialization, rising incomes, expanding urbanization, and modernization of agriculture. The most notable increase has been in the

electricity sector, where consumption has doubled over the last decade (CMIE, 2000). In the past two decades, electricity consumption has grown at a rate higher than the GDP and energy (Figure 1), and this trend has become remarkably pronounced in the present decade. Electricity demand, growing at 8.7% annually during the present decade, has outstripped the economic growth rate of 6.2% (Economic Survey, 1990-2000). Electricity consumption per person, which was 90 kWh in 1972, increased to almost 400 kWh in 2000 (TEDDY, 2000). However, on a global scale, this is still very low, six times below the global average, 5% of that in the U.S.A., and nearly a half of that in China (WRI, 2000).

Figure 1. Growth of Energy, Electricity, Emissions and the Indian Economy



Source: Government of India, Ministry of Finance. *Economic Survey (1990-1998).*

1. Growth Trends in Capacity and Generation

Growth in power generation capacity (figure 2), which increased by almost sevenfold between 1970 and 2000, was accompanied by a greater diversity of technology mix (CMIE, 1990 to 2000). The present capacity mix (2000) includes a substantial share of coal (61%) and a significant but declining share of large hydro (24%). Almost all the coal plants use sub-critical pulverized coal technology. Gas-based power, which has come up mainly during the nineties, has gained an 8% share. Nuclear power has a 2% share and renewables around 1.5%. In the last decade, generation capacity grew at 4.4% annually, whereas electricity generation has grown at 7%, due to improved plant utilization (CMIE, 2000). There has been a decline in the hydro-thermal ratio for power generation. Thermal power's share expanded, due to a shorter lead time relative to hydro plants, increasing opposition to large hydro projects on social and environmental grounds and higher political risks of hydro projects due to inter-state disputes on power and water sharing. This has added to the peak power problem. India has a hydro potential of 84 GW and only about one third of it has been exploited so far (CEA, 1997).

Gas-fired power has grown from almost nothing to one-twelfth of the total power generation in the last decade (CMIE, 2000) due to the low risk associated with lower capital requirements, shorter construction periods and higher efficiencies. Compared to the use of coal for power generation, gas use has much lower environmental impacts. With an increase in private participation in the power sector, plants are being built in coastal areas near ports with terminals capable of handling liquefied natural gas (LNG). However, inland use of imported LNG remains expensive compared to coal, so natural gas is competitive in

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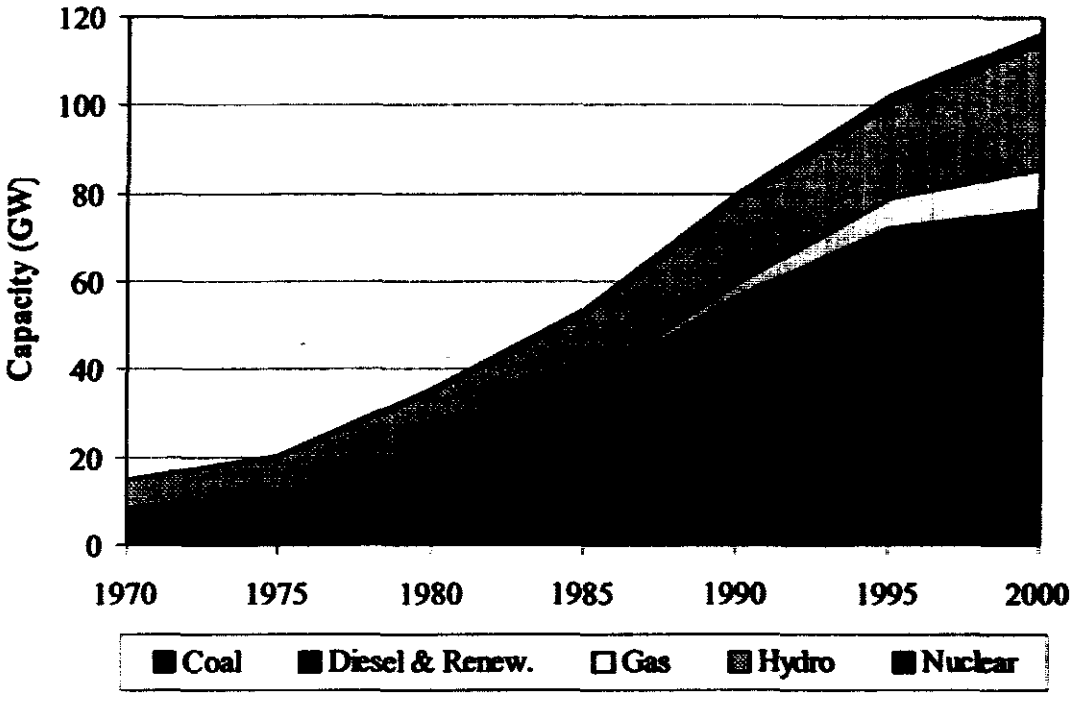
these regions only if transported by pipeline directly from the production field. Nuclear power contributes less than 3% to total generation, from India's ten nuclear reactors. There has been a considerable improvement in the capacity factor of these plants during the last five years and they now operate above 80%, as compared to 60% earlier (http://www.npcil.org). Renewables presently have a small share in the capacity. However, India has a significant program to support renewable power, targeting 12 GW by 2010 (http://mnes.nic.in).

Figure 2. Power Generation Capacity



2. *Energy Consumption*

Electricity generation has the largest share of the primary energy consumption in the country, with 40% of primary energy and 70% of coal use (CMIE, 1999). Despite enhanced competition from other fuels, coal remains the mainstay of power generation. Domestic availability helps coal to retain a competitive advantage over imported fuels that have associated risks in the long run from fuel security and exchange rate uncertainties. A sizable infrastructure of mining and manufacturing industries and transport has evolved around coal-based power. Lately, however, certain factors have influenced the investment in power generation to shift to other fuels. The slow additions to domestic coal mining capacity, inadequate coal transportation linkages, relaxation of fuel imports and investments by international power companies who import to meet their own fuel needs have been responsible for a preference for gas. This shift has been enhanced by the low risk associated with gas-fired power: it enjoys lower capital requirements and shorter construction periods. Gas-based generation has high operational efficiencies and reduced environmental impacts. The long-term power purchase agreements, which are based on the cost-plus principle and operating efficiency incentives, have also aided penetration of gas-based power.

3. *Growth in Captive Power*

Faced with an unreliable external power supply, many energy-intensive industries such as aluminum,

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steel, and fertilizer have invested in on-site power generation, which is growing at an annual rate of 8% (CMIE, 2000). Captive power generation has grown from about 1.6 GW in 1970 to almost 14 GW in 2000 with almost half being coal-based. Many captive generating plants have excess capacity that could supply power to the grid, given the right policy incentives. Some steps have been taken in this direction regarding wheeling of power and allowing third party sale.

4. Transmission and Distribution System

Transmission and distribution (T&D) losses now amount to over one-fifth of generated electricity (CMIE, 2000). Commercial losses from theft, non-metering and non-billing account for about one-quarter of these losses. The government still maintains a monopoly over power transport. Power quality suffers from widening frequency and voltage fluctuations and frequent grid disruptions. Inadequate capacity, inefficient operations, insufficient maintenance, the predominance of low voltage lines (low to high line ratio is above 16) and technological obsolescence cause these problems. High losses cripple the financial viability of the state-owned power transport system, resulting in a persistent lack of funds for expanding and improving the network.

5. Inter-Regional Transfer of Electricity and Grid Integration

The country is divided into five regional grids with very little trading among the regions. Regional distribution of power generation in India varies significantly, due to uneven electricity demand and endowment of resources across the country. Balancing the economic advantage of transporting fuels versus the transmission of electricity has therefore remained an important issue for national planners. There are opportunities for the latter through regional grid integration, which will help in shifting the power supply from surplus to deficit regions. This will help reduce T&D losses, peak shortages and overall capacity requirements by better load management among regions. Despite coordination and financial and technical bottlenecks, grid strengthening is already underway, with plans for the completion of the national grid by 2012 (CEA, 1999). Power trading with neighboring countries like Nepal, Bhutan, Pakistan and Bangladesh is also assuming increasing significance (IE, 1999a and 2000a).

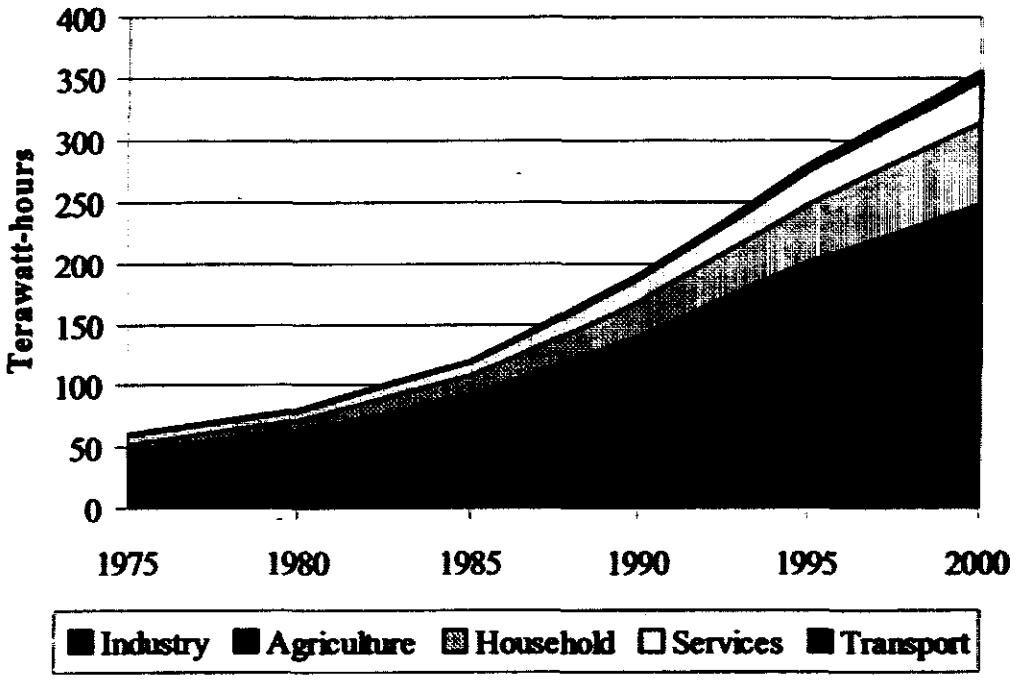
6. Electricity Consumption Trends

The sector consumption profile has undergone substantial change in the past two decades. The agricultural and household sector consumption has grown over 12% annually, while total power use grew at 8.6% (Figure 3). Industry's total share of power use over the period therefore fell from almost 60% to just under 45% (TEDDY 1995/96 to 2000/01). The phenomenal rise in energy consumption from agricultural activities is due to greater irrigation demand by new crop varieties, the very low price of electricity for farmers, and booking some T&D losses as agriculture sector consumption to show better T&D performance by state utilities.

7. Electricity Costs and Tariffs

The electricity tariff structure in India is the main cause of investment disincentives and widespread demand-side inefficiencies. The average tariff has remained below the average cost of supply by almost 20%, resulting in a net drain on public funds (TEDDY, 2000/01) (Table 1). The gap mainly arises from subsidized rates to agricultural and domestic consumers. In 1997, the electricity subsidy to agriculture and domestic sector consumers amounted to over Rs. 200 billion, which was the equivalent of nearly half of the new investments in the electricity sector in that year (TEDDY 1998/1999). Nearly 80% of this subsidy goes to agriculture, with industrial consumers cross-subsidizing half of the total subsidy. The abnormally high rates for industrial consumers erode their competitiveness. Early rationalization of the tariff structure should therefore be an important agenda of the reform process.

Figure 3. Final Electricity Consumption by Sector



Source: TEDDY, 2000/01.

Table 1. Average Cost of Power Supply and Tariffs (at 2000 Prices)

1990	2.19	1.63	0.52	0.75
1994	2.19	1.72	0.47	0.78
1997	2.41	1.93	0.47	0.80
2000	2.81	2.08	0.73	0.74

Source: TEDDY, 2000/2001.

8. *Environmental Concerns*

A number of environmental concerns are associated with power generation in India, mostly with coal and large hydro projects. Over the past three decades, surface mining of coal has increased in India. Poor mining practices have caused significant deforestation, land degradation and contamination of water bodies. While reducing the dependence on coal may seem environmentally sound, it can significantly impact the socio-economic dynamics in coal producing regions of India. The revenues of states like Jharkhand, Bihar, Orissa, Madhya Pradesh and Chhatisgarh, which supply almost 70% of India's coal, depend considerably on the royalties earned from coal extraction. These regions are also among the poorest areas of the country, with coal mining being a major source of employment. Any major shift away from coal will have serious socio-economic implications for these regions. Ironically, coal mining has also remained the major source of land degradation and deforestation in these regions. GHG mitigation

choices have to take into consideration all these aspects to be consistently integrated within the long- term sustainable national development strategy.

Coal used in Indian power plants has an average ash content of 40% (ESMAP, 1998; Biswas, 2000). This, coupled with low combustion efficiencies of around 33%, generates large amounts of ash, particulate, sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon dioxide (CO_2) and heavy metals. Social and environmental impacts of hydro projects have been a cause of major controversies and have led to massive delays in project completion. Dam construction has caused resettlement and rehabilitation problems (CBIP, 1998b). Managing environmental and social impacts has therefore drawn considerable attention in policy-making, project development and operations.

9. Institutional Structure

Government has assumed a predominant role in electricity supply, with more than 50% of the generation under the state electricity boards (SEBs) (CMIE, 1999; CEA, 1995b). There are a few central utilities like National Thermal Power Corporation (NTPC) and National Hydro Power Corporation (NHPC). SEBs in particular are wide open to political influence and tariff distortions. Their performance is far from satisfactory, with most of them having huge losses. Recent power sector reforms are aimed at changes in the institutional structure. Rising power shortages, declining efficiencies, poor financial performance and investment shortfalls spurted the reform process. Misrepresentation of agriculture consumption, over-reporting subsidy impacts and arbitrary depreciation norms are also important reasons for the poor financial performance of SEBs.

The accompanying institutional changes can be broadly categorized into: corporatization of SEBs, private sector participation, unbundling and regulatory changes. Corporatization is expected to increase professionalism, reduce political interference and enhance financial accountability. The Regulatory Commissions Act set up the Central Electricity Regulatory Commission (CERC) in July 1998. The proposed functions of CERC include proposing tariffs for central government-owned utilities and other generating companies selling power to more than one state, regulate inter-state transmission, aid and advise the central government in tariff policy and arbitrate in disputes between generation and transmission entities. Regulatory changes have also been undertaken by the states, with most of the states having already set up or in the process of setting up SERCs (State Electricity Regulatory Commissions). The Commissions' functions include tariff setting, regulation of power purchase and procurement for transmission utilities, investment, approval and arbitration of disputes, issue of licenses for T&D and regulating working of licensees, setting quality, continuity and reliability standards and promotion of competitiveness and private sector participation.

B. Power Sector Future

The future assessment of the Indian power sector is based on the current official policies of the government and expert forecasts of macro-economic, demographic and energy sector indicators. It does not attempt to precisely predict the future course of the Indian power sector; rather, it indicates a general trend under the business-as-usual scenario. The reference case is a dynamic representation and includes many pro-environmental measures, such as structural changes in the Indian economy, technology improvements, increased penetration of cleaner technologies and fuels, development of renewable energy, and adoption of end-of-the-pipe environmental technologies (e.g. flue gas de-sulfurization). Some of these measures are already visible on the ground and the reference scenario merely assumes the dynamics to proceed as usual in future.

1. Methodology

The analysis presented here spans four decades and examines a reference scenario and a few carbon

mitigation scenarios. It provides insights into the implications of mitigation commitments on the Indian power sector's fuel-technology mix, carbon emissions, power tariffs, mitigation costs and potential, and investment requirements. Power sector analysis forms a key part of the integrated analysis of the Indian energy system, both on the demand and supply side. Therefore, an integrated modeling framework for the Indian economy, energy, electric power and emissions analysis is used (Garg et. al, 2001). This framework has three modules integrating ten independent models: the top-down models, the bottom-up models and other models (Figure 4). The models are soft-linked through consistent and similar base assumptions, a shared database and talking between the models. Multiple feedback is required among the models to ensure consistency of results and policy analysis. For the present analysis, we mainly use the results from the bottom-up module (Figure 5). It integrates five individual models:

i) MARKAL - an energy systems optimization model (Berger et al, 1987; Fishbone and Abilock, 1981; Loulou et al., 1997) which is used for overall energy system analysis,
ii) AIM/ENDUSE model (Morita et al, 1994; Morita et al, 1996; Kainuma et al, 1997) which is a sectoral optimization model used to model fourteen end-use sectors,
iii) A demand model which projects demands for each of the thirty-seven end-use services,
iv) Stochastic MARKAL model for uncertainty analysis,
v) Power sector linear programming (LP) model for regional analysis.

2. *Reference Scenario Results*

Reference scenario analysis shows that all India carbon emissions continue to rise from 212 to about 740 million tons of carbon between 1995 and 2035. The emissions grow very rapidly in the short-term, at an annual average rate of four and a half percent in the next decade. The growth rate slows down in the medium-term (3.5 percent between 2010 and 2020) while in the long-term it declines to an annual growth rate of about 1.7%. Power sector emissions also grow at the same rate, maintaining a steady share in the total emissions at about 45 percent.

In the reference scenario, while the economy grows by about 6 times in the next 35 years, the demand for electricity grows by only 4 times, resulting in a decline in the elasticity of electricity demand from more than 1 at present to about 0.65 in 2035. The growth in the demand for electricity outpaces the growth in overall energy demand in the economy. While there is a 60 percent decline in the overall energy intensity in the next 35 years, the electrical energy intensity declines by only 25 percent. The decline in the elasticity of electricity demand is due to advancements in technological stock, structural changes in the economy, changing consumption patterns, and demand-side management interventions. The per capita electricity consumption becomes three times the present value in the next 35 years, but still remains at about one-fifth of the present per capita electricity consumption in the United States. The power generation capacity increases by 1.5 times in the next 10 years, doubles in the next twenty years and reaches more than three and a half times (395 GW) the present capacity in 2035. Improvements in the performance of generation technologies cause the electricity generation to grow at a faster rate than the capacity. The average Plant Load Factor (PLF) of base load generating plants increases from about 60 percent at present to more than 70 percent in the next 35 years due to advancements in technologies, improvements in operation and management practices, better grid management practices leading to higher grid availability, and increases in fuel supply reliability. Some specific insights for the technology mix are provided below.

Coal: Coal dominates in the long-term future generation capacity mix, but its use becomes more sustainable with clean coal technology penetration. The coal capacity share declines, but improvements in its performance enables it to maintain a high share in generation. Advanced coal technologies like Super-critical Pulverized Coal (PC) technology and Integrated Gasification Combined Cycle (IGCC) penetrate in the medium (2020) and long-term (2035), but their overall share in the coal capacity remains just 10 percent even in 2035. Conventional Sub-critical PC technology penetrates with Flue Gas Desulfurization

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(FGD) units, lowering local pollutant emissions from coal power plants considerably. In the medium-term, around ten percent of the Pulverized coal plants are fitted with FGD, with their share increasing to as high as 60 percent in the long-term.

Figure 4: Soft-Linked Integrated Modeling Framework

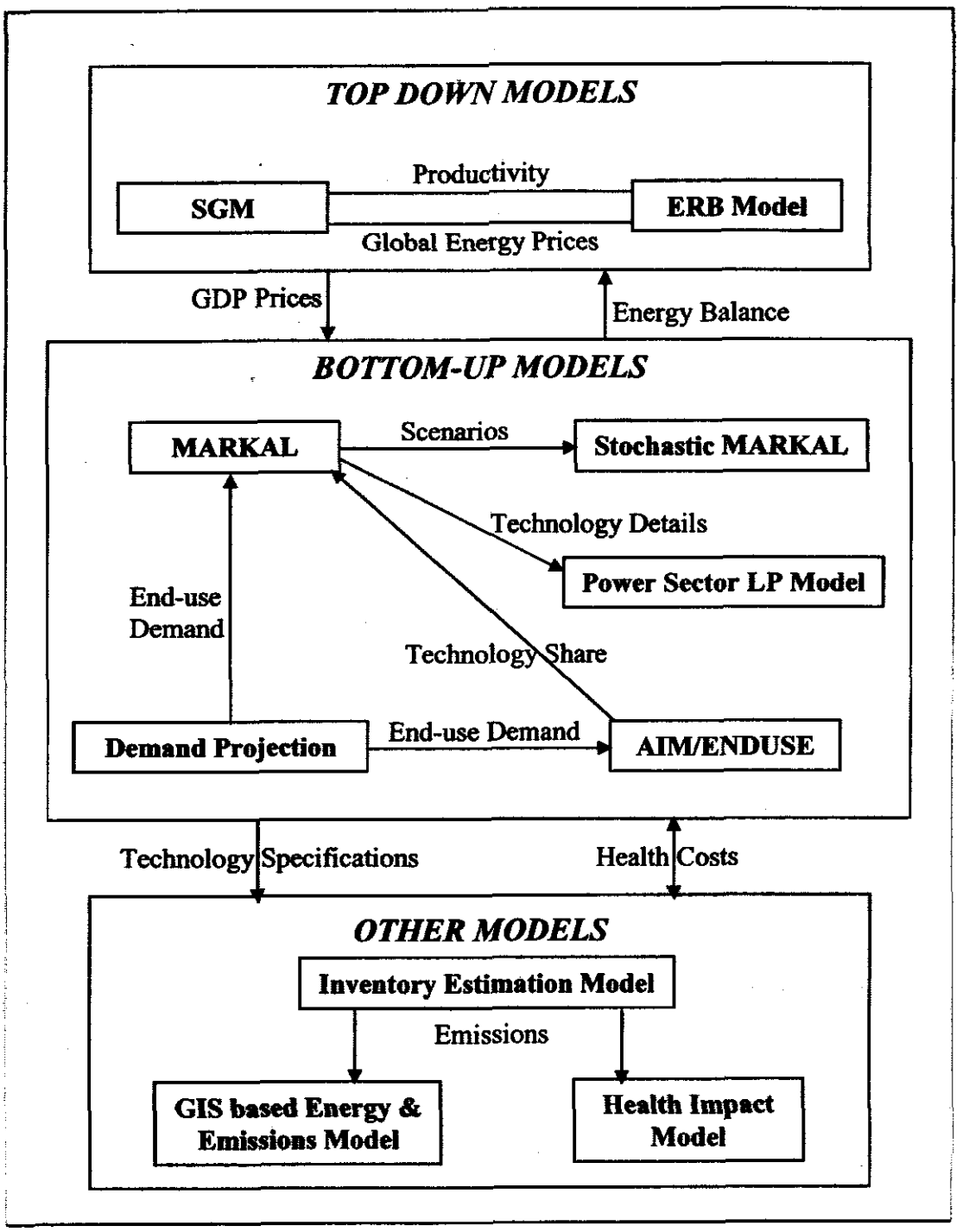

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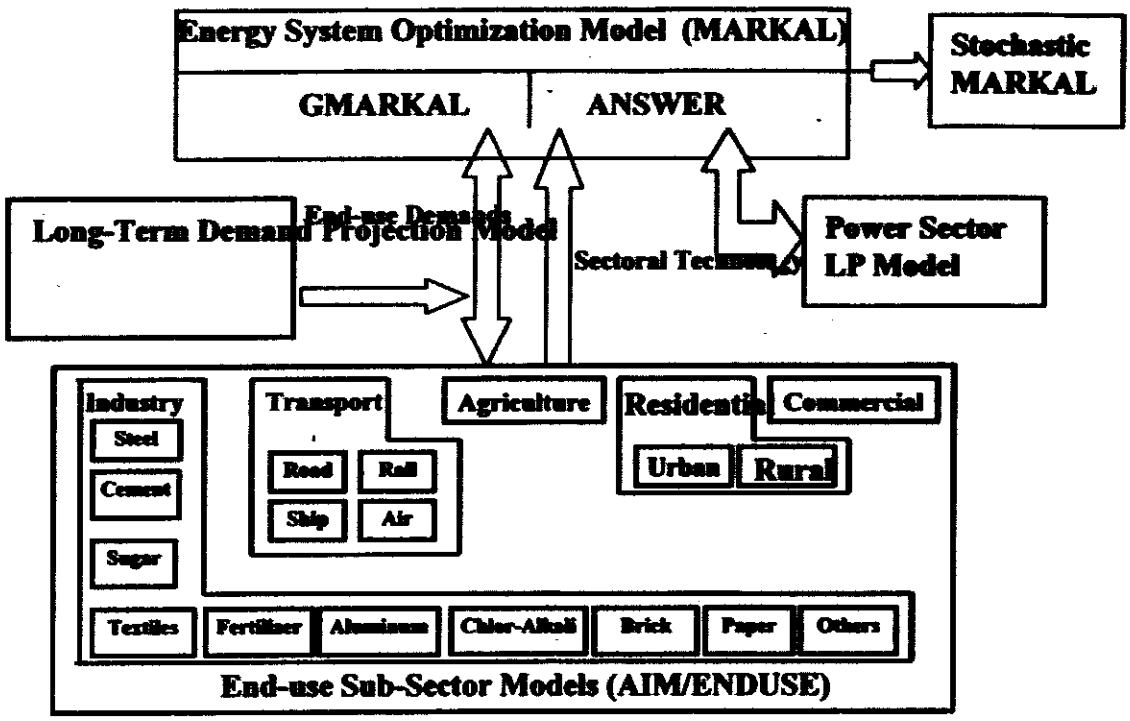
Figure 5: Soft-Linked Bottom-Up Module



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Natural Gas: There is an already existing peak demand gap in the power sector. Advancements in gas technologies and rapidly rising peak power requirements increase gas penetration in the medium-term. The low investment costs for plants employing combined cycle gas turbine (CCGT) technology, coupled with high conversion efficiencies and availability, make base load power generation using gas competitive with coal at locations far away from the pithead (example, coastal locations) where inadequate coal linkages exist and coal transportation costs are high. There are energy security implications for increasing use of natural gas, as most of the gas requirement has to be supplied by imports due to limited domestic reserves. The gas pipelines from Oman, Iran and Turkmenistan have been under consideration for quite sometime now. The recent gas findings in Bangladesh could also have a natural market in India. In this context, building of gas supply infrastructure, such as the development of ports for imported compressed natural gas, and setting up of reliable and secure transnational and domestic pipeline networks are important issues for India. The foreign exchange requirement for total natural gas imports in 2020 is projected to be about US$ 10 billion[1], with the power sector having a 50 percent share in the total consumption. Gas penetration slows down in later periods (beyond 2020), due to lowering of the growth rate in peak demand due to better load management practices and an increase in system reliability, due to a large peak reserve capacity build-up. Beyond the medium-term, gas share lowers in base load generation with the rise in natural gas prices and increasing competitiveness from coal technologies due to advancements in their technological stock and better operating and management practices.

Nuclear: At present, nuclear power plants in India operate at very low capacity utilization, mainly due to highly unstable grids that necessitate frequent shutdowns. The competitiveness of nuclear power plants is very sensitive to the plant load factor due to a very high fixed cost component and low variable costs. Expectations about improved performance of nuclear plants due to indigenous technological advancements, and better grid management practices leading to substantial increase in their capacity utilization, will increase nuclear penetration from the present 2 to 5 percent in the long-term. There will be a nine-fold increase in its capacity in the next 35 years, with socio-political and environmental considerations restricting further capacity increase.

Large Hydro: Large hydro capacity doubles in the next two decades, and reaches about 90 percent of its present estimated economic potential in 2035. Despite the high competitiveness of large hydro technology, its share is restricted to about one-fifth of the total capacity due to the large risks associated with hydro projects caused by long gestation periods, uncertainties in site identification and testing, socio-environmental and political constraints.

Other Renewables: Other renewable technologies, including small hydro, cogeneration, biomass-based power generation, wind and solar, increase their capacity by more than three times in the next decade, with a three and a half percent share in the capacity mix from the present 1 percent. In the long-term, their capacity share increases to 6 percent. Among these renewable technologies, small hydro, cogeneration and biomass technologies are highly competitive and penetrate rapidly, mainly as decentralized power options. Penetration of wind-based power generation in the initial years will depend upon a technology push policy, targeted at attracting investments, development and strengthening of local manufacturing capabilities. These push policies, in the initial years, will enhance technology competitiveness in the medium- and long-term. Internalization of the environmental costs associated with fossil fuel based power generation will give wind a competitive edge over these technologies. On the other hand, solar technologies penetrate in the medium-term due to capacity building through demonstration projects that enhance learning experiences, but long-term penetration will depend largely on international reduction of costs, lowering of their capital intensity and establishing institutions for co-operative R&D and technology transfers.

[1] The cost of infrastructure is not included in it. All cost figures in this paper are in 2000 prices and assume an exchange rate of Indian Rs.47 per US $

C. Carbon Mitigation Scenario Analysis

India does not currently have any GHG reduction commitments. However, rising emission trends necessitate an understanding and analysis of policy-induced mitigation measures such as carbon emission reduction commitments and a carbon tax. These policies prompt technology and fuel substitution by changing the relative costs of competing fuels in favor of those with lower carbon contents.

Climate change occurs due to an increase in cumulative GHG emissions over the long run (SAR, 1996, 1996a). Carbon mitigation targets should therefore be based on cumulative mitigation over the long term and annual targets should dovetail into optimum long-term mitigation targets. Cumulative carbon emissions in India are estimated at around 20 billion tons (BT) between 1995-2035 under the reference scenario. A 5% cumulative carbon reduction amounts to about one BT carbon mitigation in forty years. We analyze the impact of cumulative carbon mitigation commitments of 5, 10, 15, 20 and 25% (that is 1, 2, 3, 4 and 5 BT respectively). These are termed as low, moderate, high, extra high and excessive (Table 2). The marginal cost of carbon is a model output and it indicates the optimum carbon tax trajectories as MARKAL spreads cumulative mitigation across years and sectors in a cost-effective manner.

Table 2: Carbon Mitigation Scenario Assumptions

Reference	0	0	20
Low	5	1	19
Moderate	10	2	18
High	15	3	17
Extra high	20	4	16
Excessive	25	5	15

Carbon mitigation in India is complicated by the fact that India has large coal reserves, but limited oil and gas reserves. The substitution away from coal will make the country dependent on imported energy, which has energy security implications. While India has experience with emerging renewable technologies, the capital and foreign exchange constraints are likely to restrict a shift away from coal, unless the economic and fiscal policies to relax these constraints are instituted.

Carbon mitigation would require technological transformation of the Indian energy system. This will need investments in infrastructure to support new technologies, and reforms to remove the barriers to penetration of advanced technologies and cleaner fuels. Societies with strong reduction commitments would therefore have to start thinking differently. These are captured through different sets of assumptions for each mitigation scenario, as compared to the reference case, in the model. For example, in the Excessive mitigation scenario, the average transmission efficiency for electric power in India in 2035 improves to 93% (as against 88% in the reference case), the technological gaps in various sectors between best international practices and India reduce faster, and natural gas supply increases at higher prices.

1. Energy Consumption and Emissions

Some important results for the Indian energy system are indicated in Table 3. Inertia of existing technological stock in the energy system prevents significant fuel substitution until the year 2010 for meeting carbon mitigation targets and coal continues to dominate the energy system. However, coal consumption declines drastically in the long-term for meeting high mitigation targets. A decline in gas consumption in the medium- and long-term in high and excessive mitigation cases is due to increasing penetration of carbon free technologies like renewables and nuclear for power generation. However, coal is mainly

substituted for by natural gas in the power sector. While natural gas exhibits early penetration, renewables penetration is late due to their high initial investment costs. Due to the rising gas prices with higher use of gas in later years, the renewable energy penetration becomes higher with rising mitigation targets. Comparing the SO_2 elasticity of carbon emission reduction across mitigation scenarios also reflects this. It first increases and then reduces for each carbon mitigation target since gas emits no sulfur, while biomass does emit sulfur.

Table 3: Results of Climate Change Policy Scenarios for Indian Energy System

Coal (% change)#	-2	-5	-24	-4	-17	-38	-9	-27	-51	-20	-47	-90
Gas (% change)#	+1	+3	+19	+1	+10	+14	+1	+18	-9	+0.2	-0.8	-17
Carbon (MT)	398	549	658	386	518	606	377	486	529	362	431	394
SO_2 (MT)	6.22	7.65	6.35	6.09	7.11	5.66	5.87	6.28	4.21	5.48	5.35	3.09
SO_2 elasticity *	1.27	1.20	1.13	0.90	1.22	1.21	1.11	1.46	1.43	1.30	1.36	1.23
MC ($/tC) **	5	14	39	11	21	65	23	41	118	41	83	272

Percentage changes over the reference scenario consumption
* Elasticity of SO_2 reduction with respect to carbon reduction (over the reference case)
** Marginal Cost indicates carbon tax ($/ton carbon)

The Global GHG mitigation regimes would have implications for India's energy system. As the power sector has a very large share in the total energy consumption and has almost 50 percent contribution to the total carbon emissions, its energy and technology mix is likely to be altered under the carbon mitigation targets. Figure 6 shows the power sector carbon emission trajectories under the mitigation scenarios, along with the reference (base) scenario emissions.

2. *Demand and Supply Side Mitigation Dynamics*

Analysis of carbon mitigation scenarios provides some useful insights regarding energy supply and demand side contributions to emissions reductions (Table 4). In the early periods (2005-2015), the demand sectors show more flexibility than the supply side by contributing more to carbon emission reduction since end-use demand sector technological stock turnover is faster due to their relatively shorter lifetimes[2]. But in later periods, the supply side contribution increases, finally reaching a three-fourths share in the total mitigation in 2035. These, however, include emission reduction due to lower power generation requirements as demand side energy efficiencies improve. The inertia of supply side technology turnover is due to their much longer lifetimes, high investment requirements and longer gestation periods for infrastructure development. The supply side mitigation options are primarily associated with fuel switching from coal to natural gas. Long-term options include penetration of carbon-free technologies like nuclear and renewable technologies. Judged from a market perspective, there are large inefficiencies on the demand side due to capital shortages, risk, high transaction costs and weak financial markets. The supply side is better organized and has lower inefficiencies.

Supply side contribution increases in the medium- and long-term with the retirement of existing capacities and buildup of progressively new capacity. Table 5 shows the technology shares in electricity generation capacity in the reference and carbon mitigation scenarios.

[2] The demand side includes all end-use demand technologies that consume electricity, like electric arc furnaces for steel making and fluorescent lamps for lighting. The supply technologies are the electricity generation technologies.

Figure 6: Power Sector Carbon Emissions

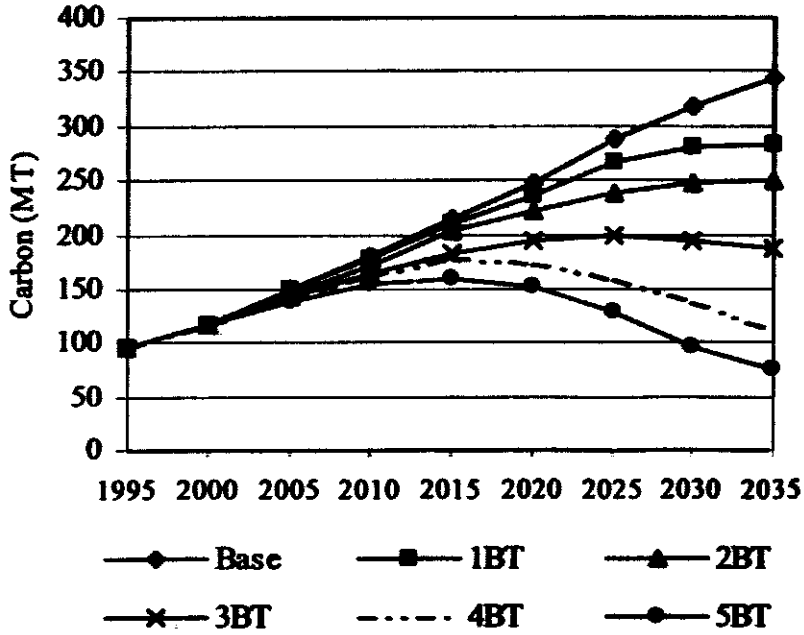

Table 4: Power Sector Contribution in Carbon Mitigation

Low (1 BT)	Carbon mitigation (MT)	3	11	62
	Share in total mitigation (%)	37	50	77
	Demand side contribution (%)	31	28	14
	Supply side contribution (%)	69	72	86
High (3 BT)	Carbon mitigation (MT)	15	54	156
	Share in total mitigation (%)	52	64	75
	Demand side contribution (%)	45	37	28
	Supply side contribution (%)	55	63	72
Excessive (5 BT)	Carbon mitigation (MT)	25	96	270
	Share in total mitigation (%)	58	68	79
	Demand side contribution (%)	46	32	25
	Supply side contribution (%)	54	68	75

There are no significant changes in the supply technology mix in the short-term (2010) under the low and high carbon mitigation scenarios. The excessive carbon mitigation scenario results in a 20 percent decline in the coal capacity in the short-term, with higher shares of natural gas and other renewable technologies.

In the medium-term (2020), alterations in the technology mix are caused mainly by capacity increases of gas and other renewable technologies. The high carbon mitigation scenario leads to a 30 percent increase in wind power capacity and the renewable capacity doubles over the reference scenario. Moreover, there is a 45 percent increase in large hydro capacity, thereby increasing its share in the generation capacity mix to about 29 percent.

emission reductions back to the sectors contributing in emission reduction can assist in the lowering of mitigation costs and ensure the sustainability of the regime in the long-term.

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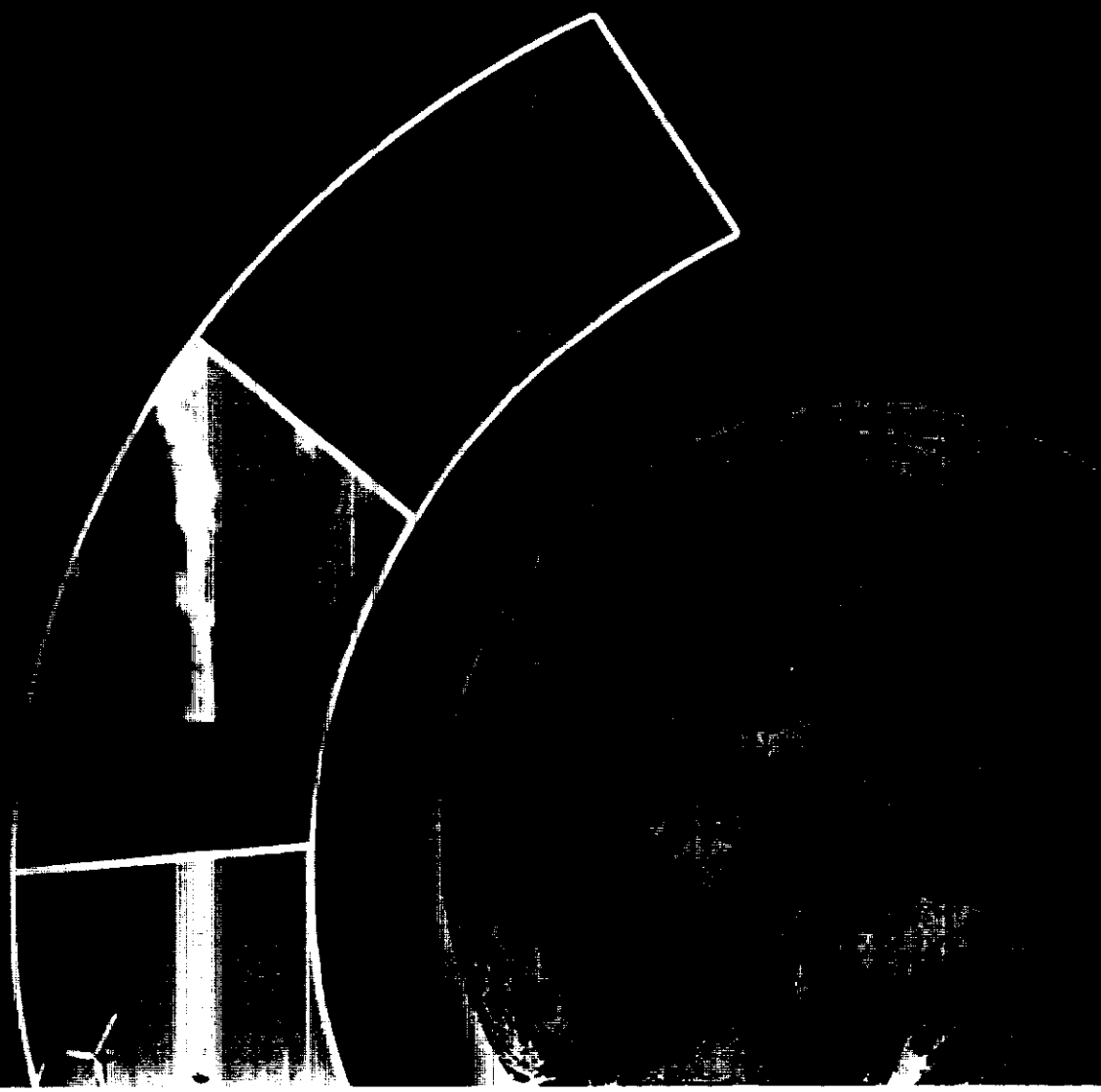
Energy and Emissions at Global Levels in Urban Transport in India



ENERGY AND EMISSIONS AT GLOBAL LEVELS IN URBAN TRANSPORT IN INDIA

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ABSTRACT

The massive increase in the requirements of urban transportation in India over the past few decades has led to congestion of cities, proliferation of private vehicles, increased energy usage and increased pollution. The situation is made worse by the shift of a modal split away from railways and toward road transport, and the inadequate capacity of public transport leading to rising emission levels of pollutants and increased energy usage due to the unchecked proliferation of private vehicles. Four metro cities, viz., Delhi, Mumbai, Kolkata and Bangalore, are reported along with some data analysis for some of the other cities and overall road transport in India. Econometric models for transportation requirements show the need for the introduction of alternate fuels and increasing efficiency of the vehicles. Recommendations also include increased emphasis on public transport by buses and mass transport, in the metros and second level of cities, and efficient design of cities.

I. INTRODUCTION

A sustainable Urban Transport System should be economically and socially equitable and efficient. When low income groups do not have access to a reasonably-priced transportation system, this imposes hardships on them. Energy is wasted in commuting, making them inefficient, thus sending them in a vicious circle of poverty and inefficiency.

Transport is a critical infrastructure for the developmental process. The sector accounts for a major share of the consumption of petroleum products in India. Transport is responsible for an appreciable share of pollution, both local and global. Problems due to the emissions of local pollutants get concentrated in urban areas. Transport activities thus occupy central concerns of local pollution in many urban areas of developing countries. The emission of global pollutants, especially of carbon dioxide (CO_2), from transport is a problem of increasing concern in the global environmental scenario.

Managing the transport sector while minimizing externalities such as local pollution, congestion and global pollution is a major challenge. Rapid urbanization is taking place in developing countries. It is expected that more than 50% of the population in India may reside in urban areas by 2025, a substantial increase from 28.9 % in 1999. An efficient transport system is a key ingredient for the cities for economic productivity and quality of life.

In this paper, we first carry out a preliminary review of the performance of the Indian transport sector, by rail and road, with particular emphasis on urban transport in the past few decades, and with a view to identifying the changing patterns of use of different modes and fuels, and to assessing emission of local and global pollutants. Later, depending on the data availability, specific information on the four megacities of India, namely Mumbai (formerly Bombay), Delhi, Kolkatta (formerly Calcutta) and Chennai (formerly Madras), on pollutant emissions are estimated. Important macro-economic variables responsible for these changes are econometrically identified. Econometric models are used to generate future transport scenarios for passenger and freight traffic in India. Energy consumption and CO_2 emissions also increase from this sector at an equivalent rate. The effects of various policy options aimed at mitigating the CO_2 emissions are analyzed.

II. REVIEW OF TRANSPORT CHARACTERISTICS

The main focus of this work is on urban passenger transport. However, we first give an overall review of the transportation sector in terms of both passenger and freight transport to see the magnitude of the urban transport.

A gradual transformation from rail-dominated transport to road-dominated transport has been witnessed in the last few decades. As can be seen in Table 1, the share of railways has decreased from 32.9% of the total Passenger Kilometers in 1970-71 to 20.0% in 1996-97. During the same period, the share of railways for freight transport (Ton-Kilometers) declined from 65.5% to 40.0%. Note that the values do not sum to unity, the remainder being the share of domestic air transport. Although figures for the recent part are not available, the broad trend is the message. These are estimated periodically using assumptions.

The total passenger kilometers (PKM) and Ton Kilometers (TKM) by Indian railways were 404.1 and 281.5 billion, respectively, in 1998-99 (Table 2). The growth rate in rail passenger transport during 1980-94 has reduced to nearly half of the growth rate of 1970-80, whereas the rate has nearly doubled for freight traffic. However, the growth rates have increased in 1993-98. Bulk commodities (dominated by coal) have constituted about 85-90% of the total revenue originating tonnage on railways.

Suburban rail traffic has grown at a slightly higher rate than the non-suburban segment during the Seventies and Eighties. Suburban rail travel in Mumbai constitutes more than 68% of this traffic, while other metropolitan cities, namely, Calcutta, Chennai (formerly Madras) and Delhi constitute about 25%, 6% and 0.6%, respectively.

Table 1 : Trends in relative rail and road traffic 1970/71 to 1996/97

Mode	70-71	73-74	76-77	79-80	82-83	85-86	88-89	96-97
Freight Traffic								
Rail(%)	65.5	61.5	62.3	54.6	48.6	48.7	48.0	40.0
Road(%)	34.5	38.5	37.7	45.4	51.4	51.3	52.0	60.0
Total(billion TKM)	194.41	199.05	251.53	285.85	365.89	422.68	505.00	
Passenger Traffic								
Rail(%)	32.9	31.6	29.7	27.9	23.7	22.2	23.0	20.0
Road(%)	67.1	68.4	70.3	72.1	76.3	77.8	77.0	80.0
Total(billion PKM)	359.05	427.60	549.33	710.40	955.90	1079.2	1169.0	

Sources: 1. CMIE..Basic Statistics Relating to Indian Economy,
2. Ministry of Railways 1998..Status paper on Indian Railways.
3. Ministry of Finance 1999 Economic Survey, Government of India

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Table 2: CO_2 Emissions in India, China and World

1980	305.97	1491.34	18658.1	0.0164	0.0799
1981	338.22	1474.86	18337.2	0.0184	0.0804
1982	349.88	1537.74	18202.8	0.0192	0.0845
1983	374.01	1618.53	18334.6	0.0204	0.0883
1984	386.63	1757.34	18891.4	0.0205	0.0930
1985	424.75	1888.28	19391.8	0.0219	0.0974
1986	460.75	2003.98	19761.8	0.0233	0.1014
1987	494.42	2136.52	20443.0	0.0242	0.1045
1988	533.28	2274.54	21095.9	0.0253	0.1078
1989	568.62	2364.21	21426.4	0.0265	0.1103
1990	599.78	2398.29	21245.9	0.0282	0.1129
1991	635.28	2485.86	21446.9	0.0296	0.1159
1992	672.57	2552.70	21391.7	0.0314	0.1193
1993	705.22	2699.37	21534.2	0.0327	0.1254
1994	750.05	2844.21	21607.2	0.0347	0.1316
1995	817.32	3035.00	22073.4	0.0370	0.1375
1996	863.19	3179.72	22784.4	0.0379	0.1396
1997	880.71	3161.95	22981.1	0.0383	0.1376

Source: International Energy Agency (1999): "CO_2 Emissions from Fuel Combustion"

Table 3: Per Capita CO_2 Emissions

(Tonnes CO_2)

1980	0.45	1.51	4.23	11.42
1981	0.48	1.48	4.09	10.94
1982	0.49	1.52	3.99	10.51
1983	0.51	1.57	3.95	10.36
1984	0.52	1.69	4	10.57
1985	0.56	1.79	4.04	10.65
1986	0.59	1.87	4.05	10.57
1987	0.62	1.96	4.12	10.76
1988	0.65	2.05	4.17	10.93
1989	0.68	2.1	4.17	11.02
1990	0.71	2.1	4.07	10.77
1991	0.73	2.15	4.04	10.71
1992	0.76	2.18	3.97	10.68
1993	0.79	2.28	3.94	10.75
1994	0.82	2.38	3.89	10.8
1995	0.88	2.51	3.92	10.85
1996	0.91	2.6	3.99	11.14
1997	0.92	2.56	3.97	11.18

Source: International Energy Agency (1999):
"CO_2 Emissions from Fuel Combustion"

which use reduced form equations without structural details and the implied policies behind them remain unclear. Another approach of top-down modeling is the computable general equilibrium (CGE) approach, where equilibrium prices and quantities are computed for one period and repeated sequentially for several periods. The main choice of the economic agents is essentially of static nature confined to events occurring in a single period, with a few linking equations for capital or labor stock from one period to another. Both econometric and CGE models often assume a high substitution elasticity, which makes it easy and relatively costless to adjust to CO_2 constraints. The activity analysis approach we have adopted here permits the easy incorporation of a simultaneous choice of economic variables for several periods in a dynamic setting. It provides macroeconomic consistency and incorporates specific technological options with limited substitution possibilities. This method can be viewed as one that integrates both the top-down and the bottom-up approaches[2].

In this paper, we use an activity analysis framework to examine the effects of CO_2 emission reduction on the national economy. This model, reported in Murthy, Panda and Parikh (2000), permits exploration of alternative technologies to meet CO_2 constraints from a long-term dynamic perspective. With alternative activities representing different technologies, one can permit substitution of various kinds and incorporate non-linearities in such models. The model maximizes a social welfare function specified as the present discounted value of utility streams corresponding to the per capita consumption of an average consumer, given the resources available to it and the various technological possibilities for using them. In principle, the time horizon of the model must extend to infinity. Empirical models, however, work with a finite time horizon of length, say, T time periods only (taken to be 35 years in our case), as it is computationally impossible to work with an infinite number of time periods. Instead, they account for the post-terminal period in other ways.

Murthy, Panda and Parikh, J. (1997a) estimate the carbon emission coefficients for the Indian economy and carry out various experiments using the input-output framework to identify the major emitting sectors, both directly, through a sector's own production process, and indirectly, through the demand for various inputs. In another paper, Murthy, Panda and Parikh J(1997b) calculate the carbon emission coefficients for six different income classes in rural and urban areas and find out how much emission takes place in the production of goods and services consumed by different income classes. While the carbon emission coefficients estimated in these papers have been used here with suitable aggregation of sectors, the model structure extends from consistency analysis of the input-output models to considerations of optimality in a general equilibrium framework.

We represent the whole economy with seven commodities/goods, some of which can be produced in more than one way. In particular, electricity can be produced by coal, oil, gas (combined cycle gas turbine, CCGT) and others (hydro and nuclear). We focus on specific options for the power sector, as a large part of India's CO_2 emissions occur in this sector and policy options here need to be clearly understood. Industrial output can be produced by two alternative activities that use coal-boiler and oil-boiler technologies. Technical progress and energy efficiency gains over time are prescribed exogenously. These remain the same across all scenarios.

Income distribution is endogenous and depends on the total consumption, exogenously projected total population and specified Lorenz ratio. The portion of the population belonging to each consumption expenditure class is determined in the model. Thus, the composition of aggregate consumption changes nonlinearly as the economy grows and people move from one income class to another. Fifteen alternative consumption bundles are provided for each class to represent approximately the indifference curve of the class. This permits substitution across commodities when relative prices change. The class boundary of

[2] The model used here 'integrates' top-down and bottom-up economic models with proper environmental accounting. In this sense, the term "integrates" differs here from in a section of the climate change literature where it is used to refer to integration of population, economic and climate change modules.

the bottommost class corresponds to the poverty line and persons belonging to this class are classified as poor.

Ideally, income distribution should be linked to production structure and techniques used in the production process. Unfortunately, adequate data on income generated by such activities and how they are distributed to different income classes are not available. However, empirically, income distribution as reflected in consumption expenditure has remained very stable, with slow and miniscule changes in the Lorenz ratio. National Sample Survey (NSS) data show that it varied with minor fluctuations between 0.3417 in 1956-57 and 0.3202 in 1992 [see Panda (1999)]. Thus, an assumption of a constant Lorenz ratio over a long period of time is justified for India.

The constraints in the model include the following:

a) Commodity balance to ensure that demand does not exceed availability;
b) Production requires fixed capital, which, once allocated to an activity, cannot be shifted. Capacity constraints ensure that production does not exceed the capacity created by investment in each activity;
c) Capital accumulation constraints that restrict capital stock in each activity to increase by net investment in each activity;
d) Domestic production of oil is restricted to reflect the small oil reserves in India.

On the trade side, we impose a balance of payment constraint. There is also a wedge between export price and import price to reflect international trade and transport margins. Some restrictions are imposed on exports and import growth rates by sectors to keep the model realistic. Thus, import of agriculture is restricted to reflect a self-sufficiency requirement for a large country which is considered necessary for food security. We also restrict import of services, as not all services can be imported. Export bounds are introduced to account for fall-offs in export price and profitability consequent to large exports by India.

A savings constraint is imposed to restrict the marginal savings rate to 30 percent. Programming models often give high investments and implied savings rates. Such rates are not realistic, as governments in a democratic developing poor country are not able to force the savings rate beyond a limit. Finally, though the model is run for a period of 35 years, the post-terminal future has to be taken care of. This is done by assuming that a stationary state would prevail in the future with the composition of output, consumption, investment etc. fixed and growing at a prescribed rate. This translates into a larger weight for the terminal year consumption in the objective function.

A. Emissions Inventory

CO_2 is emitted when fossil fuels such as coal and oil are burnt in production and household activities. For a given fuel, the amount of emission is directly proportional to the quantity of fuel burnt. The CO_2 emission coefficient of a fuel depends upon its carbon content. We account for these emissions in two different ways: flows and stocks. The emissions from the production sectors are computed by considering the scalar product of the activity vector and the emission coefficient vector that indicates the amount of emissions per unit level of activity. The emission coefficient for an activity is derived by considering the fuel-specific emission coefficient and the fuel input coefficient. Apart from the production activities, emissions are also caused by the private and public consumption of fuels like kerosene, LPG and motor gasoline. We account for these by considering emission coefficients attached to each consumption activity.

The cumulative emission of CO_2 at the end of any period is computed by adding the emission flows during the current period to the cumulative emissions carried over from the previous period. CO_2 emissions are known to accumulate and reside for long durations in the atmosphere, leading to an increase in CO_2 concentrations.

B. Carbon Reduction Options

In the model, CO_2 emissions can be reduced in a number of ways. First, they can be reduced by reducing the levels of different activities. This has the direct effect of reducing income and consumption and hence a loss in the social welfare. The second method is to change the composition of production in the economy in favor of less CO_2-intensive activities. This can be done either by changing the structure of trade so that the more CO_2-intensive products are imported, or the structure of consumption and other final demand may be changed by reducing the budget share of CO_2-intensive goods in the total final demand. This leads to an indirect loss of current welfare as the investor and consumer choices get distorted.

In addition, technological options are also available for reducing the CO_2 intensity of activity levels. These have the virtue of reducing emissions without any significant loss of output. There are essentially two such options: (a) Reduce the amount of CO_2-emitting energy inputs required by different activities; additional investment may be required to install equipment that can operate these processes at higher energy efficiency; and (b) switch to less carbon-intensive fuels. For example, instead of a coal based power plant, we may install a CCGT power plant, or instead of running industrial boilers on coal, we may use oil. The CO_2 emission coefficient varies across the fuels, being highest for coal (26 tC/GJ), followed by oil (21 tC/GJ) and lowest for natural gas (14.7 tC/GJ). Thus, oil or natural gas can substitute for coal and lower CO_2 emissions.

To sum up, the model used here belongs to the dynamic optimization category in a multisectoral and intertemporal framework with particular options for technology. It maximizes an objective function which is the discounted sum of utilities from consumption. The dynamic framework permits examination of optimal intertemporal choices. There are some specific features we might wish to highlight in this model for the Indian economy. First, the model incorporates specific technological options with a choice of alternative activities (or a combination of them) for producing a commodity. Second, it traces welfare effects for the low-income groups by examining the incidence of absolute poverty in the population. Third, there are large differences in consumption patterns among different income classes in a developing country, which are represented in our model. In this context, we also specify several alternative consumption bundles for each income class, from which the respective representative consumers can choose. Thus, we permit consumer purchases to be sensitive to the relative shadow prices of commodities in our programming model. Endogenous income distribution is important because it will have considerable impact on the structure of consumption demand in the economy, as population in a lower income class today will move to a higher income class in the future as income growth takes place. Finally, we impose terminal conditions on stock variables in our model. With the inclusion of natural resources among the stock variables, the terminal conditions can be interpreted as sustainability constraints.

C. Data

We have empirically implemented the model by using recent data for India to estimate the various parameters and initial values of different variables included in the model structure discussed in the previous section. Input-output coefficients and capital-output ratios for various activities form the core of the model. This data is available from published sources for most sectors.[3] In some cases, like the capital-output ratios for the generation of electricity using alternative technologies, we have based our estimates on statistics published by the Centre for Monitoring Indian Economy (1995) on the ongoing and proposed power projects in India. Future projections of government consumption levels and of the upper and lower bounds for exports and imports (where relevant) are specified in terms of growth rates. The database for operating the model is listed in the Appendix Tables. The model is solved using the GAMS programming tool developed by Brooke et al. (1988). For endogenous income distribution consistency, we iterate over optimal solutions, changing distribution parameters between iterations till they converge.

[3] Details are available in Parikh et al. (1995)

III. SCENARIOS

We use the model described in the earlier section to evaluate the impact on economic growth and other related variables corresponding to several alternative CO_2 reduction scenarios over a reference scenario during a period of 35 years from 1990 to 2025.

Reference scenario: The reference scenario is a **'business-as-usual' (BAU)** scenario in which the pattern of growth of various variables is determined by the model *in the absence of any emission constraints.*

Emission Reduction Scenarios: We then develop scenarios in which there are restrictions on the amount of CO_2 emissions. These restrictions are applied in two different forms:

(a) reduction of 10%, 20% and 30% in *cumulative* CO_2 emissions (CEM_T) over 35 years (these three scenarios are labeled **C10, C20** and **C30** respectively);
(b) annual reduction of 10%, 20% and 30% in CO_2 emissions (EM_t) in *each year* of the 35-year time horizon (these three scenarios are labeled **A10, A20** and **A30** respectively).

Thus, we have six different scenarios of emission restrictions for comparison with the BAU scenario.

IV. IMPACT OF CARBON DIOXIDE EMISSION REDUCTION

We now discuss the results of our experiments as designed above. Tables 4-6 show the values of some important macroeconomic variables and alternative activity levels for selected years for the BAU scenario, as well as various scenarios involving cumulative and annual emission reduction. Some characteristics of the BAU scenario are as follows: The economy grows at an average annual rate of 6.3% over 35 years. This growth rate is about the same as the average of above 6% achieved since 1991, when India started a series of major economic reform measures to liberalize trade and industry. It is more than the average growth rate of the 1980s (5.5%), but lower than the government's target of 7-8% average growth over the next 10-15 years. The BAU Scenario thus is not overly optimistic, and it reflects the acceleration noticed in the Indian economy in the 1990s. The number of poor in the BAU scenario in the year 2000, at around 26 percent, is also close to the 1999 estimate from the National Sample Survey data. It falls considerably over the next 20 years as a result of sustained economic growth. Poor households are defined as those whose per capita income falls below an absolute income level; it is only natural that the number of 'poor' would decline in a growing economy if the distribution factor remains stable. Such a BAU scenario is again consistent with the past experience of India, insofar as a fast decline in poverty has been observed in periods of high per capita income growth[4]. The carbon emissions grow from 157 mtc in 1990 to 1421 mtc in 2025. Of these emissions, 61 mtc are from electricity generation and 53 mtc from industrial production in 1990, and 659 mtc and 397 mtc, respectively, in 2025. The annual emissions are plotted in Figure 1. The cumulative emissions over the 35-year period amount to 20353 mtc.

Table 4 gives the effects of CO_2 reduction on aggregate GDP and per capita consumption. Enforcing a 10%, or even a 20%, cut on cumulative CO_2 emissions has virtually no impact in the short run (3rd or 5th year) or medium run (10th year), as can be seen from column C10 or C20 of Table 4. The GDP and consumption levels fall only marginally. In the long run (30th year), however, the effects of emission restriction are more visible. In the 30th year under the C20 scenario, for example, GDP and consumption per capita fall by 1.36% and 1.85%, respectively, compared to the BAU scenario. Hence, the number of people below the poverty line increases by 5.94% (Table 5).

[4] With an average population growth of 1.8% per annum, 6.3% GDP growth translates to 4.5% per capita income growth.

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Figure 1: Annual Emission in Million tC

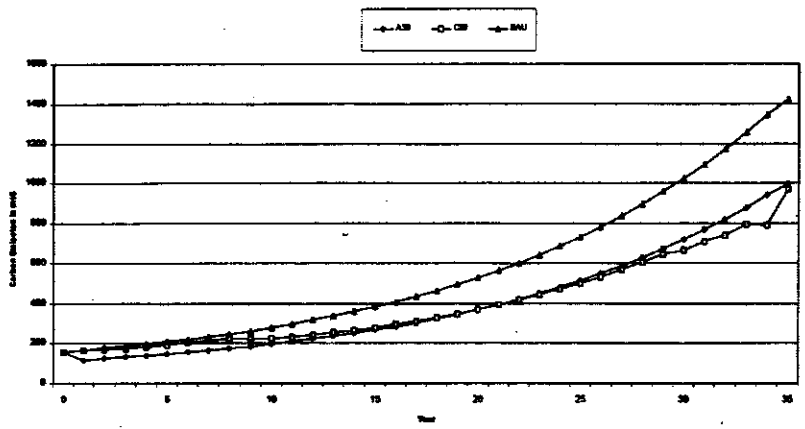

Table 4: Income and Consumption Effects of Carbon Emission Reduction in India

Gross Domestic Product (Rs. Billion)							
Year 3	4850	-0.02	-0.02	-0.19	-0.47	-3.79	-11.86
Year 5	5301	-0.02	-0.02	-0.17	-0.47	-2.83	-10.45
Year 10	6801	-0.03	-0.03	-0.62	-0.59	-2.93	-9.07
Tear 20	12307	-0.02	-0.30	-1.45	-0.59	-3.30	-10.17
Year 30	24595	-0.53	-1.36	-4.06	-0.69	-3.66	-10.70
Per Capita Consumption (Rs.)							
Year 3	3758	0.00	0.00	-0.21	-0.48	-4.18	-12.43
Year 5	3902	0.00	0.00	-0.21	-0.44	-3.13	-11.05
Year 10	4431	-0.02	-0.02	-0.74	-0.59	-3.14	-9.86
Tear 20	6520	-0.02	-0.41	-2.42	-0.71	-3.74	-11.86
Year 30	10888	-0.63	-1.85	-4.95	-0.81	-4.14	-12.03
Cumulative Emissions (mtc)	20353	-10.00	-20.00	-30.00	-10.00	-20.00	-30.00
BAU: Business as usual							
A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU							
C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU							

Source: IGIDR Model results

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As the emission restriction level is tightened from 10% to 20% and further to 30%, the effects on long run GDP and welfare become increasingly adverse. Thus, GDP falls by 0.53%, 1.36% and 4.06% and the number of poor increases by 2.1%, 5.9% and 17.5%, in the 30th year for 10%, 20% and 30% cumulative carbon emission restrictions, respectively (Tables 4 and 5). The flexibility of the economic system gets reduced, as emission restriction becomes tighter. Also, note that the loss in GDP and consumption is nonlinear, i.e., loss rises at an increasingly faster rate than emission restriction. For the case of a 30% restriction, even the short run effects (up to 5 years) are noticeable: GDP and per capita consumption loss is about 0.2% and incidence of poverty is higher by 0.3% compared to the BAU scenario. Furthermore, the losses are more severe toward the end of the target period (30th year) than near the beginning of the restriction period. The model tries to postpone the economic losses due to two reasons: it discounts the future consumption flows and it also enjoys the facility of attaining an emissions reduction target over a 35-year period rather than in just one or two years. Consequently, emission reduction also gets postponed to the last years of the time horizon in the cumulative reduction scenarios (such a flexibility does not exist in the case of annual reductions). Figure 1 very clearly reveals this for the C30 scenario.

Table 5: Poverty Effects of Carbon Emission Reduction in India

Number of Poor (Million)							
Year 3	298.80	0.03	0.03	0.34	0.77	6.58	20.67
Year 5	292.35	0.03	0.03	0.33	0.72	5.04	18.90
Year 10	258.83	0.04	0.04	1.34	1.04	5.70	19.02
Tear 20	139.58	0.08	0.99	5.95	1.65	9.42	33.22
Year 30	39.43	2.10	5.94	17.48	2.45	14.34	49.65
BAU: Business as usual							
A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU							
C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU							

Source: IGIDR Model results

Next, we consider the impacts of imposing annual reduction targets for CO_2 emissions. A 10% annual reduction target over each year of the 35-year period (scenario A10) achieves the same reduction over the period as the 10% cumulative reduction scenario (C10). But the economic losses are larger under the annual reduction scenario than the cumulative reduction of the same order. The impact differences between annual and cumulative emission reduction scenarios turn out to be particularly large with a higher order of reduction. For example, in the 20% restriction case, annual constraints lead to a GDP fall of 3.66% in the 30th year as compared to 1.36% for cumulative constraint. The GDP is lower by a whopping 10.7% for the 30% annual reduction case (Table 4). A large annual reduction in carbon emission becomes possible by diverting substantial resources for this purpose, and growth is adversely affected given the constraint on total resource availability. Annual constraints are more restrictive than cumulative constraints because they deprive the economic system of its freedom to choose an adjustment path over time, though the terminal period carbon stock level is the same under both types of constraints.

The short-run effects are also large for the case of annual constraints. GDP losses in the 3rd year vary from 0.47% in the case of 10% annual emission restriction to 11.86% for the 30% restriction. The increase in the number of poor is a large 20.67 percent increase, even in the short run, and in the 30th year the number of poor increase by nearly 50 percent, for a 30% annual reduction, which indicates a significant short run burden on the lower income segment of the population (Table 5).

The model results for alternative activity levels for the 5th and 30th years are presented in Table 6. These results clearly illustrate that, when a CO_2 emission constraint is active, India would shift away from coal-based electricity to oil- and gas-based electricity and from coal-boiler based manufacturing to oil-boiler based manufacturing. There is, however, no change-over to a new technology in the short run, when a cumulative restriction of 20% or less is affected.

Table 6: Effects of Carbon Emission Reduction on Selected Activities in India

Selected Activity Levels in Year 5							
Electricity-coal	216	216	216	173	162	142	129
Elecctricity-others	41	41	41	41	52	64	58
Electricity-oil	16	16	16	16	16	10	0
Electricity-CCGT	0	0	0	37	37	42	47
Industry-coal	3962	3961	3961	3895	3734	2330	2074
Industry-oil	0	0	0	0	164	1454	1350
Selected Activity Levels in Year 30							
Electricity-coal	1190	664	635	616	901	704	575
Elecctricity-others	10	269	289	280	36	197	251
Electricity-oil	4	4	4	0	4	4	4
Electricity-CCGT	0	229	227	224	230	221	202
Industry-coal	17526	17421	4879	1172	17362	16320	14317
Industry-oil	0	0	12689	16193	41	403	801
BAU: Business as usual							
A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU							
C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU							

Source: IGIDR Model results

V. CONCLUSIONS

The climate change problem due to carbon dioxide emission from anthropogenic sources in the industrial age has attracted the attention of many nations. Even as the world community is moving toward reduction of such emissions on an urgent basis, it also understands the need for the low income developing countries to attain a decent standard of living. Hence, it is recognized, as in the Kyoto Protocol, that a global CO_2 emission reduction strategy must safeguard the developmental objectives of the developing countries. It is for this reason that India has rightly been excluded from undertaking any binding commitment to CO_2 emission reduction.

However, the two largest countries—China and India—might contribute significantly to incremental carbon emission in the coming decades. They need to explore whatever possible emission reduction measures they can take without compromising their income growth and poverty reduction objectives. In this paper, we have attempted to examine the impact of alternative levels of carbon dioxide reduction measures from a 'business as usual' scenario on growth and poverty in India.

The results from the scenarios suggest that annual emission reductions impose costs, in terms of reduced GDP and higher poverty, both in the short and the long run, through distortions in the choice of

techniques in electricity generation as well as in energy use in industry. The quantitative dimension of the GDP fall could vary from about 0.5 - 0.7% in the case of a 10% reduction in emission to as high as 12% in case of a 30% annual emission reduction. Cumulative emission reduction targets are preferable to annual reduction targets and a dynamically optimum strategy can help reduce the burden of emission reductions. Even cumulative reduction targets increase poverty by a larger percentage, in the range of 2.1-17.5% as compared to GDP reduction of 0.5 - 4.1%, in the 30th year. GDP loss of this order is not negligible in the long run.

Thus, emission reduction imposes costs in terms of lower GDP and higher poverty. India cannot have any obligation to reduce its carbon emissions for quite some time without sacrificing its basic development objectives of GDP growth and poverty removal. If India were to reduce its carbon emissions for the sake of the global good, it should have sufficient built-in compensation or incentives for such an action. The 'flexible mechanisms' of the Kyoto Protocol, like international emission trading and clean development mechanisms (CDM), could provide such incentives to developing countries[5].

At the end, we might turn to some major limitations of the present exercise and indicate a scope for further work. First, we have not considered uncertainties in this exercise. We note that the model used here is a policy model and not a prediction model. We have adopted the BAU scenario as the most likely future path as per our judgment and considered "if-then" type comparative static exercises. It is possible that the economy would take a different path than the one depicted in the BAU scenario, even in the absence of any policy action on carbon reduction. This is the reason why we have put emphasis on deviations from the BAU scenario. As long as the BAU scenario broadly represents the path the economy would take, both the BAU and the policy scenarios would change in a similar manner and 'deviations' would be more or less representative. Even then, big uncertainties cannot be ruled out in the context of the long time horizon. In such a situation even the policy responses may differ. Given the limited time and resources available for this study, experiments with alternative BAU scenarios were not possible.

Second, we have experimented with known and feasible technological options. It is possible that new technological opportunities in the coming decades would help to significantly increase reduction of carbon emissions. In particular, low cost and large scale solar and wind energy generation, if and when these become available, would open up non-carbon energy options and carbon reduction could be feasible at a lower cost than what is estimated here.

[5] See several interesting papers in Toman (2001) in this regard.

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$$\{K_1\} = \{\bar{K}_1\} \tag{6}$$

We have computed $\{\bar{K}_1\}$ using equation 5 as an equality for t=1, assuming that there was full capacity utilization in that year. Capital stock for the later periods is accumulated through investment (Z) which mature into new capacity after a lag of one period.

$$K_{j,t} \leq (1-d_j)K_{j,t-1} + Z_{j,t-1} \tag{7}$$

where d_j is the rate of depreciation of capital stock in sector j.

The aggregate level of investment is constrained by the total savings generated in the economy. The model chooses consumption and savings levels for each period by optimizing the inter-temporal preferences. To counter the possibility of high savings rates resulting in unrealistically low consumption levels we impose an upper limit on the aggregate investment by specifying a marginal savings rate (s).

$$\sum_{j=1}^{m} Z_{j,t} \leq S^0 + s(GDP_t - GDP_0) + F_t \tag{8}$$

where F_t is the exogenously specified level of foreign capital inflows in period t.

The investment by sector of destination (Z) such as agriculture or electricity must be balanced against the investment goods available by sector of origin (N) such as machinery or construction. Therefore, we have

$$\sum_{j=1}^{m} k_{i,j} Z_{j,t} \leq N_{i,t} \tag{9}$$

where k_{ij} is capital coefficient indicating amount of i-th type of capital per unit investment in sector j.

Turning now to trade, we impose the constraint the total value of imports cannot exceed the foreign exchange available either through export earnings or through inflows of foreign capital (F_t).

$$\sum_{i=1}^{n} M_{i,t} \leq \sum_{i=1}^{n} E_{i,t} + F_t \tag{10}$$

The export markets are not unlimited for India and an upper bound on the growth rate of exports is more realistic.

$$E_{i,t} \leq E_{i,t-1}(1+g_i^{EU}) \tag{11}$$

where g^{EU} is upper bound on growth of exports. Similarly, import upper bounds are also used for a few sectors on grounds of food security as well as limited trade possibilities in sectors like electricity and transport.

$$M_{i,t-1}(1+g_i^{MU}) \geq M_{i,t} \tag{12}$$

where g^{MU} is the upper bound on imports.

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Typically, in the literature, a two-parameter standard lognormal probability density function (*SLN*) underlies the distribution function *f*. The two parameters are the Lorenz ratio (*LR*) and the per capita expenditure (*PC*). We calculate the proportion, $pop_{p,t}$, of people in the *p*-th class using the value of PC_t chosen optimally by the model and the class expenditure boundaries (e^{p-1} and e^p) for the *p*-th class and the value of the Lorenz Ratio (*LR*), each specified exogenously. The magnitude of population in the *p*-th class is given as

$$POP_{p,t} = POP_t \cdot pop_{p,t} \qquad \text{where} \quad pop_{p,t} = f(PC_t; LR, e^p) - f(PC_t; LR, e^{p-1}) \tag{17}$$

$$f(PC_t; LR, e^p) = SLN\left(\frac{1}{LR}\ln(\frac{e^p}{PC_t}) + \frac{LR}{2}\right) \qquad \text{where} \quad SLN(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{s^2}{2}} ds \tag{18}$$

Note that $e^0 = 0$ and $e^3 = \infty$ which yields $f(PC_t; LR, 0) = 0$ and $f(PC_t; LR, \infty) = 1$.

The average consumption expenditure $PCC_{p,t}$ of class *p* can be computed as:

$$PCC_{p,t} = \frac{PC_t \cdot SLN\left(\frac{1}{LR}\ln(\frac{e^p}{PC_t}) - \frac{LR}{2}\right)}{f(PC_t; LR, e^p)} \tag{19}$$

A representative consumer of the *p*-th class is allowed to choose a linear combination of *R* different types of commodity bundles. Her consumption expenditure budget ($PCC_{p,t}$) is allocated across the *R* bundles in each time period *t* so that the following identity holds.

$$PCC_{p,t} = \sum_{r=1}^{R} PCB_{r,p,t} \tag{20}$$

Each commodity bundle is composed of different commodities in fixed proportions. For example, $\mu_{i,r,p}$ is the expenditure share of commodity *i* in the *r*-th bundle available to a consumer of class *p* and this value remains fixed in the model. Nevertheless, the consumer achieves a degree of substitution between different commodities by choosing the combination of different bundles and the amounts she spends on each of them. The consumption vector (*C*) of each class as the aggregate over the set of *R* consumption bundles.

$$C_{p,i,t} = POP_{p,t} \cdot \sum_{r=1}^{R} \mu_{i,r,p}\, PCB_{r,p,t} \tag{21}$$

The economy-wide consumption vector {*H*} is then represented by the sum of consumption vectors corresponding to the individual classes.

$$H_{i,t} = \sum_{p=1}^{P} C_{p,i,t} \tag{22}$$

Since the distribution parameter (*LR*) is fixed in our model, poverty alleviation requires growth in consumption, which is chosen optimally in the model subject to the constraints.

Another point to note in this connection is that we have used the GAMS program to solve the model. GAMS, however, does not permit equations with standard lognormal functions, SLN(.) above. It, however, permits a loop where the SLN function could be computed before obtaining the optimization

Table A1
Model Parameters Related to Activities

Activities	Agri	Coal	Oil	Electricity produced from				Industry		Trans	Service
				Coal	Other	Oil	CCGT	Coal	Oil		
Commodities											
Base Year Input-Output Coefficients : [a]											
Agricult.	0.199		0.000		0.003			0.092	0.092	0.002	0.019
Coal	0.000	0.011	0.000	0.184				0.011	0.004	0.006	0.001
Oil	0.010	0.027	0.469			0.157	0.132	0.016	0.040	0.097	0.008
Electricity	0.007	0.096	0.005	0.248	0.248	0.248	0.186	0.031	0.031	0.015	0.007
Industrial	0.075	0.196	0.042	0.076	0.076	0.076	0.076	0.342	0.342	0.171	0.063
Transport	0.012	0.044	0.012	0.045	0.045	0.045	0.045	0.035	0.024	0.068	0.034
Service	0.038	0.074	0.064	0.045	0.045	0.045	0.045	0.119	0.119	0.079	0.058
Make matrix: [u]											
Agricult.	1	0	0	0	0	0	0	0	0	0	0
Coal	0	1	0	0	0	0	0	0	0	0	0
Oil	0	0	1	0	0	0	0	0	0	0	0
Electricity	0	0	0	1	1	1	1	0	0	0	0
Industrial	0	0	0	0	0	0	0	1	1	0	0
Transport	0	0	0	0	0	0	0	0	0	1	0
Service	0	0	0	0	0	0	0	0	0	0	1
Capital composition matrix: [k]											
Capital goods											
Agricult.	0.15	0	0	0	0	0	0	0	0	0	0
Industrial	0.8	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958
Transport	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Service	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
Base Year Output (10^{12} rupees)											
	1.810	0.064	0.219	0.140	0.054	0.022	0.000	3.028	0.000	0.418	1.832
Incremental capital output ratio: diagonal elements of [b]											
	2.046	1.483	1.500	5.348	6.750	6.750	6.270	0.828	0.845	3.286	1.110
Initial capital stock (10^{12} rupees)											
	3.704	0.095	0.329	0.749	0.365	0.149	0.000	2.508	0.000	1.374	2.034
Emision coefficient: [e] in grams/rupee											
CO2	0.55	39.36	13.98	399.52	0.00	221.40	85.00	17.46	12.04	47.92	1.11

1) I-O table [a] is aggregated from a 60x60 absorption matrix obtained from Planning Commission (1991).
2) Capital Coeff. matrix is obtained by taking the composition of investment demand from 1989-90 I-O matrix and assuming that the investment goods from agriculture sector are entirely used by agriculture sector itself.
3) Base Year capital stock is the product of ICOR and base year output.

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Table A2
Model Parameters Related to Commodities

Budget shares of different goods in private consumption expenditure of households							
Bottom class: {c1}	0.5594	0.0011	0.0075	0.002	0.23	0.03	0.17
Middle class: {c2}	0.4213	0.0009	0.0135	0.0052	0.2803	0.0457	0.2331
Top class: {c3}	0.2915	0	0.0196	0.01	0.3139	0.075	0.29
Budget shares of different goods in government consumption expenditure							
{g}	0.0027	0.0001	0.0195	0.0253	0.1716	0.0257	0.755
Upper bounds on annual growth rate of Imports							
g^{MU}	0.05			0.02		0.05	
Upper bounds on annual growth rate of Exports							
G^{EU}	0.05				0.12		0.12
Base year values (10^{12} rupees)							
Private consumption: C_0	1.077	0.002	0.042	0.017	0.781	0.172	0.741
Govt. consumption: G_0	0.001	0	0.01	0.013	0.088	0.013	0.386
Export demand: E_0	0.029	0	0.005	0	0.204	0.031	0.099
Import demand: M_0	0.016	0.006	0.056	0	0.345	0.039	0.027

1) Budget shares in private consumption classes are from Parikh, Panda and Murthy (1994).
Variations in budget shares are permitted around these base values as discussed in the text.
2) Government budget shares are from 1989-90 I-O matrix.
3)Imports and exports bounds appear only for some sectors indicated above.

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	Table A3	
	Other Model Parameters	
1	Total investment in base year in 10^{12} rupees	0.991
2	Maximum domestic incremental savings rate	0.300
3	Annual growth rate of government consumption	0.050
4	Annual foreign borrowings in the dynamics-as-usual scenario (in 10^{12} rupees): Ft	0.120
5	Annual social discount rate:	0.100
6	Post-terminal annual growth rate	0.055
7	Population in base year in 10^6	821.9
8	Annual growth rate of population (%)	1.8
9	Lorenz ratio of private consumption expenditure distribution: LR	0.38
10	Upper cut-off level of expenditure for bottom class: (rupees)	2250
11	Upper cut-off level of expenditure for middle class: (rupees)	4000

Municipal Solid Waste Management for Climate Change Mitigation

MUNICIPAL SOLID WASTE MANAGEMENT FOR CLIMATE CHANGE MITIGATION

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I. STRUCTURE OF PRESENT PAPER

Methane is a Greenhouse Gas (GHG), twenty one times more potent than carbon dioxide. Decomposition of the organic components of municipal solid wastes is one of the major sources of methane generation. Proper management of municipal solid waste through reduction of waste, utilization of reusable parts, and transformation of waste into economically useful products will reduce the volume of waste disposed of and left out for decomposition, and would thus reduce methane emission.

This paper starts with a brief introduction to climate change, sources of greenhouse gas emissions and contribution, etc. The main thrust of the paper is how, through proper management of municipal solid waste, methane emission could be brought down, a step toward climate change mitigation. The paper gives a brief introduction to various solid waste management techniques and discusses in detail the biomethanation process where generated methane could be transformed to energy for useful purposes.

II. INTRODUCTION

A. *Sources of Methane Emissions*

Methane is produced from a wide variety of anaerobic processes. Two main pathways for methane production have been identified. These are (i) reduction of CO_2 with hydrogen, fatty acids or alcohols as hydrogen donors and (ii) transmethylation of acetic acid or methyl alcohol by CH_4 producing bacteria. The major anthropogenic sources of methane emissions include rice cultivation, livestock and other animals, biomass burning, coal mining, oil and gas systems, and landfills. It is estimated that 525 Tg CH_4 is emitted per year into the atmosphere from all natural and anthropogenic sources as indicated in Table 1.

Table 2 gives an estimate of methane emissions from India due to various anthropogenic activities.

Ice core data indicate that the atmospheric concentration of methane (CH_4) averaged around 0.8 ppmv between two hundred and two thousand years ago, increasing to 0.9 ppmv one hundred years ago.

Atmospheric methane concentrations have been measured directly since 1978 when the globally averaged value was 1.51 ppmv. Currently, methane concentration in the atmosphere is 1.72 ppmv, corresponding to an atmospheric reservoir of about 4,900 Tg ($1Tg = 10^{12}g$), and it is increasing at the rate of 14.617 ppmv per year (40 to 48 Tg per year) or 0.8 to 1.0 percent per year. The atmospheric concentration of CH_4 in the Northern Hemisphere is 1.76ppmv, compared to 1.68ppmv in the Southern Hemisphere.

While methane's concentration in the earth's atmosphere is small, it has a significant contribution to future global warming because it is a potent greenhouse gas with its global warming potential 21 times more than that of carbon dioxide. The contributions of various gases to the total increase in climate forcing during the 1980s is shown as a pie diagram in Figure 1. Methane currently contributes over 15 percent to the change in radioactive forcing (global warming) from 1980 to 1990.

Table 1 : Global Estimated Sources of Methane[1]

Natural		
Natural Wetlands	115	100-200
Enteric Fermentation (animal)[2]	80	65-100
Termites	40	10-100
Oceans	10	5-20
Freshwater	5	1-25
CH_4 Hydrate Destabilisation	5	0-100
Human Activities		
Rice Paddies[3]	110	25-170
Gas Drilling, venting, transmission	45	25-80
Biomass Burning	40	20-80
Coal Mining	35	19-50
Landfills	40	20-70
Total	**525**	

Table 2 : Methane Emissions from Human Activities in India[4]

1	Biomass burning	1579
2	Solid Fuels	330
3	Oil and natural gas	626
4	Enteric Fermentation	7563
5	Manure management	905
6	Rice cultivation	4,070
7	Field burning of agricultural residues	116
8	Solid waste disposal on land (landfills)	334
9	Domestic and commercial waste water	49
10	Industrial waste water	2,905

[1] *Scientific Assessment of Climate Change Intergovernmental Panel on Climate Change (IPCC), 1990.*

[2] *Indian domestic livestock population increased from 450 million in 1978 to 467 million in 1992, expected to increase to 625 million in 2020.*

[3] *The paddy-harvested area is 42.32 mha in India – largest in Asia.*

[4] *Asia Least-cost Greenhouse Gas Abatement Strategy : India (ALGAS), 1998*

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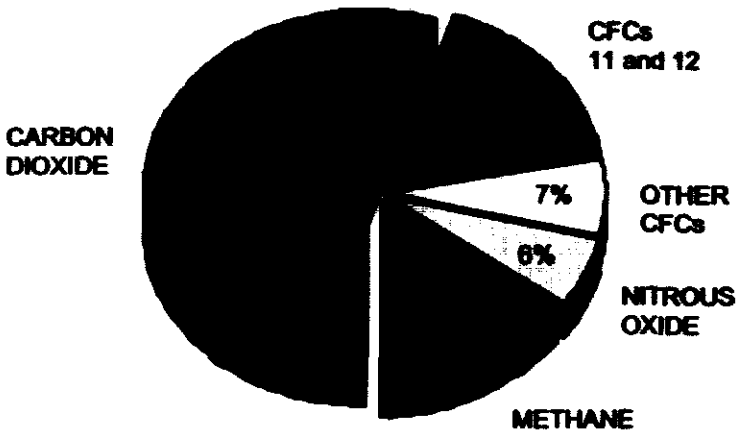
Figure 1 : The Contributions of Human Induced Greenhouse Gases to the Change in Radiative Forcing from 1980 to 1990 (IPCC, 1990)



Concentration of methane in the atmosphere is increasing rapidly. Its strong ability to absorb infrared radiation, combined with its relatively short atmospheric lifetime of 10 years (as against 50-200 years for carbon dioxide), makes its control an important opportunity for mitigation of climate change.

B. Climate Change: Contribution of Methane, particularly from Municipal Solid Waste

The solid waste arising from domestic, commercial and industrial activities has become one of the major environmental problems causing excessive pollution and threat to human health. The problem gets worse because of the fact that solid wastes are often indiscriminately disposed of. The problems are already acute in cities and towns as disposal facilities are not keeping pace with the quantum of waste generated.

In India, ironically, only a small fraction of the total waste generated is disposed of through the various disposal techniques available; a large part of the waste is simply dumped in open dump-yards. Decomposition of solid waste, when dumped into dump-yards without any disposal, gives rise to the generation of methane, which is a greenhouse gas and responsible for global warming, climate change and related impacts.

Methane emissions from solid waste are a major cause for concern in developed countries, and these countries have started recovery of methane from landfills and its re-use for energy recovery. However, in India, there are no landfills and solid waste is simply dumped in open dump-yards. This does not provide us an opportunity for methane recovery. In view of this, other options for the disposal of waste and recovery of resources from the waste should be tried out so that methane emissions from municipal solid waste are reduced.

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III. MUNICIPAL SOLID WASTE GENERATION IN INDIA

Municipal solid waste is defined as refuse from households, waste from commercial establishments, refuse from institutions, market waste, yard waste and street sweeping (World Bank, 1994). The quantity of MSW generated by a city depends upon a number of factors such as food habits, standard of living and degree of commercial and industrial activity in the city.

In 1982, a study was conducted by the World Health Organization on 'Rapid Assessment of Sources of Air, Water and Land Pollution'. As per the study, per capita municipal solid waste generated in the lowest income areas in South East Asia is 0.4 kg/day. The National Environmental Engineering Research Institute (NEERI), Nagpur, through its surveys, has reported that in cities like Bombay, Calcutta and Hyderabad, the generation of solid wastes varies from 0.33 kg / capita / day to 0.5 kg / capita / day.

A similar study, conducted by the Environment Protection Training Research Institute (EPTRI), Hyderabad, has shown that in Indian towns and cities the per capita wastes generated range between 0.3 kg / day to 0.6 kg / day. India has about 300 class I cities and towns. A recent survey by the Ministry of Non-Conventional Energy (MNES) indicates that about 56,900 metric tons per day of solid waste is generated from the cities/towns in India.

A. Quantum of Wastes Generated

The generation of solid waste is directly related to consumption patterns. Within India, there is a large inter-city variation as far as per capita waste generation is concerned. According to the Central Pollution Control Board (CPCB, 1995), the daily per capita generation of solid waste in small, medium and large cities/towns is about 0.1 kg, 0.3 to 0.4 kg and 0.5 kg, respectively. Twenty-three metropolitan cities, which contain as much as 32.5 percent of the urban population according to the 1991 Census, are the major contributors to the total waste generated in the country. Table 3 shows that 23 cities together generate 37.7 thousand tons out of 65.37 thousand tons of solid waste generated every day in urban areas of the country. In view of these facts, management of solid waste is primarily an urban issue in India.

Table 3 : Quantity of Solid Waste Generated in Metropolitan Cities

Mumbai	5000	Jaipur	1021
Calcutta	3500	Kochi	680
Delhi	4600	Coimbatore	710
Chennai	3500	Vadodara	900
Hyderabad	2800	Indore	800
Bangalore	2700	Patna	714
Ahmedabad	1600	Madhurai	711
Pune	1527	Bhopal	500
Kanpur	1314	Vishakapatnam	630
Nagpur	1100	Varanasi	660
Lucknow	1043	Ludhiana	656
Surat	1000		
Total		**37,666**	

Source: Central Pollution Control Board, 1995

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B. Composition of Indian MSW

The composition of MSW in India indicates lower organic matter and high ash or dust contents. It has been estimated that recyclable matter in Indian solid wastes varies from 13 to 20 percent and compostable materials from 35-45 percent. A typical composition of Indian Solid wastes is given in Table 4.

Table 4 : Composition of Indian MSWs

Vegetable, leaves	40.15
Grain	3.80
Paper	0.81
Plastic	0.62
Glass/Ceramic	0.44
Metal	0.64
Stones / ashes	41.81
Miscellaneous	11.73

Source: Central Pollution Control Board, 1995

C. Physical & Chemical Characteristics of Indian MSW

Knowledge of the chemical characteristics of the MSW is essential for selecting and designing the waste processing and disposal facilities. The physical and chemical characteristics of Indian MSWs are given in Table 5 and Table 6 below.

Table 5 : Physical characteristics of MSWs in Indian Cities

01. to 0.5	12	2.91	0.78	0.56	0.33	44.57	43.59
0.5 to 1.0	15	2.95	0.73	0.56	0.32	40.04	48.38
1.0 to 2.0	09	4.71	0.71	4.56	0.49	38.95	44.73
2.0 to 5.0	03	3.18	0.48	0.98	0.59	56.67	40.07
5.0 and above	04	6.43	0.28	0.94	0.80	30.84	53.90

** all values are in percent and are calculated on net weight basis*
Source : Background Material on SWM, NEERI, 1996

Table 6 : Chemical characteristics of MSWs in Indian Cities*

0.1 - 0.5	12	25.81	37.09	0.71	0.63	0.83	30.94	1009.89
0.5 - 1.0	15	19.52	25.14	0.66	0.56	0.69	21.13	900.61
1.0 - 2.0	9	26.98	26.89	0.64	0.82	0.72	23.68	980.05
2.0 - 5.0	3	21.03	25.60	0.56	0.69	0.78	22.45	907.18
75.0	4	38.72	39.07	0.56	0.52	0.52	30.11	800.70

** All values except moisture, on dry weight basis*
+Caloric value on dry weight basis
Source : Background material for Manual on SWM, NEERI, 1996

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- *Temperature*
  Warm temperature in a landfill speeds up the growth of methane producing bacteria. The temperature of waste in the landfill depends on landfill depth, the number of layers covering the landfill and climate.
- *pH*
  Methane is produced in a neutral environment (close to pH 7). The pH of most landfills is between 6.8 to 7.2.

G. Degradation of MSW

Anaerobic decomposition of MSW in landfills starts sometime after the dumping of the waste. This process consists of several phases. These are :

- *Aerobic phase*
  In this phase, the oxygen present in the landfill is consumed in the (aerobic) degradation of organic compounds. This phase is relatively short (several days to several weeks), since the quantity of oxygen present is limited.
- *Hydrolysis phase*
  In this phase, the large organic molecules are converted into small soluble molecules such as lower fatty acids, simple sugars and amino acids.
- *Acidogenic phase*
  Under anaerobic conditions (absence of oxygen), hydrolized compounds are degraded by bacteria into fatty acids. In this way, the acidity level (pH) is reduced. The gases that are formed in this phase are mainly hydrogen (H_2) and carbon dioxide (CO_2).
- *Methanogenic phase*
  During the methanogenesis phase, the fatty acids formed in the acidogenic phase are decomposed mainly into methane (CH_4) and carbon dioxide (CO_2). The methanogenesis can sometimes take several months to years before methane is formed. In contrast to the microorganisms in the acidification phase, the methane-forming bacteria are sensitive to sudden changes in the environmental condition. It is, therefore, important that during the methanogenic phase the landfill remains under anaerobic conditions.

Because a landfill is highly heterogeneous, the stages described above will occur simultaneously in a landfill.

The rate of degradation is determined mainly by the temperature and moisture content of the wastes. The temperature in the landfill remains initially rather high as a result of heat released in the aerobic degradation (temperature rises to 30-50^{0}C). Due to heat loss to the environment, the temperature falls after a period of time, to values which result in a far slower growth of methane-forming bacteria. This fall in temperature occurs over a period of several years. Ultimately, the temperature will reach a level similar to the temperature of the environment.

Mobility of free water in the landfill body (leaching) ensures that enzymes and bacteria present in the water obtain access to the organic material, which has so far not been degraded. The slow movement of water is one of the reasons that the formation process of landfill gas can take many years.

IV. Municipal Solid Waste Management Practices in India

With about 300 class I cities and towns, India produces nearly 56,900 metric tons of municipal solid wastes per day. In urban areas, the responsibility of solid waste management lies exclusively with the urban local bodies, that is, municipal governments. However, the municipalities in most states in India are not statutorily responsible for collecting garbage from the households. They usually perform the third and fourth stages of the SWM function.

The Government of India has brought out Gazette Notification in September, 2000 on "The Municipal Wastes" (Management and Handling Rules, 2000). These rules shall apply to every municipal

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authority responsible for collection, segregation, storage, transportation, processing and disposal of municipal solid wastes. This 'Notification' will be discussed in greater detail later in this status report

Solid Waste Management (SWM) usually refers to the collection, recycling, resource recovery (composting, waste to energy, etc.), transfer, and disposal of municipal solid waste.

Three major activities involved in the management of MSWs are the following :

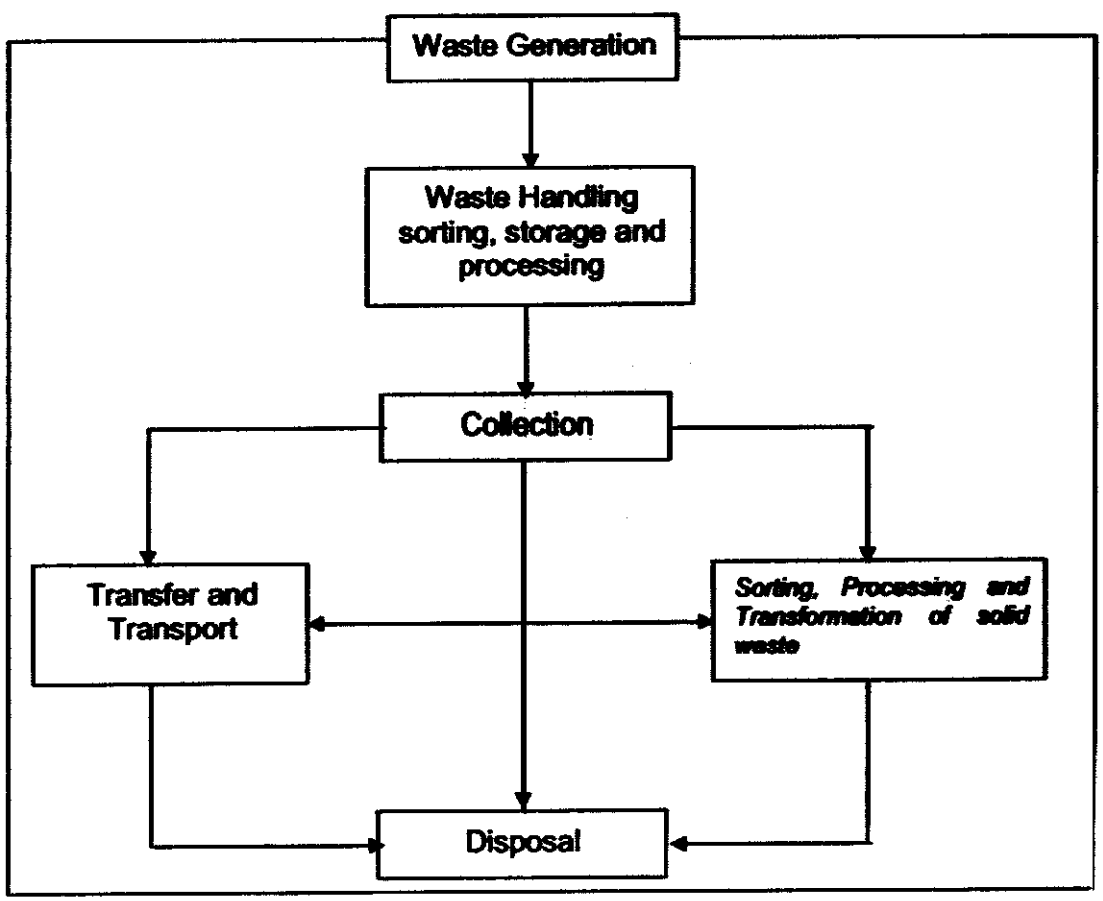
- Collection
- Transportation
- Disposal of wastes

These CTD activities can be further sub-divided into the following :

i. Waste generation
ii. Waste handling, sorting and storage and processing at source
iii. Collection
iv. Sorting, processing and transportation
v. Transfer and transport
vi. Disposal

The inter-relationship between the different activities in the MSWs management process is schematically depicted in Figure 2.

Figure 2 : Functional Elements of a MSW Management System



Source : Manual on Municipal Solid Waste Management, Ministry of Urban Development, Central Public Health and Environmental Engineering Organisation (CPHEEO), GOI, New Delhi, January 2000

The highest rank of the Integrated Solid Waste Management (ISWM) is waste minimization or reduction at source, which involves reducing the amount of wastes produced. Reduction at source is the first in the hierarchy because it is the most effective way to take care of all the issues related to solid waste and its management, the environmental impacts and the cost associated with its handling.

The second highest rank in the hierarchy is recycling, which involves (a) separation and sorting of waste materials; (b) preparation of these materials for reuse or reprocessing; and (c) reuse and reprocessing of these materials. Recycling is an important factor, which helps to reduce the demand of resources and the amount of wastes requiring disposal by landfilling.

The third in rank is waste processing which involves alteration of wastes to recover conversion products (e.g. compost) and energy. The processing of waste materials usually results in the reduced use of landfill capacity. Shredding and compaction may also be undertaken to reduce waste volume. Moreover, such an ISWM has other associated benefits that include reduced public health hazards, reduced surface and ground water pollution, air pollution, and production of compost material for use as fertilizer etc.

Landfilling / dumping is the last in the hierarchy and involves controlled disposal of MSWs on or in the earth's surface.

A. Primary Collection of Garbage from Households and its Transportation to Collection Points

1. Community Efforts

The task of collecting garbage from households and taking it to a collection point primarily is an activity performed by the households themselves. In many cases, where the residents are economically better off and hygienically conscious with active resident welfare associations (RWAs), efforts are made to organize the collection of garbage from each household and transport it to the collection point. These efforts, although still nascent, are now visible in many cities in India.

Instances of finding door-to-door collection of garbage are more common in group housing societies, people staying in high-rise apartments and RWAs in colonies of individual houses. In most of these cases, safaiwallas (cleaners) are employed privately who collect garbage from every household and transport it to a common collection point from where the municipality picks it up. In fact, in Delhi, in the residential colonies constructed by the Delhi Development Authority (DDA), it is stipulated that RWAs have to be formed to provide these facilities, since neither the DDA nor the municipality provides the facility of door-to-door collection of garbage. In Mumbai, in many high-rise apartments, the garbage from all the flats is collected and placed in large bins at the entrance to each apartment. The municipality pickup vehicle comes at a pre-decided time to collect this garbage. In many areas, the pick-up vehicle announces its arrival by ringing a large bell or blowing a horn. This method of collection prevents the accumulation of garbage at round-the corner collection points. In Mumbai, a major nuisance is thus avoided, since the humidity in the atmosphere causes the garbage to degrade very fast, leading to unhygienic conditions. In cities like Delhi, the collection points do become an eyesore, especially if the municipality does not collect garbage regularly. The garbage is seen to spill out on the adjacent road attracting cattle, flies and other stray animals.

The practice of garbage collection from households ceases in most unplanned and unauthorized settlements. The responsibility of taking the garbage to a collection point is with the residents. As a result, the garbage is thrown anywhere along the road or in a vacant plot, and sometimes even in parks. In such places, garbage is swept away by the safai karmacharis.

2. Segregation of Waste and Resource Recovery

A stage between the collection of garbage and its disposal is that of resource recovery. The municipality in any city in India does not do segregation of garbage into biodegradable and non-

biodegradable waste. Since the volumes of garbage handled by the municipality are very large, it would be a very labor-intensive job. Segregation, however, does happen in an informal way before the garbage is disposed of. In door-to-door collection of garbage, the workers involved remove all recyclable items that have a resale value, like plastic items, unsoiled paper, metal pieces, glass, etc. Ragpickers in every city, of course, most efficiently perform segregation.

In India, paper, plastic, glass, rubber, ferrous and non-ferrous metals – all the material that can be recycled – are salvaged from the waste to produce low-cost products extensively used by the lower-income groups of the society. Of the wide array of recyclable material present in Indian household waste, it is paper and plastic that get maximum attention, because the two together form the single largest component of household waste. The reusable materials are sold off in waste recycling centers, which are small-scale industries.
The municipalities, however, are unable to take up any projects on segregation and recycling due to the high costs involved. Segregation of waste into biodegradable and non-biodegradable is done more efficiently in programs run by NGOs. A few efforts have been initiated by NGOs to involve households in separating the garbage into biodegradable and non-biodegradable waste. However, these efforts have never paid off. Such efforts were tried at residential areas of highly academic and aware people like *IIT* and *JNU* in Delhi, but they have not been sustained. Ultimately, paid workers have to be engaged in the task of waste segregation.

B. Secondary Transportation of Garbage

The situation of secondary transportation of garbage is dismal. On average, 20 to 30 percent of the total waste generated remains uncollected, creating environmental hazards in urban settlements. The collection, transportation and disposal of waste are labor-intensive activities. In large metros like Mumbai, some of the Municipal wards have started using modern, automated systems of collection, thereby increasing efficiency. However, in cities like Hyderabad and Ahmedabad, in many areas when the municipality does not collect garbage, the sweepers resort to burning the garbage on the spot, thus creating air pollution problems locally. Very often, the garbage is swept into the open gutters/drains, causing problems of choking and stagnation, which leads to unhygienic conditions.

Solid waste is usually transported in open trucks, compaction vehicles, tractor-trailers or carrier-containers. The vehicles are normally owned and maintained by municipal authorities. Lately, however, a few corporations have resorted to hiring vehicles from private contractors. Hired vehicles have been found to work more effectively and efficiently, if monitored and held accountable for the services they rendered. In smaller (rural) towns, bullock carts, tractor-trailers, power tillers, tricycles etc. are mainly used for the transportation of waste. These vehicles are being used for the primary collection of waste from the streets, as well as for the collection of waste from the dust-bins.

Some of the problems faced in transporting MSW in large towns and cities are listed:

- The number of vehicles is inadequate and the percentage of vehicles remaining off the road is large
- The fleet of vehicles is not optimally utilized
- Transportation fleet does not synchronize with the types of dust-bins provided
- The Hydraulic vehicles need proper maintenance and well-trained staff in the work shops
- *Double handling of waste becomes inevitably necessary*
- Waste handling is done manually and loading and unloading is time consuming. This reduces the productivity of manpower and vehicles
- The system is a potential health hazard for the workers as all type of waste including hospital infectious waste, human excreta etc., are disposed off in the common dust-bin
- Arrangement for the separate collection of infectious hospital waste is practically nonexistent
- Dust-bins are not cleared on a day-to-day basis. Many bins are cleaned once or twice in a week or even less. The backlog thus built up gives rise to unsanitary conditions

C. Actual Disposal of Waste

There are a variety of methods for the disposal of the refuse collected from different collection points in a municipality. According to CPCB (1994), the prevailing technological options for municipal solid waste disposal include:

- Sanitary landfill
- Incineration
- Anaerobic digestion
- Composting
- Fuel pelletization

The prevailing technological options being followed for Municipal Solid Waste (MSW) disposal in our country are (unscientific) land filling, burning in the open and composting. The wastes are normally brought to a designated landfill site, normally a low-lying area on the outskirts of a city. The choice of a site is more a matter of what is available than what is suitable. Only a few cities follow such good practices as organized tipping of wastes, using mechanized equipment for leveling and compacting the wastes, and covering the top layer with earth before compacting it further. In small towns and cities very often the garbage is dumped in ponds or on the banks of a river. In hill towns, the garbage is dumped along the hillside on the outskirts of the town, which attracts monkeys and various other animals. Collection of recyclable items like plastic, paper, etc. and transporting it to large towns for recycling is not an economically sound option. Efforts are required to organize the collection of these recyclable material from hill towns or else these towns will be enveloped by waste.

The lack of a scientific and efficient Municipal Solid Waste Management (MSWM) system in most of the cities and towns poses a serious health and environmental problem. Therefore there is an urgent need to improve the MSWM by capacity building of the municipal managers to modernize (i) collection, (ii) transportation and (iii) disposal systems with a view to waste minimization and reduction of methane emissions. Such a MSWM system must reduce the local and global environmental impacts of municipal wastes and should operate at a cost acceptable to the community.

V. Regulatory Provisions of the Government of India for Management and Handling of MSW

The Ministry of Environment and Forests, Government of India, through the Gazette Notification of 25 September, 2000, has brought into force the Municipal Solid Wastes (Management and Handling) Rule, 2000, applicable to every municipal authority responsible for the collection, segregation, storage, transportation, processing and disposal of municipal solid wastes. As per the notification, the municipal authorities are required to furnish an annual compliance report to the State Government or the District Magistrate on or before 30 June every year and the State Boards and the Committees have to prepare and submit to the GoI an annual report with regard to the implementation of these rules by 15 September every year.

The Rule stipulates detailed compliance criteria and procedures for the management of municipal solid waste by the municipalities in India.

Under the provisions of management of MSW by the municipalities, detailed compliance criteria for (1) collection, (2) segregation, (3) storage, (4) transportation, (5) processing and (6) disposal of MSW have been outlined under Schedule II of the Notification. Under Schedule III, 'Specification for Landfill Sites' has been brought out, particularly under 'Site Selection', 'Facilities at the Site', 'Specification for Landfilling', 'Pollution Prevention', 'Water Quality Monitoring', 'Ambient Air Quality Monitoring', 'Planting at Landfill Site', 'Closure of Landfill Site and Post-care' and 'Special Care for Hilly Areas'. Each of the specifications for landfill sites is further discussed briefly. For details, one should refer to the original Notification of the GoI.

A. Specification for Landfill Sites

Site selection must be based on an examination of the environmental issues. While selecting such sites, either the site should be in the vicinity of a waste processing facility or the waste processing facility should be planned as an integral part of the landfill site. The landfill site selected must be sufficiently large to last for 20-25 years. The landfill site has to be away from habitation clusters, forest areas, water bodies, monuments, National Parks, wetlands and places of important cultural, historical or religious interest. Further, a zone of no-development has to be maintained around the landfill site. These aspects must be incorporated in the land use planning while doing the Town Planning. The site selected should be away from an airport/airbase and approval of airport or airbase authorities must be obtained before setting up of the landfill site.

The landfill site has to be well-protected to prevent entry by unauthorized persons and stray animals. Other important facilities that need to be provided are (i) a waste inspection facility to monitor wastes brought in for landfilling, pollution monitoring equipment, and a weigh bridge to measure the quantity of waste brought into the landfill site.

B. Specification for Landfilling

MSWs should be compacted using compactors to achieve a high density of wastes. Wastes should be covered immediately or at the end of each working day with a minimum of 10 cm of soil, inert debris or construction material until such time as waste processing facilities for composting, recycling or energy recovery are set up, as per Schedule I. Special precautions are needed during and prior to monsoon season (a cover of soil 40-65 cm thick must be spread over the MSW in the landfill).

C. Pollution Prevention

In order to prevent pollution problems from landfill operations, the following provisions are required to be made :

- diversion of stormwater drains to minimize leachate generation, prevent pollution of surface water and avoid flooding and marshy conditions
- a non-permeable lining system at the base and walls of waste disposal areas is to be provided with a high density polyethylene (HDPE) geo-membrane as per specification given in the 'Specification for Landfilling'
- provision for the management of leachates' collection and treatment
- prevention of run-off from the landfill area entering any stream, river, lake or pond

D. Water Quality Monitoring

As regards water monitoring, a water quality baseline within 50 meters of the periphery of the landfill site should be established and recorded properly for future reference. Monitoring of water quality has to be taken up periodically within 50 m of the periphery of the landfill to ensure that ground water is not contaminated beyond acceptable limits.

E. Ambient Air Quality Monitoring

A landfill gas control system and collection of LFG are needed to be installed at the landfill site to minimize odor generation, prevent off-site migration of gases and protect vegetation planted on the rehabilitated landfill.

F. Plantation at Landfill Site

The landfill site, when exhausted, has to be provided with vegetative cover.

G. Closure of Landfill Site and Post-Care

As per the notification, post-closure care of a landfill site has to be conducted for at least fifteen years. A long-term monitoring or care plan should consist of the following :

- maintaining the integrity and effectiveness of final cover on the landfill site
- monitoring leachate collection
- monitoring ground water as required under the provision
- maintaining and operating the LFG collection system to meet the standard

The Notification stipulates compliance criteria for the municipalities as follows :

1	Setting up waste processing and disposal facility	By 31-12-2003
2	Monitoring the performance of waste processing and disposal facilities	Once in six months
3	Improvement of existing landfill sites as per provision of these rules	By 31-12-2001 or earlier
4	Identification of landfill sites for future use and making site (s) ready for operation	By 31-12-2002

H. Disposal of MSW

Landfilling must be restricted to non-biodegradable, inert waste and other wastes that are not suitable either for recycling or for biological processing. Landfilling also has to be carried out for residues of waste processing facilities as well as pre-processing facilities.

VI. Technological Options for Methane Emissions Reduction

The problem of waste mis-management can be addressed through the adoption of improved methods of collection, transportation and scientific and environmentally friendly technologies for the treatment and processing of waste before it is disposed of.

A. Resource Recovery through Waste Processing

Processing of MSW may provide energy (electricity) or rich compost, depending upon the technology adopted. It has been estimated that there is a potential of generating about 1,000 MW of power from urban and municipal wastes and about 700 MW from industrial wastes in the country. The total Indian market for Municipal Solid Waste treatment and disposal technologies (excluding collection and transportation) in 1997 is estimated at US$270 million[7]. The market is projected to grow at an average annual rate of 20 percent during the next 3 years.

B. Advantage of Recovery of Energy from MSW

Generation of energy from MSW has certain distinct advantages, such as:

- The total quality of waste gets reduced substantially
- The quality of leftover waste, from the point of view of causing environmental degradation, is improved
- Demand for land for disposal of wastes is reduced
- Carriage cost is reduced, as garbage need not be carried to a faraway place for dumping

[7] *Field Survey, Ministry of Non-conventional Energy Sources, New Delhi*

- Proceeds from the sale of energy/products (e.g. pellets) improve the commercial viability of a waste disposal project

C. Choice of Technology

The technologies mentioned above have their advantages and disadvantages. Selection of technology for a certain location will depend on factors like quantity and quality of garbage, climatic conditions (such as temperature, rainfall and humidity), local requirements and the lifestyle of the people.

Some of the important physio-chemical parameters that need to be considered for the selection of technology are :

- Size of constituents
- Density
- Moisture content
- Mixed carbon/inert content
- Calorific value.

D. Waste-to-Energy Initiative World-wide

Cities in the developed countries have well-organized waste management systems. Until some years back, landfill had been the accepted system of waste disposal in most developed countries. However, there is now a general trend worldwide to discourage disposal of combustible and organic wastes into landfills. Some of the countries, like Austria, Belgium, Canada, Denmark, Finland, France, Germany, Netherlands, Norway and Sweden have already banned landfills or have decided to reduce reliance on landfills. Landfills occupy large areas of space and also create environmental problems. The wastes produce methane, which is a greenhouse gas affecting the ozone layer.

Incineration is becoming more popular with the growing difficulties in locating landfill sites. But it is found that incineration also produces a lot of pollution from the smoke emitted in the process. Waste left after the process is substantial and has a high concentration of toxic materials. It is found that, with a gasifier by gasifier system of proper design (based on the pyrolysis process) it is possible to process MSW with extremely low contaminating emissions and very little left after the process. The gas produced can be directly used in an IC engine. However, factors like greater capital, operation and maintenance cost and also frequent changes in pollution control regulations are retarding the widespread application of such plants. However, state-of-the art incineration technology now exists that meets the strictest international standards for air emissions. As regards the toxic material getting concentrated in the ash, this occurs because they are present in the feed municipal solid waste. Unlike in options such as composting, in which such toxic materials actually find their way into the environment, the incineration technology actually helps in their isolation for subsequent controlled disposal.

E. The Indian Scene - Potential of Power from MSW

The urban areas of India produce about 30 million tons of solid waste from household and commercial activities every year. It is estimated that there is a potential for generating about 1,000 MW of power from MSW in India. If this potential is to be effectively used, it will not only contribute substantially to the overall power generation capacity but will also give a good return on investment, apart from improving the environment.

So far. the vast energy potential of MSW of urban areas of the country remains almost totally untapped. Unlike in developed countries, the waste of Indian cities has a high fraction of degradable organic matter, between 35% to 75% of garbage compared to only 12% to 15% of garbage in the U.S.A and U.K. As such, the garbage of Indian cities has a very high energy potential.

There are at least seven domestic companies offering technologies and/or turnkey project services for implementing municipal solid waste treatment and disposal projects in the country. Of these companies, only one has been able to successfully implement projects to produce compost based on the aerobic process. Excel Industries Ltd. has an almost 60 percent share of the composting technology market in India at present. The company has developed the low cost composting technology indigenously and has been able to make an impact on the market, creating more demand for its technology. The main reason for the company's success has been its ability to partially fund these projects, and also provide assistance in marketing the end product - ***compost***. However, a number of projects under implementation by the different municipalities are using newer, more capital-intensive technologies such as Biomethanation and Sanitary Landfilling.

This market was virtually non-existent until a few years ago. Several key factors and pressing environmental concerns led to the creation of this market, which has been growing at a fast pace. The major factors[8] that will lead to market growth and are likely to play a dominant role in the future are as follows :

- Strict environmental regulations enforced by the Central Pollution Control Board and the Ministry of Environment and Forests.
- Judicial intervention by the Supreme Court of India, directing municipal corporations / Urban Local Bodies to ensure better municipal solid waste management.
- Financial and fiscal incentives offered by the Ministry of Non-Conventional Energy Sources to encourage the promotion of waste-to-energy projects based on municipal solid waste.
- 74th Constitutional Amendment Act empowering the urban local bodies to make independent decisions on promoting municipal solid waste disposal and treatment projects.
- Emphasis on privatization and allowing private entrepreneurs to promote such projects on a Build-Own-Operate and/or Build-Own-Operate-Transfer basis.

Various technologies are available for utilizing MSW profitably and these can be classified under the following heads :

Biological option (with or without the aid of oxygen)
- Composting
- Biomethanation

Physio-chemical option
- Pellitization

Thermal option
- Pyrolysis
- Gasification
- Incineration
- Plasma arc

All these options of waste processing and recovery of energy and other useful products are discussed one by one. Their comparative advantages and limitations have also been highlighted.

BIOLOGICAL OPTIONS

Composting

Composting can be defined as the biological decomposition of the organic constituents of wastes under controlled conditions. This process can take place in the presence or absence of oxygen, that is, aerobic or anaerobic composting. Aerobic composting, if efficiently carried out,

[8] *US Department of Commerce, 1998-05-13*

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can rapidly produce a pathogen-free product; anaerobic composting requires more time and is seldom free of pathogen or odour problems.

The end product, organic manure, has a very good acceptability among the farmers for agriculture as well as horticulture crops. The organic manure improves soil fertility, soil texture and water retention capacity of soil, thereby increasing production.

There are two main groups of organisms, which decompose organic matter

- Anaerobic bacteria which work in the absence of oxygen, and
- Aerobic bacteria which work in the presence of oxygen.

The main characteristics of anaerobic composting are :

- The process is a lengthy one, extending over a period of 4 to 12 months.
- It is a low temperature process and the destruction of pathogens is accomplished by their exposure to an unfavorable environment over a long period.
- The gaseous products of reduction are methane, hydrogen sulfide and other gases with offensive odors

The main characteristics of aerobic composting are :

- Rapid decomposing, normally completed within 4-6 weeks.
- During the composting period, high temperatures are attained, leading to speedy destruction of pathogens, insect eggs and weed seeds.

The following factors affect the rate of successful composting :

- Moisture content (20 to 30%) and temperature maintenance (65-70°C)
- Regular turning of the heap to ensure uniform moisture content, innoculant content and proper aeration.
- Carbon-to-Nitrogen ratio (20 to 25)

Vermicomposting is composting aided by earthworms. Certain specific species of earthworms can consume organic residue very rapidly and fragment them into much finer particles. For vermicomposting, the most significant aspect is the selection of earthworms. There are three broad varieties of earthworms: surface variety, subsoil and deep burrowing. For vermicomposting, the best variety is the surface variety because they feed on the surface. Some of the species of earthworms that aid in vermicomposting are *Eudrilus eugeniae, Eisenia foetida, Perionyx excavatus*, etc. The following products are obtained from the whole process of vermicomposting :

- **Vermicompost** (end product), which is the castings (excreta) of the earthworms; this is rich in plant nutrients
- **Vermiwash** (by-product), which is a solution of nutrients obtained from the percolation of water through the vermicastings
- The earthworms themselves, which are very good sources of proteins; this is used as feed for fish, poultry and pigs

Vermicomposting has immense potential and has been very successful at the community level. So far it is taken up only on the small scale at the community level. There are no examples of vermicomposting on a large scale. However, the present techniques may be modified and tried to handle large amounts of waste and significantly address solid waste management issues.

Biomethanation / Anaerobic Digestion

This is a process used for production of methane from solid wastes. In this process the organic fraction of the waste is segregated and fed to a closed container (Biogas digestor) where, in the presence of methanogenic bacteria and under anaerobic conditions, it undergoes bio-degradation, producing methane-rich biogas and effluent. Biogas mainly consists of methane

(about 60%), carbon-dioxide (about 40%) and small quantities of NH_3 and H_2S. It has a calorific value of about 5000 k.cal/cu.m. Depending upon the waste composition, the biogas production ranges from 50-150 cu.m./ton of wastes. This biogas can be utilized either for cooking or heating applications or for generating power or electricity through gas engines, gas turbines or steam turbines. The sludge from anaerobic digestion, after stabilization, can be used as a soil conditioner or manure.

PHYSIO-CHEMICAL OPTION

Pelletization

Pelletization is the production of fuel pellets from solid waste. The process is essentially a method that condenses the waste or changes its physical form and enriches its organic content through removal of inorganic materials and moisture. Pellets can be used for heating plant boilers and for the generation of electricity. They also act as a perfect substitute for coal/wood used in home/industry. Pelletization offers the possibility of decentralized garbage treatment facilities.

Pelletization of MSW involves the processes of segregating, crushing, and mixing high and low heat value organic waste material and solidifying it to produce fuel **pellets** or **briquettes**, also referred to as **Refuse Derived Fuel (RDF)**. This can be conveniently stored and transported and used as a supplementary fuel for combustion processes and utility boilers. The calorific value of RDF is about 4,000 kcal/kg and it depends upon the content of combustible organic materials in the waste, additives and binder materials, if any, used in the process.

Table 8 : Evaluation of Pelletization

1. This process results in production of high calorific value pellets 2. Pellets can be conveniently stored and transported 3. Pellets can be used as a supplementary fuel for combustion process and boilers	1. The garbage processing unit cannot be operated during rainy season , as the garbage is too wet 2. High moisture content of Indian MSW increases the cost of drying 3. The process consumes more energy than the biological process, such as composting 4. Uncontrolled burning of pellets may lead to harmful emissions 5. Even a trace amount of plastic content in the pellets can be harmful

THERMAL OPTION

Gasification

Gasification is the process involving partial combustion of a carbonaceous fuel to generate a combustible fuel gas rich in carbon monoxide and hydrogen. A gasifier is actually an incinerator operating under reduced conditions. Heat to sustain the process is derived from the exothermic reactions, while the combustible components of the low-energy gas are primarily generated by the endothermic reactions. The kinetics of the gasification process are quite complex and a subject of considerable debate.

When a gasifier is operated at atmospheric pressure with air as the oxidant, the end products of the gasification process are a low-energy gas typically containing 10% CO_2, 20% CO, 15% H_2 and 2% CH_4 (by volume), with the balance being N_2 and a carbon-rich char. Because of the diluting effect of nitrogen in the input air, the low-energy gas has an energy content in the range of 5.2 to 6.0 MJ/m^3. When pure oxygen is used as the oxidant, a medium-energy gas with

D. Biomethanation Projects – Case Studies

1. Case Study 1 : Nagpur Municipal Corporation

The Nagpur Municipal Corporation plans to treat the city MSW through biomethanation using a Belgian technology called the DRANCO (Dry Anaerobic Composting) process. This project would generate 4.75 MW of electrical power by processing 520 tons of MSW every day. This would also generate 150 tons of sludge.

a. Details of the Technology

The DRANCO process consists of a thermophilic, one-phase anaerobic fermentation step, which is followed by a short aerobic composting phase. Before the waste is fed to the digestor, it passes a pre-treatment, where the particle size is reduced to a maximum of 40 mm in two dimensions and inert material is taken out of the waste stream. The digestion takes place in an upright, closed fermenter, which is fed from the top and from which the material is extracted at the bottom. Before the fresh waste is pumped into the fermenter, it is mixed externally with inoculum. This inoculum is digested residue coming from the fermenter. During this mixing, steam is added into the mixing unit to heat up the substrate to a temperature of about 55°C, which is needed for the thermophilic digestion. During the anaerobic digestion phase in the enclosed digestor, the degradable organic material is converted into biogas.

The digested residue is extracted from the digestor, dewatered to a dry matter content of about 50°C and then aerobically stabilized during a period of approximately two weeks.

Table 10 : Salient Features of the Project

1	Name of the project	Municipal Solid Waste to Energy, Nagpur
2	Mode of implementation	BUILD, OWN, OPERATE
3	Name and address of Investor/ Promoter	M/s. Enbee Infrastructure Ltd. Plot No.5, Zone -II, M.P.Nagar, Bhopal -462001, M.P.
4	Location of the project	Bhandewali/Nagpur
5	Type of Waste	Municipal Solid Waste
6	Quantity of Waste available from (Corporation/Council/Solid waste/ sewage)	520 MT/day
7	Land Requirement	10 acres
8	Power Requirement	750 Kwh
9	Water Requirement	151cum/day
10	Estimated cost of the project	Rs. 4730 lakhs

Table 11 : Post - Treatment Products and Recovery Per Day

1	Manure	65100 MT/Year	49500 MT/Year
2	Power	42.77 million units/Year	37.62 million units/year
3	Scrap	4000 MT/Year	3900 MT/Year

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b. Proposed Power Generation Capacity

a) Installed Capacity		:	5.4 MW (generation)
b) Auxiliary Consumption		:	0.75 MW
c) Net generation capacity utilization (in %)			
1st Year	60%	:	25.66 MKwh
2nd Year	65%	:	27.80 MKwh
3rd Year	75%	:	32.08 MKwh
d) Nearest substation of MSEB		:	Wathoda
e) Utilization of power generated		:	
i. Captive use		:	0.75 MW
ii. Sale to third party		:	4.0 MW

c. Status of Disposal of Wastewater after Power Generation

The wastewater generated will be disposed off after proper biological treatment, according to Nagpur Municipal Corporation.

This project has been taken up as pilot study, but due to operational problems, the project has been abandoned.

1. Case Study 2 : Lucknow Project

The Lucknow project would treat MSW using **BIMA** (Biogas Induced Mixing Arrangement) digestors. This technology has been developed by M/s Entec of Austria. Their technical collaborators in India are M/s Enkem Engineers Pvt. Ltd, a Chennai based environmental engineering company. The plant would treat 350 TPD of MSW in the first phase and generate 5 MW of power. The Entech technology is suitable for high-BOD waste materials having some sulfate content. The digestor converts the waste materials into biogas and 75 tons of sludge.

a. Details of the Technology

The **BIMA** digestor is an anaerobic digestion system. The **salient features** of the **BIMA** system are as follows:

- There are no moving parts for mixing; so this reduces installation, service and maintenance costs
- There are no narrow pipes inside the digestor; so clogging does not occur
- The main chamber of the digestor can take wastes with a dry matter content up to 12%; resulting in shorter residence times , smaller volumes and a reduction in investment costs
- No short passes are possible in the chamber system and hence there is a plug flow effect

BIMA digestors can be operated at mesophilic (15-35° C) or thermophilic (55-65° C) temperature ranges, depending on the type of substrate and the process requirements.

It is also possible to design a two stage anaerobic digestion if required. The methane content of the gas is 60-65%.

b. Process Description

The **BIMA** digestor is divided into three separate sections, and interconnected to provide passage for flow of liquids and gas. The three chambers are the main chamber, the upper chamber and the central tube to which the feed pipe is connected. In the central tube, pre - hydrolysis of the substrate takes place. Most of the biogas is generated in the main chamber through the decomposition of organic materials. By closing an automatic valve in the gas pipe between the two chambers, the gas produced in the main chamber stays there, which in turn displaces an equal amount of digested substrate to the upper chamber. This builds a level difference. When the required level difference is achieved, the

gas is released to the upper chamber by an opening in the valve in the gas connecting pipe. Thus, the substrate displaced in the upper chamber flows back to the main chamber with high velocity. A portion of the waste flows to the main chamber through the mixing shafts. On account of this fresh substrate, scum and sediments are perfectly mixed with the contents of the main chamber. Thus the new pre-hydrolyzed substrate is mixed with active biomass in the digestor. Another portion of the digested substrate, which flows through the mixing shafts, pours onto the surface of the main chamber, thus avoiding scum.

This patented way of mixing ensures that the most important zones of the digestor are optimally controlled by :

- The turbulent mixing of the substrate
- The distribution of degradation products from the bacteria as well as the optimum supply of fresh substrate to them
- The control and stirring up of settled sludge
- The control, destroying and mixing of the skimming

3. *Case Study 3 : Tata Energy Research Institute (TERI), New Delhi*

TERI has developed a two-stage process consisting of acidification and methanation, called the TEAM process. The study has been conducted on mixed vegetable waste: cauliflower, cabbage , radish , spinach , mustard and carrot, procured from a local vegetable market. Anaerobic batch digestion of this waste has been done at 5% TS concentration in a 10 liter capacity digestor. Digestion of waste after 47 days resulted in 0.16 m^3 of biogas per kg of TS added. This biogas had a CH_4 content of 68.4%. The decline in COD of vegetable waste slurry was approximately 65%. Degradation of the waste was also studied in a solid bed reactor of 64.3 liter capacity by sprinkling water at regular intervals. The COD of the leachate obtained from the solid bed digestor ranged between 1,500-25,000 mg/l.

a. Details of the Technology

The TEAM (TERI's Enhanced Acidification and Methanation) process is a two - stage process consisting of acidification and methanation. In the acidification phase, the organic content of the solid waste is leached out to make a high strength liquid of 20,000 mg/l COD by decomposition of the waste with continuous sprinkling of water. In the methanation phase, this high strength leachate is treated in a high rate UASB (Upflow Anaerobic Sludge Blanket) reactor to produce biogas. The sludge produced after digestion is dried to produce good quality manure.

b. Process Description

- Acidification reactor

The acidification reactor consists of a rectangular digestor, a filter and a reservoir. The rectangular digestor has a water seal opening at the top, which provides an anaerobic environment in the digestor. Shredded waste is loaded into the digestor from this top opening. The bottom reservoir is filled with fresh water, which is sprinkled over the shredded waste bed in the digestor by means of a perforated sprinkler situated in the door of the top opening. Liquid percolates through the bed of the waste and collects in the reservoir through the filter. The collected leachate is recirculated using a small pump. The process continues till extraction of the organic matter from waste into the leachate is complete. The leachate has a COD (Chemical Oxygen Demand) of 20,000 mg/l. An arrangement for the periodic removal of digested solid waste is provided in between the filter and reservoir. Dried digested solid waste is a good quality manure consisting of 2.1% of nitrogen, 1.6% of phosphorus and 24% of potassium.

- *Methanation of leachate in the UASB reactor*

The leachate collected from the acidification reactor is treated in a UASB reactor. The Microbial

consortia in the granular sludge degrade 90% of the organic matter present in the fed leachate and convert it to a high calorific value fuel, i.e. biogas. The gas formed constitutes of 70-75% methane, 20-25% of carbon dioxide and traces of hydrogen and hydrogen sulfide. Treated leachate can be recycled back to the acidification reactor for sprinkling. Thus, the use of water is minimal, unlike in a conventional biogas plant.

VIII. CONCLUSION

Municipal solid waste and its improper handling and disposal methods pose a serious threat to human beings and their environment. A large part of the total waste generated in India is simply dumped in open dump-yards, giving rise to unhygienic surroundings, health hazards, contaminators of ground water, an unclean look to the cities and generation of methane—which contributes to global warming—and other obnoxious gases. A proper municipal solid waste management system is a major challenge in the protection of the local and global environment.

A number of technological options exist to minimize municipal solid wastes and reduce emissions of methane. The municipal managers need to be given adequate exposure to and training with these technological options for application in their municipalities to minimize wastes and reduce methane emissions. At present, most of the municipalities are constrained due to a lack of financial resources and infrastructure facilities to introduce modern municipal waste management to the municipalities.

Keeping in view the ever-growing problem of solid waste generation, its management and associated impacts, the Ministry of Environment and Forests has brought out a set of guidelines for the municipalities for Management and Handling of Municipal Solid Wastes. These guidelines concern (i) collection, (ii) segregation, (iii) storage, and (iv) disposal of municipal solid wastes in sanitary landfilling. The notification makes it obligatory for the municipalities to restrict landfilling to non-biodegradable inert waste, and other wastes that are not suitable either for recycling or for biological processing. With this in mind, the guidelines also prohibit dumping of the biodegradable component of the waste into the landfills, thereby avoiding a chance of methane generation.

Under the present circumstances, and in view of the GoI Notification on the disposal of municipal solid wastes, there is hardly any scope for recovery of methane from landfills for re-use for energy purposes. The best technological options to reduce methane emissions for such wastes is to adopt an efficient solid waste management system to reduce wastes and adopt the technological options already well known in the country for dealing with wastes to wealth. Options like biomethanation, however, offer opportunities for waste to energy recovery and avoidance of methane generation. A city, however, needs a huge amount of financial resources to adopt any of the technologies mentioned above for handling its solid waste. To address the problem, the involvement of the private sector is a must and government policy should provide support for this.

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Sustainable Practices for the Construction Sector in India

SUSTAINABLE PRACTICES FOR CONSTRUCTION SECTOR IN INDIA

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I. INTRODUCTION

The construction sector is the driving force behind the economy. Building materials are closely linked with the construction sector, whether they are needed for infrastructure, housing, trade or development projects like irrigation, hospitals or schools. These sectors represent the aspirations of individuals, communities, and societies backed (or hindered) by government policies.

The relative importance of construction in the Indian economy can be assessed by the fact that around 36.5% of gross domestic investment in 1996-97 is accounted for by the construction sector. The share of the construction sector in the GDP in India was around 5.6% in 1996-97 and is projected to grow to 7.4% in 2005-06 (NICMAR, 1998). Construction is an important component of investment in many other sectors.

The construction sector is strongly linked with building construction, road construction, ports and waterways, airports, railways, construction of canals and irrigation systems and so on. Each of these activities has a very different range of building materials requirements.

Why do we need to look at this sector in detail in the context of greenhouse gas (GHG) emissions? First, it has a high share in most investment and infrastructure projects. Second, it requires energy-intensive materials. Third, it is also highly GHG intensive in terms of overall magnitude.

Some of the building materials (BM) required for construction are energy intensive. An associated issue with the high-energy intensity of building materials is the high volume of emissions that are released due to the burning of fossil fuels in the manufacturing process of these building materials.

II. OVERVIEW OF THE CONSTRUCTION SECTOR (CS)

We now look at the overall construction sector, its role in investment, its energy consumption and GHG emissions for India.

Table 1 shows how important the construction component is in every sector of the economy in India. Obviously, housing, roads and commercial buildings have 100% component, as they are synonymous with the CS. The share of the CS in irrigation, highways and urban development—such as water supply and so on—is 70 to 80%. Even service oriented sectors such as tourism, civil aviation, posts and railways have high shares of the CS, ranging from 40% to 60%.

Table 1 presents the construction component of the investment in various sectors of the economy.

[1] Dr. Piyush Tiwari is Assistant Professor at Tsukuba University at Japan. This paper is prepared for LBG under GERPP sponsored by USAID.

Table 1: Construction Component of Investment in Key Sectors

Agriculture	34
Rural development, Poverty alleviation programs	40
Irrigation and flood control	80
Environment and forests	60
Power (hydro, thermal, nuclear and others)	50
Housing	100
Roads and buildings	100
Highways and waterways	80
Ports, docks and lighthouses	50
Railways	42
Communication, information and broadcasting	40
Industries	30
Mineral and mining	42
Education and culture	25
Social welfare	30
Health	37
Urban development, water supply, sanitation, city level services	70
Civil aviation	42
Tourism, hotels and hospitality industries	60

Sources: NICMAR, 1998 and Our estimates

Table 2 shows the energy requirements of building materials in the units of megajoules (MJ) per kg. These are very high for aluminum, plastics, copper and steel. The table also gives materials with low energy contents. Moreover, the construction sector is a major provider of employment.

Using an input-output table for 1989-90, Parikh Jyoti et al. (1995) showed that when both the direct and indirect emissions are considered, construction was the most carbon-intensive sector in the economy, as it required energy intensive building materials such as aluminum, steel, bricks, glass, cement, plastics and so on (see Figure 1). It is for this reason that we undertake a special study on the construction sector.

III. METHODOLOGY

The objectives of this paper are two-fold: (i) to estimate the future requirements of building materials and (ii) to analyze the possibility of substitution among building materials toward less emission-intensive materials.

We have adopted the following procedure:

Step 1: We project the total construction investment based on the data from NICMAR (1998) and India Infrastructure Report (1996).

Step 2: We project key building materials based on their current trends.

M2

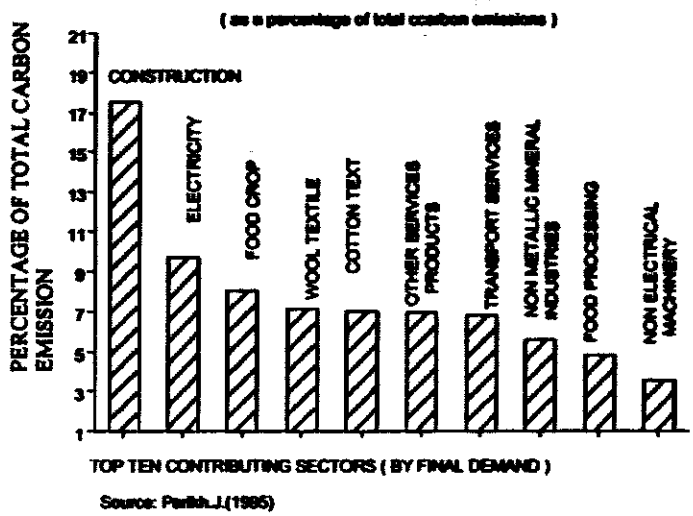
Table 2: Energy Requirements of Building Materials

Very high energy	
Aluminum	200-250
Plastics	50-100
Copper	100+
Stainless steel	100
High energy	
Steel	20-60
Lead, Zinc	25+
Glass	12-25
Cement	5-8
Plaster board	8-10
Medium energy	
Lime	3-5
Clay bricks and tiles	2-7
Concrete	
In situ	0.8-1.5
Blocks	0.8-3.5
Precast	1.5-8
Sand lime brick	0.8-1.2
Timber (sawn)	0.1-5
Low energy	
Sand, aggregate	<0.5
Fly ash	<0.5
Soil	<0.5
Mud blocks	<0.2

Source: Building materials in India: 50 Years – A commemorative volume, edited by T. N. Gupta (Building Materials and Technology Promotion Council, New Delhi, India, 1998).

Figure 1

Direct and Indirect Carbon Emissions : 1989-90



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Step 3: We estimate the relative shares of key construction components and use them to estimate the share of different construction activities.

Step 4: Using our technical models (Tiwari, Parikh and Parikh 1999 and Tiwari, 2001), we project the building materials requirements for new construction. The new construction consists of construction of houses, industries, roads, ports, bridges etc. However, in this paper we will focus on housing and industrial building construction only. Besides housing construction activity maintenance, upgrading and remodeling of existing houses is also one of the major activities in India. Though it is not easy to estimate the activity involved in the maintenance, upgrading and remodeling of housing, we have adopted the following elimination approach to estimate emissions due to maintenance, upgrading and remodeling of existing houses, etc. Each year, government policies target to construct 2 million new houses. We assume that this is the level of new housing activity in India. The cement industry estimated that in 1999, of the 95 million tons of cement production, nearly 60% went to housing. We computed the cement requirement for 2 million new houses; it is around 14 million tons. The remainder we tried to account for upgrading, maintenance etc. (it did not match exactly but, comes very close). We believe that in India, the upgrading activity is quite significant due to incremental housing approach that households adopt. Households build part by part as they accumulate finances. In our informal observation, it's quite common in India that households add another floor or room or upgrade their katcha houses to pucca in an incremental way. This approach, we thought, would be necessary to balance the final figures on materials and investment at the macro level.

Step 5: Finally, we estimate the possibilities of reducing emissions by substituting alternative techniques.

As a first step, we estimate the value of proposed construction, which is given in Table 3 based on a simple line projection of the data from NICMAR (1998). The table indicates that the construction investment in 2000-01 is Rupees 1,669.9 billion and will grow to Rupees 4,073.3 billion at current prices.

Table 3: Annual Estimated Value of Proposed Construction (Billion Rupees)

2000-01	1669.9	1669.9
2001-02	1842.7	1738.4
2002-03	2035.2	1817.1
2003-04	2250.1	1906.8
2004-05	2490.3	2008.3
2005-06	2759.1	2122.4
*2006-07	3060.4	2250.3
*2007-08	3366.3	2370.6
*2008-09	3703.0	2502.0
*2009-10	4073.3	2638.1

Source: India infrastructure report, 1996
NICMAR, 1998
*Based on our estimates.

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Table 4 presents the share of different construction activities in total investment for 1995-96. We have assumed that the share of different activities would remain the same until 2009-10.

Table 4: Share of various construction activities in total construction investment in 1995-96

Housing	50%
Urban services, Electricity, Gas and Water supply	24%
Industries	10%
Highways	6%
Railways	4%
Ports	1%
Telecommunication	4%
Others	1%

Source: Our estimates

Table 5 presents the total investment in different construction activities based on the shares of Table 4.

Table 5: Projected Construction Investment in Various Sectors
(Billion Rupees, at 2000-01 Constant prices)

2000-01	835	401	167	100	67	17	67	17
2001-02	870	417	174	105	70	17	70	17
2002-03	909	436	182	109	72	18	72	18
2003-04	953	458	191	114	76	19	76	19
2004-05	1004	482	201	120	78	20	78	20
2005-06	1062	509	212	128	85	22	85	22
2006-07	1125	540	225	135	90	23	90	23
2007-08	1185	569	237	142	95	24	95	24
2008-09	1251	601	250	150	100	25	100	25
2009-10	1323	635	264	158	106	27	106	27

Source: Authors' estimates

To project the building materials requirements, we use the projected value of construction as given in Table 5 as the upper limit of construction investment in that sector. We translate this investment into the construction activity that can be carried out and finally estimate the requirements of building materials under the Business-As-Usual (BAU) scenario. We will focus on housing and industries, which together constitute 60% of the construction activity in India. We overview the existing sectoral features and Government policies and try to match up the policies (projected construction targets) with the projected investment of Table 5, with Table 4 as the upper bound. The results of the BAU scenario are presented in Section 4.

IV. BUILDING MATERIALS REQUIREMENTS UNDER BUSINESS-AS-USUAL

A. Housing

1. Housing Sector in India

The aggregate picture of the housing situation in India can be judged from the relative quantitative and qualitative improvement in the total residential houses, vis-a-vis the household growth rate during 1981-91[2]. From the data presented in Table 6, it is seen that the growth during 1981-91, in the total residential houses, has been higher than the household growth overall and separately for rural and urban areas. Qualitatively, also, the dwelling units have exhibited significant improvements. The proportion of *pucca*[3] houses has gone up significantly, both in rural and urban areas, by almost 8 percent during 1981-91.

Despite the quantitative and qualitative improvements in housing stock in India, the housing shortage persists. The Planning Commission (1992) estimated the housing shortage in 1991 at 18.5 million units (Table 6). The growth in housing supply has always lagged behind the demand as shown in Table 7. During the last census decade (1981-91), there have been slight improvements in the growth rate of housing supply, but there already exists a huge unmet demand.

2. Building Material Requirements in Housing

The demand for building materials in housing emanates from two factors: (i) construction of new houses, and (ii) maintenance, extension and repair of existing houses. It is possible to have an idea about the planned construction of new houses through Government policy documents, but estimating the construction activity for maintenance, extension or repairs is not possible. To project building materials in house construction, we adopt the following procedure.

1. We estimate the building materials requirement for the new house construction activity.
2. We guesstimate the amount of maintenance, repairs and extension from the total investment in housing construction minus the investment required for new house construction,
3. We use material required per billion Rupees of investment in new housing as a norm and apply this norm to estimate building materials required for maintenance, repairs etc.

a. Building Materials for New Housing Construction

The Indian Government, through its 'National Agenda', has set a target of constructing two million houses every year (Ministry of Urban Affairs, 1998). For the purpose of this paper, we will focus on the target of two million houses every year and would analyze the building materials required to meet this target under the Business-as-Usual scenario. Table 8 presents the distribution of households according to the number of rooms. The proportion of each type of house that would be constructed is assumed according to Table 8.

Based on the technical model (Tiwari, Parikh and Parikh, 1999; see Appendix I), we estimate the materials requirements for the construction of two million new houses every year. Since the number of houses to be constructed is two million each year during the period under consideration (2000-10), we have quoted in the following tables the cost, carbon dioxide emissions and building materials requirements for 2000-01.

[2] We have based our discussion on the 1991 Indian Census data. The data collected during the 2001 Census is not yet available.

[3] Pucca houses: Houses with wall and roof made of permanent materials. Material of wall can be burnt brick or other metal sheets, stone, or cement concrete. Roofs can be made of tiles, slate, shingle, iron, zinc or other metal sheets, bricks, lime and stone, stone and reinforced concrete.
Kutcha: Houses with wall and roof made of temporary materials. Wall may be made of grass, leaves, bamboo, mud, unburnt bricks or wood. Roofs may be made from grass, leaves, bamboo, thatch, burnt brick or wood.

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Table 6: Quantitative and Qualitative Aspects of Houses During 1981-91
Number of residential houses and household size

	1981	1991	Resi. Houses	Households	1981	1991	1981	1991
Total	118.63	155.43	31.02	25.2	5.6	5.53	664	860
Rural	89.59	112.87	25.99	21.22	5.63	5.56	504	628
Urban	29.04	42.56	46.55	37.73	5.52	5.45	160	232

	1981	1991	1981	1991	1981	1991		
Total	32.67	41.61	34.04	27.44	33.29	30.95		
Rural	22.53	30.59	40.55	33.76	36.93	35.65		
Urban	64.7	72.75	13.50	9.56	21.8	17.69		

1991 housing census	18.5	13.7	4.8

Source: Planning Commission (1992)

Table 7: Housing Needs *vis-a-vis* Housing Supply

1971-81	44.8	23.7
1981-91	49.9	31.4

Source: Planning Commission (1992)

Table 8: Distribution of Households According to Rooms in 1991

1	41.41
2	30.58
3	13.85
4	7.14
5 or more	7.02

Source: Census of India 1991 Housing and Amenities, Paper 2 of 1993

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Table 9: Cost of Various Inputs for New Houses

2000-01	275	38900

The requirements for building materials are given in Table 10.

Table 10: Building Materials Requirements in Each Year (BAU Case) for New Houses

Cement (Mt)	13.99
Bricks(billion)	36.1
Coarse sand (Million m^3)	34.7
Fine sand (Million m^3)	8.13
Stone aggregate (Million m^3)	30.4
Steel (thousand ton)	529.2

b. Building Material Requirements for Maintenance, Repair, Extension etc. of Existing Houses

To estimate the total building materials required for maintenance, repair and extension, etc., we use materials intensity per billion Rupees in investment in housing as a norm and we apply the same materials intensity to the available investment for this purpose. Table 11 presents the material intensity for the housing sector.

Table 11: Material Intensity for Building Construction in the Housing Sector

Cement (Mt)	0.051
Bricks(billion)	0.13
Coarse sand (Million m^3)	0.13
Fine sand (Million m^3)	0.03
Stone aggregate (Million m^3)	0.12
Steel (thousand ton)	1.91

Using the material intensity of Table 11, we have projected the materials required for maintenance, repair and extension every year. Table 12 presents the building materials requirement for this activity.

Table 12: Material Requirements for the Repair, Maintenance and Extension in Housing Sector (CP-BAU Case)

2000-01	28.56	72.8	72.8	16.8	67.2	1069.6	78960
2001-02	30.345	77.35	77.35	17.85	71.4	1136.45	83895
2002-03	32.334	82.42	82.42	19.02	76.08	1210.94	89394
2003-04	34.578	88.14	88.14	20.34	81.36	1294.98	95598
2004-05	37.179	94.77	94.77	21.87	87.48	1392.39	102789
2005-06	40.137	102.31	102.31	23.61	94.44	1503.17	110967
2006-07	43.35	110.5	110.5	25.5	102	1623.5	119850
2007-08	46.41	118.3	118.3	27.3	109.2	1738.1	128310
2008-09	49.776	126.88	126.88	29.28	117.12	1864.16	137616
2009-10	53.448	136.24	136.24	31.44	125.76	2001.68	147768

B. Industries

The share of industries in total construction investment is 10% in 1995-96. We assume this yearly share would remain the same up to 2009-10. The construction activities of industries require the building of industrial premises. It is not easy to generalize the nature of industrial buildings because the type of building would depend on the type of load that industry is envisaged to carry. However, as a guiding principle, we assume that the basic unit of construction of industrial buildings is similar to that of housing. This may at most be considered as the lower bound for the materials requirements.

Using the material intensity of Table 11, we project the materials requirement in the industrial sector. Table 13 presents the materials requirements in the industrial sector.

Table 13: Material Requirements in the Industrial Sector (CP-BAU Case)

2000-01	8.4	21.54	21.03	5.01	20.04	315.6	23340
2001-02	8.76	22.44	21.93	5.22	20.88	328.8	24330
2002-03	9.18	23.49	22.92	5.46	21.84	344.1	25440
2003-04	9.63	24.63	24.06	5.73	22.92	360.9	26700
2004-05	10.14	25.92	25.32	6.03	24.12	379.8	28080
2005-06	10.68	27.36	26.7	6.36	25.44	400.8	29610
2006-07	11.34	29.04	28.35	6.75	27	425.4	31440
2007-08	11.94	30.6	29.85	7.11	28.44	447.9	33120
2008-09	12.6	32.4	31.5	7.5	30	472.5	34920
2009-10	13.32	34.2	33.3	7.92	31.8	498.9	36900

C. Carbon Dioxide Emissions from Housing and Industrial Building Construction under BAU Scenario

We can now pull the number together to get total CO_2 emissions from the construction sector. These are shown in Table 14. Note that this accounts for only 60% of the construction sector.

Table 14: Carbon Dioxide Emissions from Construction Sector: BAU Scenario

2000-2001	38,900	78,960	23,340	141,200
2009-10	38,900	147,768	36,900	223,568

The CO_2 emissions for housing repairs look large compared to construction. It may be noted that since the same coefficients are used for new construction and maintenance, the split between the two does not matter for the estimate of carbon dioxide emissions.

V. ALTERNATIVE TECHNOLOGIES TO MITIGATE EMISSIONS AND MATERIAL REQUIREMENTS FOR HOUSING

As we have discussed earlier, housing activity involves two types of construction activities: (i) construction of new houses and (ii) repairs, maintenance and extension of existing houses. It is possible to use alternative energy-efficient technologies for both these activities, but the technological possibilities are rather limited for existing houses. For example, for an existing house, it would not be possible to replace an existing brick wall with a mud block wall. In this section, we have therefore restricted ourselves only to the new construction houses.

In the Business-As-Usual scenario, we assume that the houses are constructed as usual with bricks and cement, the commonly used building materials in India. Using our technical model (Tiwari, Parikh and Parikh, 1999), we introduce various alternative construction technologies. Let's say we need to construct houses which are cost effective and are also energy efficient. There are many technologies, which can be used to construct houses. To simplify, the house considered for analysis is measured in units of a room of hypothetical size (3.5 x 3.5 x 3.14 m). A house may be assumed to be a combination of such rooms, which can exist anywhere in the building up to three floors. Up to three floors, the minimum wall thickness is one brick and beyond this, the minimum wall thickness increases (Khanna 1992). However, in normal construction practices, the walls in a building taller than three floors are actually load bearing. Generally, a framework of columns and beams is constructed which is load bearing and the space in between is filled with non-load-bearing brick walls. The energy estimates for buildings above three floors will be slight underestimates, since emissions due to columns are not accounted for. The model is an activity analysis model. It accounts for various engineering constraints (for example, wall types and foundations have to be related) to ensure that the selected set of techniques make engineering sense. Appendix I provides technical details of the model. The model is solved with an objective to minimize cost and a constraint on carbon dioxide emissions. Some technical definitions are required before presenting the scenarios.

A. Alternative Materials and Techniques

Common practices:
We define common practices as the case where the construction materials like bricks, stone, cement and concrete are used for construction. The technical alternatives in this type of construction present a choice between brick masonry or stone masonry.

Low cost techniques
A number of construction technologies using cost effective, low energy building materials are available (Dost et al.,1991; Balkrishnan; Eashwaran; Niazi; Radhika et al.,1993; Sharma, Sreedevi; Sriraman,1993a; Sriraman,1993b; Valmeekinathan). We have compiled these building materials and technologies and they have been incorporated into our technical model. The techniques considered are briefly and broadly discussed below.

Hollow Concrete Blocks (Jain,1992)
These are generally made of (1:5:10) cement:sand:stone aggregate on a gospel machine which has a vibrator and a ram. The blocks are of size 40x20x10 cm and are around four times the size of ordinary bricks. They are used in wall construction.

Hollow Concrete Blocks with Flyash (Jain,1992)
These are similar to the hollow concrete blocks, with the difference that 25% of the cement is substituted with flyash. Their application is in wall construction.

Balram techniques (Nathan and Revi, Singh)
These techniques of compressed mud blocks have been developed by Development Alternatives for their use in wall construction. The size of the blocks is 20x10x10 cm. The average strength of these blocks is around 14-16 Kg/cm^2. Though this is less than the compressive strength of fired clay bricks of 35 Kg/cm^2, it is sufficient to take loads up to three floors, provided the minimum thickness of the wall is one block. The total number of operators required for 1500 blocks is around five. Sometimes, these blocks have to be stabilized using stabilizers such as cement, lime, flyash etc. if the quality of soil is not good or the construction is in a zone which has high rainfall. The alternative components of these mud blocks are following. These have been named as Balram with suffixes one to ten.
Balram 1: Good local soil
Balram 2: Local soil + maximum 50% outside soil
Balram 3: Local soil + 5% cement stabilized
Balram 4: Local soil + 5% cement stabilized + 50% outside soil
Balram 5: Local soil + 8% lime stabilized
Balram 6: Local soil + 8% lime stabilized + 50% outside soil
Balram 7: Local soil + 4% asphalt, bitumen or cutback stabilized
Balram 8: Local soil + 4% lime + 8% flyash stabilized
Balram 9: Mud block is dipped in a mix of one part sodium silicate and three parts water.
Balram10: Local soil + 5% molasses as stabilizers

Filler slab with 2 M.P. tiles (Parikh K. et al, 1974)
These have been developed by Central Building Research Institute, Roorkee. These are flat slabs and can be used for floors as well as roofs. The basic idea is to substitute substantial portions of concrete below the neutral axis, which does not contribute anything to the strength of the slab, with M.P. tiles. This not only saves the concrete but also makes the structure light.

Filler slab with Manglore tiles (Parikh K. et. al., 1974)
In this method the redundant concrete is substituted by Manglore tiles.

Precast beam and Hourdis (Parikh K. et. al., 1974)

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In this method precast reinforced concrete beams are used to carry hourdis as roofing and flooring systems.

Jack Arch Roofing (Sriraman, Jain,1992)
This is basically a flat roofing system, formed of shallow segmented arches over precast R.C. beams. This is used for roofing.

Funicular Shell (Jain,1992)
These are doubly curved thin membranes which use very little materials and yet are very strong.

Mortars (Sriraman)
The cost of mortars can be reduced by substituting the cement/lime by flyash.

Plasters (Niazi, Scott and Revi)
The various types of low cost, low energy plasters which may be used without compromising the longevity and performance of earth walls.

Using the above materials and technological possibilities, we have constructed three carbon dioxide reduction scenarios for common practices and two carbon dioxide reduction scenarios for low cost technologies. The alternative materials considered, 43 in all, are listed in Appendix II. The list of techniques which are evaluated in this paper is presented in Appendix III. There are three technologies for the foundation bed construction under load bearing and partition walls, technologies for foundation construction, 136 technologies for load bearing wall construction, 64 technologies for partition wall construction, 13 technologies for roof construction, 14 technologies for floor construction, and 12 technologies for external and internal plastering, evaluated in this paper. These techniques are suitable for India and we design the room according to Indian building code IS 456.

The nomenclature for various scenarios is given below:

B. Common Practice and Improvements Scenarios

CP-BAU: In this common practice – business as usual scenario, there is no carbon dioxide reduction constraint and this replicates the current construction technological scenario.
CP-5: In this scenario we impose a constraint that the construction would have to choose those technologies that reduce carbon dioxide emissions by 5% from the base case level.
CP-10: This scenario imposes a constraint that the construction would have to choose those technologies that reduce carbon dioxide emissions by 10% from the base case level.
CP-20: This is similar to the above two scenarios, except that the level of carbon dioxide emissions reduction is by 20% from the base case level.

1. Cost effective, energy efficient technologies (EE)

For the low cost technologies we construct three scenarios:

EE-BASE: There is no carbon dioxide reduction constraint in this scenario.

EE-5: There is a constraint to reduce carbon dioxide emissions by 5% from the EE-Base level.

EE-10: There is a constraint to reduce carbon dioxide emissions by 10% from the EE-Base level.

We could not construct a 20% reduction scenario for the low cost technologies because the model became infeasible with the present set of low cost technologies.

The above model is solved using the optimization module of GAMS software (Brooke et al. 1995).

C. Cost

Table 15 presents the costs and emissions for CP and EE techniques for the construction of 2 million houses in 2000-01. With a shift among these techniques, there is substantial change in the cost and carbon dioxide emission level. With the carbon dioxide constraint being imposed, the cost of construction rises by 2.54% for a 5% reduction in carbon dioxide emissions from the CP-BAU levels. The cost increases non-linearly with further reduction in carbon dioxide emissions. A reduction of 10% in carbon dioxide emissions increases the cost by 2.6% and the reduction by 20% in carbon dioxide emissions increases the cost by 10.7%.

The second group of techniques evaluated are low cost techniques. These techniques, besides being cost effective, are associated with less carbon dioxide emissions. The cost of construction of 2 million houses in 2000-01 by using EE-Base is 58% of the cost of construction by using the CP-BAU case and carbon dioxide emissions for the EE-Base are only 35% of the common practices.

Table 15: Cost of Various Inputs

Cost (Billion Rupees) in 2000-01	275	282	285	307	160	166	174
Carbon dioxide emissions (Thousand tons)	38900	36955	35010	31120	13598	12918	12238
Percent change in cost over BAU	-	2.54	5.09	11.64	-	3.75	8.75
Percent reduction in emissions over BAU	-	5	10	20	-	5	10

The annual emissions due to construction of houses would remain the same during our period of consideration.

D. Material Requirements

The requirement for building materials under various scenarios is presented in Table 16. The table indicates that by the imposition of the carbon dioxide constraint, the consumption of cement, bricks and steel reduces, causing a reduction in emissions. Table 16 indicates the quantity of building materials that would be required each year.

It may be noted that the EE-Base scenario uses a lot of compressed mud blocks in place of bricks in the CP-BAU scenario. It also uses manglore tiled roofs in place of reinforced cement concrete roofs, leading to a substantial reduction in the use of steel and cement. A Manglore tiled roof cannot be used as a ceiling/floor in a multi-storied building. Thus the assumption in the model is that all buildings are single storied. This is perhaps true of 60 to 70 percent of the buildings in the country. The results, therefore, have to be treated as providing upper bounds on cost savings and carbon savings.

Table 16: Final Input Requirements

Cement (Mt)	13.99	14.82	15.33	11.05	6.64	5.9	6.1
Bricks(billion)	36.1	27.61	20.93	20.93	6.39	6.13	3.2
Coarse sand (Million m^3)	34.7	38.06	41.13	26.23	26.62	24.3	24.3
Fine sand (Million m^3)	8.13	8.13	8.13	11.61		0.11	1.25
Stone aggregate (Million m^3)	30.4	30.47	31.36	33.1	19.4	19.5	20.91
Unslaked lime (Mt)				48.14		9.87	12.74
Steel (thousand ton)	529.2	529.2	487.06	398.4	43.81	43.8	43.8
Flyash (Million m^3)					6.41	6.41	6.41
Mud blocks (Billion)					29.35	29.35	29.35
Manglore tiles (Million Square meter)					0.35	0.35	0.35
Stone at quarry(Million m^3)		28.13	50.33	30.25		0.67	8.78
Through stones (Million Number)		158.2	282.9	282.9		4.72	57.5
Surkhi(Million m^3)				8.71		1.57	2.02

VI. IMPLEMENTATION AND BARRIERS FOR HOUSING

The results may appear remarkable. If there is such a large scope for cost reduction, why are not such techniques followed? There are many barriers to the adoption of such techniques. Land may not be available for single storied buildings in urban areas and financing may not be available in rural areas. There are, however, many other barriers.

For different types of construction, the decision-making is done at different levels, with different criteria. For example, the decisions concerning housing are made by ordinary citizens with the help of professionals. Prime criteria are costs, safety and prestige. On the other hand, the decisions concerning other sectors, such as highways and industries, are made by professionals and with a lot of technical requirements. We therefore discuss each type separately.

Table 20 demonstrates that, with the implementation of low energy, low cost technologies, it is possible to reduce emissions up to 60% for new construction of houses. The low cost technologies, as discussed above, use locally available building materials. One of the problems with the use of conventional building materials for house construction is a very high reliance on bricks. One of the studies by Development Alternatives indicates that there will be a brick production saturation level at 46.5 billion. In India, there is

an installed capacity for cement of around 116 million tons and the level of production in 2000-01 is 95.94 million tons (of which around 50% is used in housing). Going by this trend, the availability of cement would not pose any concern during 2001-10. The use and availability of bricks is the major concern. The above discussion presents opportunities to substitute bricks with mud blocks (Balram) which are cost and energy efficient and can be manufactured locally. The issue that emerges from the above discussion is that there are possibilities for reducing emissions and costs of house construction, but it would require some cultural and technological changes.

A. Cultural Mindset

The construction costs in the country have registered an increase of up to 15 percent yearly, primarily due to the rise in the cost of steel, cement, bricks, timber and other inputs; as well as the cost of labor. The cost of construction using conventional and contemporary building materials and construction forms is around Rs.5000 per sq.m. Such costs are beyond the paying capacity of the economically weaker sections of the population, the low-income groups and even a large section of the middle-income groups, resulting in a widening gap between housing demand and supply.

A construction culture with its emphasis on the "frills" rather than the essentials also makes excessive use of energy-intensive and high-cost building materials like steel and cement. This has an adverse effect on scarce natural resources.

There is a misconception that Cost Effective Environment Friendly (CEEF) technology cannot be applied for multistoried buildings. Actually, the various technologies coming under CEEF classification are those developed by premier research institutions in India after years of research. Most of these technologies are covered by Indian Standards. In order to demonstrate the application of this technology for bigger buildings, Nirmithi, an NGO in Kerala which has long promoted such techniques for small buildings, has started taking interest in bigger projects. Nirmithi has also been trying all along to promote a traditional style of architecture. This has been demonstrated in the Ettuketu (two-courtyard, traditionally-designed structure), constructed by Nirmithi at Mahatma Gandhi University, Kottayam, Kerala. Nirmithi's major projects include the construction of Cochin University of Science and Technology, Trivandrum Titanium Products, and Kerala University, among many others . The Nirmithi campus itself is a sample of cost effective technology. These structures demonstrate the possibility of adopting CEEF technology for bigger buildings, without compromising on their safety.

B. Technology Dissemination

There is a need for the adoption of cost-effective and environment-friendly alternatives for habitat development, but there is no effective delivery system for the transfer of such technologies from the research and development institutions to the ultimate users. There is also a lack of trained manpower to propagate alternative technology options at the grass-roots level, and there are little or no inputs of cost-effective technology options in academic programs at technical institutions. From initiatives which have been taken up in the name of "low-cost housing", a general perception has emerged that the options are inferior, ugly, of low quality and of low durability.

What is needed is to give a decisive shift in the selection and application of building materials and technologies leading to cost effectiveness and yet providing durable, functional and aesthetically-pleasing options as against conventional options. Its relevance to housing as an alternative option rather than an inferior option has to be clearly established and its application for categories of housing and building construction needs to be reinforced. There is a challenge to sell these new options to the beneficiaries and to evolve suitable strategies using local initiatives to involve the beneficiaries, so as to minimize resistance to this "new" technology.

C. An Approach for Implementation

An approach to involve the users directly; delinking the development from government rigidities; coordination of the efforts of government officials, voluntary organizations and technologists; and judicious channeling of available resources would help in promoting low cost technologies. The Indian Bureau of Standards should ensure quality, standards and specifications for cost-effective building materials and formally incorporate them in the building design codes.

Low cost technologies require skilled labor during both the production of materials and the construction. To combat the shortage of skilled labor familiar with cost-effective construction technologies, skill upgrading programs should be organized in masonry, carpentry, plumbing, electrification, landscaping, interior design etc. Print and electronic media, as well as seminars, workshops, conferences and demonstrations, should be used to disseminate the suitability of low cost technologies.

D. Existing Programs

The Government of India, through Housing and Urban Development Corporation (HUDCO), gives financial assistance for housing by way of an initial seed grant or subsidy as a one-time start-up contribution. After this initial assistance, supplementary support is given in the form of soft loans for equipment, machinery and working capital. To promote the spread of building centers, where the low-cost technologies can develop and spread, the government has given fiscal incentives, such as an exemption of excise duty and a reduction of customs duty for the production of various building elements and components.

The achievements of the Building Centers Movement, an NGO effort, has had moderate success:

- the use of cost-effective, environment-friendly technologies has led to solutions with 15-40 percent savings over conventional technologies;
- the network of building centers has spread to 385 locations throughout India;
- over 55,000 masons, carpenters, bar benders, plumbers and other construction artisans have been trained to use innovative and cost-effective technologies;
- women construction workers have been imparted training on skills and can earn equal wages as their male counterparts;
- construction worth over 2 billion Indian Rupees has been completed using the innovative technologies;
- innovative technologies have been used in building social amenities and infrastructure buildings, lending credibility to the use of such technologies for all applications; and
- the production of building materials and components required in the application of the technologies has contributed to the development of micro-enterprises.

HUDCO has demonstrated the use of cost effective technologies in housing construction. HUDCO's diverse application of appropriate and cost-effective technologies in different states of India is summarized in the table below.

Andhra Pradesh	The building center network available in all 22 districts is fully linked with the massive weaker section housing program of about 200,000 houses each year. The centers are used for construction of low-cost sanitation units, school buildings and community centers. The special feature of this approach is the cyclone-resistant housing schemes in 9 coastal districts.

Kerala	The expansion of the network with more than one building center in all 14 districts has contributed to the movement. All categories of housing, school buildings, health centers, community centers and institutional buildings have been constructed.
Rajasthan	With excellent and strong networking of building centers in all 27 districts, there has been massive housing implementation, construction of public asset buildings, sanitation programs and many miscellaneous construction programs for roads and drains.
Tamil Nadu	The initiatives have been fully used in the development programs in all 31 districts for housing construction of all groups, community centers, schools, sanitation units and institutional buildings.
Maharashtra	In the two earthquake-affected districts of Latur and Osmanabad (make a link here), the establishment of 10 building centers has resulted in demonstrating those features of house construction, especially in use of certain materials and training for rehabilitation, reconstruction and retrofitting.

Despite the vast network and impressive achievements, the impact of the Building Centres Movement has been very small compared to the overall size of the housing construction industry. There is a need to take the low cost housing technologies further from Government-supported programs to much wider adoption.

E. Strategy

The strategies that would be key to the success of low cost technologies' adoption are:

- construction of affordable shelters with innovative construction techniques;
- provision of housing guidance and information to beneficiaries.
- shift in the funding pattern with more and more emphasis on private entrepreneurial participation;
- reduction of consumption of energy-intensive materials (such as cement and steel) and use of appropriate technology;
- utilization of locally available and innovative materials;
- assistance in the production of various building components at the grassroots level;
- training and skill-upgrading of construction artisans in terms of alternative, innovative and sustainable building materials and technologies;
- utilization of the services of trained artisans along with beneficiary households in housing construction employment-generation schemes;

VII. CONCLUSIONS

We have shown that the construction sector is the most carbon intensive sector and any strategy to reduce GHG emissions has to give attention to it. Some 17 percent of India's CO_2 emissions, roughly 170 million tons of CO_2, is directly or indirectly from the construction sector.

We have projected building construction, which constitutes 60 percent of construction activities, and associated materials and CO_2 emissions. An annual emission of 140 million tons in 2000-2001, growing to 225 million tons of CO_2 in 2009-2010, is projected in the Business-as-Usual scenario. A 5 percent reduction in CO_2 emissions will increase costs of building construction by 2.5 percent, a 10 percent reduction by 5 percent and a 20 percent reduction by 11.6 percent.

The opportunities for alternative construction materials and techniques and the range of savings that can be made are also explored. It is found that such materials and techniques can reduce costs by some 42 percent. This is an upper bound, but does show promising possibilities. At the same time, CO_2 emissions are also reduced by 66 percent for new construction. Such an attractive win-win option, however, faces many barriers. These include:

- paucity of land in urban areas
- lack of financing in rural areas
- a mindset for ostentatious housing
- a mindset that equates low-cost with cheap and inferior
- vested interests in existing techniques
- vested interests in the high cost of construction
- lack of right kind of training of architects and engineers

The most important action needed relates to change of mindset. One needs to persuade elites in the society to build and take pride in functional low-cost construction.

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APPENDIX I: TECHNICAL NOTES

The house considered for analysis, is measured in units of a room of hypothetical size (3.5x3.5x3.14 m). A house may be assumed to be a combination of such rooms, which can exist anywhere in the building up to three floors. Up to three floors, the minimum wall thickness is one brick and beyond this, the minimum wall thickness increases (Khanna 1992). However, in normal construction practices, the walls beyond the third floor are rarely load bearing. Generally, a framework of columns and beams is constructed which is load bearing and the space in between is filled with non-load-bearing brick walls. The energy estimates for buildings above three floors will be slightly underestimated, since emissions due to columns are not accounted for.

A model has been developed in this paper, which is an extension of earlier works by Tiwari et al. (1999). A building can be constructed using a number of technologies. A builder will optimize his choice of technology based on the cost, carbon dioxide emissions and available technology. The choice of technology requires a combination of materials and labor, which are constrained by their availability. The construction of a building consists of the following ten stages: stage 1 - foundation bed under load bearing wall; stage 2 - foundation bed under partition wall; stage 3 - foundation for load bearing wall; stage 4 - foundation for partition wall; stage 5 - wall construction; stage 6 - partition wall construction; stage 7 - roof construction; stage 8 - flooring; stage 9 - external plastering; stage 10 - internal plastering.

The model identifies technologies at different stages of construction (viz., foundation, wall, etc., as defined below) to meet output levels for various activities required at each stage to construct the room. Besides resource availability, there are structural design constraints (discussed later in more detail) which also restrict the combination of technologies at different stages. The process of building construction has three types of activities, as shown in figure A.1: activities related to primary resources required to produce the intermediate and final inputs to be used for construction of the structure, and activities related to various technological alternatives of construction of each stage of the building. Primary resources include fuel (electricity, coal), limestone, gypsum, etc. which are required in the production of cement, bricks, lime, steel, etc. which can be either directly used in construction (final inputs) or can be used in manufacturing of final inputs such as concrete blocks, which are used in building construction. The detailed list of inputs is given in Appendix II. Input prices are calibrated at 2000-01 prices. If the resources are used to manufacture inputs, which are used in construction and are not used directly in building construction, they are referred as *intermediate inputs*.

In this model, different technical specifications that provide the same outputs (a house with a combination of functional rooms of the size defined earlier) are considered. The levels of resources and production activities are determined so that the overall cost of construction of the specified house is at a minimum. The notations for different sets appearing in this model are: 'p' is the set of primary inputs; 'i' is the set of intermediate inputs; 'j' is the set of production-activity levels; 'q' is the set of different wage classes; and 'g' is a set of different stages in construction. The optimization process will choose those techniques, which minimize the overall cost of construction.

Two groups of techniques[4] are considered for analysis: common practices and low cost techniques. The list of techniques which are evaluated in this paper is presented in Appendix III. There are three technologies for the foundation bed construction under load bearing and partition wall, sixteen technologies for foundation construction, 136 technologies for load bearing wall construction, 64 technologies for partition wall construction, 13 technologies for roof construction, 14 technologies for floor construction, and 12

[4] Three groups of technologies are defined in this model. Common practices are those technologies, which are commonly used in India. These technologies primarily use materials like cement, bricks, concrete, steel etc. Low cost technologies are those, which include building materials such as stabilized mud blocks, jack arch roofing, tile roofing and technologies like rat trap brick bond for walls. There are many low cost technologies available in building construction.

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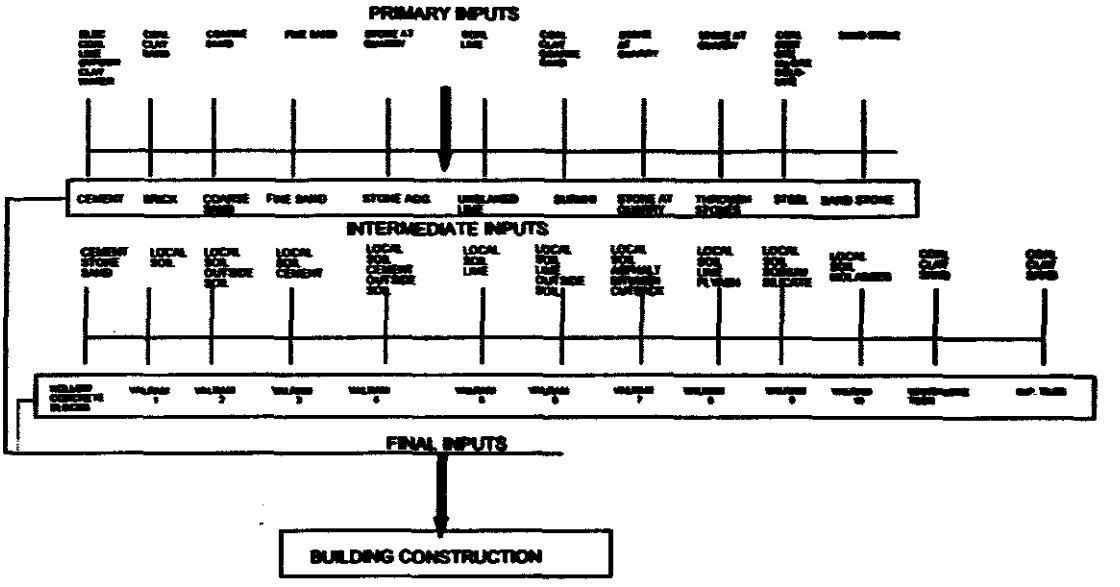
technologies for external and internal plastering, that have been evaluated in this paper. These techniques are suitable for India and we design the room according to Indian building code IS 456.

Figure A.1: Direct and Indirect Inputs in Building Construction



Model equations are given below:

Objective Function

The objective function to minimize

$$cost = \sum_i \sum_j c_i a_{ij} x_j + \sum_q \sum_j w_q d_{qj} x_j . \qquad 1$$

Intermediate + *Direct*

Inputs *Labor* ,

where c_i is the cost coefficient for the ith intermediate input corresponding to the ith activity and w_q is the wage rate for the qth class of labor. The requirement for the ith intermediate input to produce unit output of the jth activity is given by element a_{ij}. For each stage we have a matrix of intermediate input coefficients, a_{ij}, which are fixed for a set of technologies and each column of this matrix refers to one technology. x_j is the level of the production techniques. d_{qj} is the qth type of labor employed directly for unit production level of activity j. d_{qj} is also a fixed coefficient matrix, with each column referring to one technology. The matrices, a_{ij}, and d_{qj} have been compiled based on technologies from Tiwari et al. (1996).

Resource Constraint

If N_g is the number of alternative techniques available at stage of construction g, the total number of techniques available is

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$$N = \sum_{g} N_g \qquad 2$$

All levels of activities from G stages taken together are represented as

$$(x_1, x_2, \ldots x_j, \ldots x_n) = X'. \qquad 3$$

For detailed list of x_j refer to Table 4. a_{ij} is the requirement of final inputs to produce unit output of jth activity, i.e.

Final inputs

$$\sum_j a_{ij} x_j \leq r_i. \qquad 4$$

requirements $\leq$ *availability.*

The element r_i is the total amount of the ith final input required to run the production activity at a level X. The element b_{pi} gives the requirement of the pth primary input to produce unit output of the ith final input, i.e.

Primary inputs

$$\sum_i b_{pi} r_i \leq t_p. \qquad 5$$

requirements $\leq$ *availability.*

where t_p (p=1,P) is the total amount of the pth primary inputs required to produce the intermediate inputs r_i. Combining Eqs.(7) and (8) yields

Primary inputs

$$t_p \geq \sum_i \sum_j b_{pi} \cdot a_{ij} \cdot x_j. \qquad 6$$

availability $\geq$ *requirement.*

The model faces two resource constraints: (i) final inputs (Eq.7) and (ii) primary input constraints (Eq.9).

Direct and Indirect Employment

d_{qj} is the qth type of direct labor required for the jth activity. This is the labor that is required at the construction site and is constrained by the availability of construction workers Dlq. s_{qi} are the indirect labor requirements of the qth earning class to produce the ith intermediate input. The direct and indirect labor requirement for each wage class is

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Direct labor

$$\sum_j \sum_i d_{qi} a_{ij} x_j \leq Dl_q \qquad 10$$

requirement ≤ *availability*,

Indirect labor

$$\sum_j \sum_i s_{qi} a_{ij} x_j \leq Il_q \qquad 11$$

requirement ≤ *availability*,

where l_{qi} is the qth type of labor required to produce the ith intermediate input. The total supply of indirect labor is Ilq.

Output Constraint

The task level for every stage of building a house varies with the choice of the technique of construction. For example, to support the same load, the thickness of a stone wall should be more than that of a brick wall. The type and quantity of materials required change according to principles of structural engineering. The material requirement at every stage is a polynomial function of the area and height of the building (Tiwari et. al., 1999). The output constraint is

$$\sum_j z_{jg} x_j \leq y_g. \qquad 12$$

Output ≤ Task level.

The element z_{jg} represents the output coefficient of the jth activity at stage g. y_g is the task level for each stage.

Engineering Constraints

In building construction, the choice of techniques for one stage is not entirely independent of the choice of techniques for other stages. These interdependencies and internal balances in production have to be taken care of. These engineering constraints are written as

$$u_{ij} \; x_{ij} \geq 0. \qquad 13$$

To understand this constraint, it is necessary to explain how the u_{ij}'s are derived. Consider two activities, x_1 and x_2, corresponding to stages 1 and 2, respectively. Let 1 correspond to the foundation and 2 to the superstructure wall. Now, if the wall is constructed by using technique x_{2j}, it is required that the foundation be built only by using x_{1j}. This constraint is introduced as follows. Let x_2 = superstructure wall work in m^3 built by using technique x_{2j}, and x_1 = foundation work in m^3 built by using technique x_{1j}. As the dimensional details of both wall and foundation are known from engineering calculations, the lengths for which x_1 and x_2 are built are calculated by multiplying their levels by proper constants.

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If k_1x_1 is the length for which the foundation is built by using x_{1j} and k_2x_2 the length for which the wall is built by technique x_{2j}, then x_2 depends only on x_1, so that k_1x_1 should be at least equal to k_2x_2, i.e.

$$k_1x_1 - k_2x_2 \geq 0 \quad \text{or} \quad x_1 - (k_2/k_1)x_2 \geq 0. \qquad 14$$

The coefficients of x_i and x_j become the u_{ij}.

Environmental Constraint

In this model, the environmental constraints appear as

$$\sum_p t_p E_p \leq TC.$$

$$CO_2 \textit{ emissions} \leq \textit{Upper limit on } CO_2. \qquad 15$$

Only indirect CO_2 emissions due to production of the primary inputs are considered. E_p is a vector of the CO_2 emission-coefficients for p primary inputs. The total requirements of p primary inputs to meet the levels of intermediate-input requirements are calculated. When multiplied by emission coefficients associated with each of the p primary inputs and aggregated over p, we find the total CO_2 emissions related to construction. TC is the upper limit on CO_2 emissions.

We run the above model for various alternative scenarios of emissions (CP-BAU, CP-5, CP-10, CP-20, EE-Base, EE-5 and EE10). The imposed constraints lead to changes in technologies, at various stages. We have not presented the changes in technologies in the main text to avoid technical details. However, we present them here and table A.2 reports the changes in technologies.

Table A.2: Alternative Technology Choices

	CP-BAU	CP-5	CP-10	CP-20	EE-BASE	EE-5	EE-10
Foundation under load bearing wall	1:4:8 Cement concrete						
Foundation under partition wall	1:4:8 Cement concrete						
Foundation under load bearing wall	1:6 Cement coarse sand brickwork			1:1:1lime surkhi sand brickwork 1:1:1 lime surkhi sand random stonework	1:6 Cement coarse sand brickwork	1:1:1 lime surkhi sand brickwork 1:1:1 lime surkhi sand random stonework	1:1:1 lime surkhi sand random stonework
Foundation under partition wall	1:6 Cement coarse sand brickwork			1:1:1 lime surkhi sand brickwork	1:6 Cement coarse sand brickwork	1:1:1 lime surkhi sand brickwork	
Load bearing wall	1:6 Cement coarse sand brickwork	1:6 cement sand random stone work 1:6 cement coarse sand brickwork	1:6 cement sand random stonework	1:6 cement sand random stonework 1:1:8 Cement lime sand random stonework	1:4:8 cement flyash sand Valram 1		
Partition wall	1:6 Cement coarse sand brickwork		1:2 lime surkhi brickwork	1:1:1 lime surkhi sand barickwork	1:4:8 cement flyash sand Valram 1		
Roof	1:2:4 RCC balanced		1:2:4 RCC balanced 1:3:6 RCC balanced	1:3:6 RCC balanced	Filler slab with mangalore tiles		
Floor	40mm thick 1:2:4 cement concrete flooring				Filler slab with mangalore tiles		
Internal plastering	12mm thick 1:6 cement plastering			12mm 1:1:1 lime surkhi sand mortar	12mm thick 1:6 cement plastering		
External plastering	12mm thick 1:6 cement plastering				12mm thick 1:6 cement plastering		

Note: The blanks mean that there is no change with respect to previous column.

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APPENDIX II: LIST OF INPUTS

Primary Inputs	Intermediate Inputs	Final Inputs	Labor Wageclass1-6
Coarse sand	Cement	Cement	Rs. 0-40
Fine sand	Bricks	Bricks	Rs.41-50
Quarry stone	Coarse sand	Coarse sand	Rs.51-60
Coal	Fine sand	Fine sand	Rs.61-70
Electricity	Stone aggregate	Stone aggregate	Rs.70-80
Limestone	Unslaked lime	Unslaked lime	Rs.>80
Gypsum	Surkhi	Surkhi	
Clay	Stone at quarry	Stone at quarry	
Water	Through stone	Through stone	
Ironore	Sand stone	Sand stone	
Dolomite	Steel	Steel	
Sand stone	Manglore tiles	Balram 1-10	
Mangnese ore	M.P. tiles		
	Hourdis		
	Bitumen		
	Flyash		
	Asphalt		
	Sodium silicate solution		

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APPENDIX III: TECHNIQUES EVALUATED FOR CONSTRUCTION OF A HOUSE

Techniques	Proportion
FOUNDATION BED UNDER LOAD BEARING WALL / FOUNDATION BED UNDER PARTITION WALL	
Cement concrete	(1:4:8),(1:3:6),(1:2:4)
FOUNDATION AND BASEMENT/ FOUNDATION FOR PARTITION WALL/ PARTITION WALL	
Brickwork	
Cement:coarse sand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
FOUNDATION AND BASEMENT / LOAD BEARING WALL/ PARTITION WALL	
Stonework:coursed;random	
Cement:sand	(1:4),(1:6)
Lime:surkhi:sand	(1:1:1)
Cement:lime:sand	(1:1:8)
FOUNDATION AND BASEMENT / FOUNDATION FOR PARTITION WALL	
Lime:surkhi	(1:2)
Block work/block masonry	
Precast	
LOAD BEARING WALL/PARTITION WALL	
Pressed soil blocks	
Cement:coarse sand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Concrete blocks with flyash	
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Balram	(1;2;3;4;5;6;7;8;9;10)
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)

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Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
PARTITION WALL	
Soil cement blocks	
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:1)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Mud bricks	
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Hollow concrete blocks	
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Earth Blocks	
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Rat trap bonding brickwork	
Cement:coarsesand	(1:3),(1:2),(1:4),(1:6)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)
Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6)
Compressed earth blocks	
Cement:coarsesand	(1:3)
Cement:lime:sand	(1:1:6),(1:2:9),(1:1:8),(1:1:3)

Lime:surkhi:sand	(1:1:1)
Cement:flyash:sand	(1:3:6),(1:4:8)
Brickwork	
Cement:flyash:sand	(1:3:6),(1:4:8)
ROOF/FLOOR	
Flat R.C.C balanced	(1:2:4),(1:1.5:3),(1:1:2),(1:3:6)
Flat R.C.C over reinforced	(1:2:4)
Flat R.C.C under reinforced	(1:2:4)
Filler slab with 2 M.P. tiles	
Precast beam with hourdis	
Filler slab with Manglore tiles	
Jackarch	
Funicular shell	
ROOF	
Raniganj tile	
Manglore tile	
FLOOR	
40mm thick cement concrete	
Brick flooring	
Cement mortar	(1:4),(1:6)
Sanstone:rough chiselled / fine chiselled	
Cement mortar	(1:5)
INTERNAL PLASTERING / EXTERNAL PLASTERING (12mm thick)	
Cement:sand	(1:6),(1:3),(1:4)
Cement:lime:sand	(1:1:7),(1:2:9)
Lime:surkhi	(1:2),(1:4),(1:6)
Lime:surkhi:sand	(1:1:1)
Lime:coarsesand	(1:3),(1:4)
Lime:cement:coarsesand	(1:1:8)

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