Integrated Modeling System: Energy and Environment Policies

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Abstract

Integrated modeling system offers advantages over a huge monolith model in addressing diverse issues in energy and environment modeling for a vast country like India. It utilizes the inherent strengths of strong individual top-down and bottom-up models that are best suited to address specific energy and environment issues. The Integrated modeling system soft links these models through consistent and similar assumptions for all the models, a shared database and talking between the models as against hard linking them through model codes and runs. Multiple feedback is required among the models to ensure consistency of results and policy analysis. The paper discusses an integrated modeling system for India that uses ten models and presents some results to highlight their in-depth coverage and capability to address energy and environmental concerns.

Keywords: Energy, Environment, Integrated Models, Dynamic Optimization

INTEGRATED MODELING SYSTEM: ENERGY AND ENVIRONMENT POLICIES

1 Overview and Context

Due to the complex and dynamic interactions between economy, energy and the environment, the study of integrated macro-economic, energy and environmental issues offers varied challenges and opportunities for contribution to policy research. Growth and structural transformations in the economy and alterations in production, consumption, investment, market relations, resources, technologies and institutional structure affect energy and environment trajectories. Policy issues explore the manner in which long term energy and environment trajectories are influenced by macro-economic effects such as energy price feedback, revenue recycling, economic growth, trade and evaluation of various policy measures like carbon or energy taxes. Developing countries like India can leapfrog the conventional development paths through policy decisions on infrastructure like rails and communications, renewables and energy efficient technologies, managing the urbanization pattern, location planning to promote lower logistics and educating consumers to influence the consumption behaviour.

The long-term and global character of the energy system and the multiplicity of resources, technologies and uses tend to expose the energy decisions to uncertainties from energy prices, technological innovations, consumption behaviour, structural shifts in the economy and environmental impacts. Uncertainties arise due to the long-term nature of energy investments, global character of resources and environmental interface of energy use with inherently uncertain phenomenon like climate change. Investment decisions and policies need to incorporate these uncertainties to derive hedging strategy that minimizes risk and for developing preparedness plan to deal with extreme events.

In the energy-environment systems, diversity exists at various levels such as- regional energy resource availability and consumption, sectoral, temporal, emission-type, technology, and future energy paths. Diversity of emissions includes greenhouse gases (GHGs) like Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Chloro-fluoro carbons (CFCs), Per-fluoro carbons (PFCs) and Sulfur hexafluoride (SF_6) and local pollutants such as Nitrogen Oxides (NO_X), Sulfur dioxide (SO_2), Suspended particulate matter (SPM) and Carbon mono-oxide (CO). The Indian energy system is characterized by the predominance of coal use due to huge domestic reserves of coal, but limited gas and oil reserves. Most carbon emissions arise from use of coal in electric power and industry sectors, which is a major contributor towards global warming. Rising particulate and SO_2 emissions due to coal combustion is a concern among policy makers. Integrated macro-economic, energy and environment paths need to address issues related to investment requirements and their availability, energy supply (indigenous availability vis-à-vis imports), technology R&D and transfer issues, local and global environmental implications, institutional requirements and capacity building measures. Some specific policy concerns for India are rising demand supply gap in the power sector retarding economic growth, rising petroleum oil imports, low energy efficiency of industry as compared to international

levels resulting in reduced competitiveness, and rising pollution levels in various urban centers and their adverse impact on human health. The synergy between economic policies, energy and environmental policies is therefore vital for sustainable national development that addresses the above concerns.

Technology representation poses a challenge and forms an integral part of the analysis for addressing policy issues. The complexity in technology representation arises from the diverse array of technological stock across sectors with widely varying characteristics. For electricity generation, say, the technologies have widely varying cost and performance parameters differing in type of input fuel, conversion efficiencies, capital investment requirements, scale economies, suitability to meet peaking loads, and pollutant emission levels etc. The dynamism in technological change is related to reduction in costs and performance improvements through learning, that affects the relative competitiveness of technologies over a period of time. Complexity also arises from the fact that most of the decisions have long-term implications (30 to 40 years) due to the inherent nature of the technologies on the energy supply side, especially for electricity generation. Energy prices are a critical factor affecting technology choices. Location specific factors like land and labor prices also affect their relative costs. These diversities create non-linearity in technology grades (Loulou et al., 1997). The criteria for evaluation of technologies include economic and social considerations (average and marginal costs, capital and operating costs, opportunity costs, implications for development, effects on trade, interest and inflation rate, equity considerations); environmental consideration (local and global pollution abatement); administrative, institutional and political considerations (Grubler et.al, 1996). System discount rates reflecting variations in the cost of capital affect the relative competitiveness of the technologies. Technology assessment needs to consider inter-related technical, economic and market deployment potential of the technologies. A "push" policy in the initial stages of technology life cycle through innovation, niche market commercialization and initial diffusion initiates technology penetration by improving competitiveness through the learning-curve effect. This leads to "market pull" mechanisms taking over in later stages resulting in rapid technology penetration.

Complexities arise in diversity representation of energy resource endowments. Different energy sources appear to be competitive at different geographical locations and times mainly depending upon the availability of the resource, extraction costs and transportation costs. This results in competition among multiple energy sources that results in their partial penetration. Coal is the mainstay of Indian energy system. However other energy sources also become competitive at different geographical locations and times due to interplay of fuel quality (mainly heat value, sulfur and ash contents), delivered fuel costs (extraction and transportation) and relative costs of conversion technologies. Therefore near Maharashtra and Gujarat coasts, imported natural gas may become competitive to high ash coal mined and transported from eastern India. The partial penetration of multiple energy sources may be represented by incorporating the energy source prices as probability distributions rather than the deterministic average values (Kanudia, 1996).

Scenario analysis forms an integral part of the assessment of energy and environment policies. Each scenario is one alternative image of how the future can unfold and represent the interplay of certain economic, social, technological, environmental and policy paradigms. Scenarios are viewed as a linking tool, which integrate stories of the future, quantitative formulations to enhance understanding of how the system works and to capture systems behaviour and evolution. They should not be taken as policy recommendations. The complexities in assessment of energy and environment policies lend itself to diverse modeling approaches. This paper presents an integrated modeling approach for assessment of long-term energy and emission trajectories for India, using a wide spectrum of models under different future scenarios.

2 Alternate Modeling paradigms

Alternate modeling approaches can be adopted for addressing the above energy and environment policy requirements- a single monolith model or an integrated framework employing diverse models, each with its inherent characteristics. A monolith model will have to establish complex inter-linkages across diverse economic, technological, social, environmental and energy sector variables. This hard linking, i.e. integrating model codes and runs is a very complex process. It corresponds with state-of-the-art energy and emissions modeling practice. The hard linked bottom-up and top-down models are not available (IPCC, 1996). MARKAL-MACRO model (Manne and Wene, 1992) has such a linkage, however the top-down component in this model remains very weak. The literature on Integrated Assessment Models (IPCC, 1996) suggests enormous time and resource requirements for setting up such models. They are also not suitable for detailed analysis of individual components. On the other hand, an integrated modeling framework utilizes the inherent strengths of existing individual models that are best suited to address specific energy and environment issues. The models are soft-linked through consistent and similar assumptions for all the models, a shared database and talking between the models. Multiple feedbacks are required among the models to ensure consistency of results and policy analysis. However a high level of skill is needed in integrating various models and it necessitates being conversant with the nuances of all the models for consistent integration.

Evidently, each model offers different possibilities for policy analysis. The integrated use of models helps to take advantages from each model. However, the critical consideration is to ensure that the model specifications are harmonized, if models are used in conjunction. We ensure the consistency through soft linkage whereby the scenario specifications across the models are harmonized. While this does not ensure the consistency in theory, in practice the results from different models can be made consistent through meticulous scenario specifications and cross checks. Soft linkage belongs to the art of modeling, whereas hard linkage is more a scientific exercise. Our experience with soft linked model integration framework suggests that the methodology leads to better policy analysis than the analysis from any single model.

This paper presents an integrated modeling framework for energy and emissions future analysis using bottom-up and top-down energy and economy models along with a few other specific models, discussed in the next section. Soft-linkages between the models, within an

integrated framework, capture the inter-linkages between economy, energy and environment, while preserving the inherent strengths and characteristics of individual models. This allows very detailed assessment of specific sectoral policies, while at the same time allowing integration within the energy system forming a part of the overall economy, thus mirroring reality. Bottom-up models follow the optimistic "engineering paradigm" in that they presume the existence of an efficiency gap. Top-down models reflect the pessimism of the "economic paradigm" which originates from the assumption that the present technology mix is the result of an efficiently functioning market. They are appropriate tools to endogenously derive the macro-economic indicators for a reference future and aggregate behaviours of economic agents based on prices and substitution elasticities. Bottom-up models are more appropriate for policy analysis involving assessment of the impacts on technology and fuel mix within a sector involving detailed representation of fuel flow and technological linkages. They examine technology options in energy supply side and enduse sectors in terms of costs, fuel inputs and emission characteristics, with detailed representation of technologies. The framework presented here also captures geographical diversities in energy use and emission patterns in India and addresses local, regional and global environmental concerns. It also represents the diversity of macro-economic sectors and their consistent representation with macro-economic parameters and future demand projections, that pose a modeling challenge. The policy assessment builds in future scenarios, each of which is defined by an internally consistent and reproducible set of assumptions about key relationships and driving forces of change.

3 Integrated modeling system

The integrated modeling framework for energy, economy and emissions mitigation analysis is shown in figure 1. This framework has three modules; the top-down models, the bottom-up models and other models. These three modules are soft-linked through various parameters. For example, the top-down models provide GDP and energy price projections that are used as inputs to the bottom-up models. The bottom-up models, on their part, provide future energy balance that is used for tuning the top-down models. Such multiple feedbacks ensure that the results from both the modules are in congruence. Similarly the bottom-up models provide detailed technology and sector level emission projections that are used for health impact assessment. These projections along with future scenario assumptions also provide inputs to the GIS based energy and emissions mapping for the country. The other models provide health costs to the economy and these help in analyzing local pollution control policies through the bottom-up models. The objectives, outputs and policy issues addressed by each model are indicated in table 1.

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Insert Figure 1 and table 1 here

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Each module consists of multiple individual models. The top-down module uses two models namely Second-Generation Model (SGM) and Edmonds-Reily-Barnes model (ERB). The Second Generation Model (Edmonds et. al, 1993, Rana and Shukla, 2001) is a computable

general equilibrium (CGE) model. The long-tern analysis of India's energy and emissions profiles is done using the ERB model (Edmonds and Reilly, 1983; Reilly et al., 1987; Edmonds and Barns, 1992, Rana and Shukla, 2001). Linkage between the models is soft, in the sense that the consistency is attempted by reconciling the scenario inputs for each model. For instance, for a given scenario, the end-use demands that are used as inputs for bottom-up models are projected using the sectoral GDP projections from SGM which in tern drive the Demand projection model. The models are however not hard-linked. Similarly the bottom-up module integrates five individual models:

i) MARKAL - an energy systems optimization model (Berger et al, 1987, Fishbone and Abilock, 1981, Shukla, 1996) 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.

Each of these models address specific questions and complement one another for a comprehensive analysis of energy and environmental concerns. The demand projection model, for example, provides end-use demands to the MARKAL and AIM/ENDUSE models that are demand driven. The integration of demand and supply within a bottom-up framework is achieved through a soft linkage of MARKAL with the AIM/ENDUSE model whereby the output of each end-use modeling exercise using AIM/ENDUSE is exogenously passed to the MARKAL model as an input. The power sector LP model is used for regional analysis of the power sector in India as well as for the regional energy system analysis for South Asia. A similar analysis using MARKAL or one of the top-down models would require setting up individual models for each region and then integrating their runs. This would be a mammoth task requiring considerable resources. Integrated modeling system therefore not only uses the appropriate individual model for various policy questions, it also reduces overall resource requirements considerably. For example, to estimate power trading possibilities between Northern and Western power grid in India, we would have to set up MARKAL for both the regions modeling power exchange as import and export in each model. The LP model, on the other hand, is capable of directly modeling these regions in a single model and analyzing the impacts of grid integration. The technology details for the LP and MARKAL models have to be same for a consistent analysis.

The analysis, which spans four decades, examines a reference scenario and several other policy scenarios like carbon mitigation, local pollution control, grid integration, regional co-operation etc. This provides insights like implications of mitigation commitments on energy and technology mix, energy costs, mitigation costs and competitiveness of Indian industries.

3.1 Bottom-Up Model Integration

Figure 2 expands the soft-links among the components of the bottom-up module. Figure 3 shows the integration between *bottom-up* and *other model* modules. The time horizon of the present analysis is forty years, from 1995 to 2035. However ANSWER version of MARKAL permits extending it further and we are currently extending the bottom-up analysis also up to 100 years. For each period, the MARKAL model decides the energy and technology for forty years while minimizing the discounted capital and energy cost. End-use sectors are modeled separately for two reasons. First, the technology selection in each end-use sector is determined by the sector-wide objective. Second, separate modeling of each end-use sector allows detailed representation of technologies within the sector. AIM/ENDUSE (Asian-Pacific Integrated Model – End-use Component), a bottom-up model developed by researchers in Japan (Morita et. al, 1996), is adapted for modeling of end-use sectors. AIM/ENDUSE selects the technology mix within each end-use sector while minimizing the discounted costs of capital, energy and materials over a forty years horizon.

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Insert Figure 2 and 3 around here

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This technology mix for each end-use sector is provided as an input to MARKAL together with exogenous bounds on technology penetration. For each end-use sector, the technology mix thus gets selected via an end-use sector model that is soft-linked to MARKAL. Such an integration of bottom-up models facilitates consistent and detailed assessment of technology policies. The long-term end-use demand projections are exogenous inputs to energy system model and end-use sector models. These are projected using logistic regression (Loulou et. al., 1997) in a manner, which ensures macroeconomic consistency.

3.1.1 End-Use Demand Projection Model

End-use demand projections are made for forty years. Since India is now in a high growth phase, whereas in the long run the growth shall have to saturate and stabilize at a lower level, we use logistic curve regression for projecting the end-use demand for each sector. The consistency of the end-use demand projections with the macro-economy is achieved by using macro-economic parameters such as the sectoral gross domestic products (GDP) as independent variables for demand projections. The overall consistency is achieved by using an integrated demand projection framework that accounts for all sectors at the bottom level and overall GDP and consumption at the top level. Logistic projections are made using past sectoral consumption data as well as estimates, if available, from other detailed studies for some future years. Expert opinions are used for factoring in the future expectations.

3.1.2 AIM/ENDUSE Model

AIM/ENDUSE is a bottom-up, dynamic end-use sector model. It considers demands for energy services, economic growth, sectoral structure, and then calculates the period-wise technology mix that minimizes the discounted sector-level cost. The cost includes capital, energy and material costs. AIM/ENDUSE model is based on the sectoral reference system which links energy service demands, service devices (technologies), and energy resources for the sector (Kainuma et al, 1997).

Indian AIM/ENDUSE model is developed for fourteen end-use sectors, including ten industries, transport, agriculture, urban and rural households, and services sectors. The choice of these sectors is based on their importance in the national energy consumption. For instance, the ten industrial sectors that are separately modeled account for over seventy percent of industrial coal consumption and fifty five percent of electricity consumption by industries. Each sector is modeled with considerable technological details about consumption of different energy forms, emission of various gases, cost components, and technological shares. Time horizon of the model analysis spans forty years, from 1995 to 2035. AIM/ENDUSE model provides a solution where an end-use sub-sector optimizes its cost with an exogenously given state of the supply side and other demand sectors. Hence, the output from the Indian AIM/ENDUSE models are used to introduce exogenous technology penetration bounds in the Indian MARKAL model. This approach allows scope for response of an end-use sector to the changes in the rest of the economy, and helps in achieving partial equilibrium of the energy system.

3.1.3 MARKAL Model

MARKAL is a multi-period, long-term model of the integrated energy system of a geographic or political entity, which encompasses the procurement as well as the transformation and the end-use of as complete a mix of energy forms as is desired (Manne and Wene, 1992). Various energy extraction, conversion, and consumption activities are quantified in the model through individual technologies that play a role in the energy system. The model is dynamic and a technology is linked not only with other technologies through energy flows, but also with itself across successive time periods. Another important characteristic of MARKAL is that it is driven by a set of demands for energy services (an energy service is an economic demand whose satisfaction involves energy consumption, e.g. passenger travel, or household cooking, or steel production). MARKAL selects the technology mix (in both supply and demand sectors) that minimizes the discounted cost of energy system, which includes capital and variable costs. This optimizing feature of the model ensures that MARKAL computes a partial economic equilibrium of the energy system, i.e. a set of quantities and prices of all energy forms and materials, such that supply equals demand at each time period (Loulou et al, 1997).

Indian MARKAL (Kanudia, 1996) is set up for the forty-year period spanning years 1995-2035. It has been updated to represent 235 present and future technologies (table 2). Demand technologies are identical to those in the AIM end-use sector model. Supply technologies fall under two categories: electricity generation technologies and oil refineries. There are 22 different types of electricity generating technologies (pulverized coal, gas

turbine, large hydro, nuclear fission etc) and one refinery technology representing different fuel mix and cost structure. The future technological progress is assumed to consist of three factors: autonomous energy efficiency improvement, improvements in present technologies and investments in new technologies. Bounds on penetration of demand technologies are set around the optimal technology mix trajectories obtained from the AIM/ENDUSE model.

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3.1.4 Stochastic MARKAL Model

The long-term and global nature of the energy system and the multiplicity of resources, technologies and uses tend to expose the energy decisions to myriad uncertainties such as: i) the future prices of energy, ii) rates of technological change, iii) consumption behavior, iv) changes in the structure of the economy, and v) nature of environmental impacts. These uncertainties often have greater consequences on energy system decisions in developing countries due to their rapid growth rates, institutional weaknesses and scarcity of capital. We analyze the impacts of uncertainties singularly and jointly using the Stochastic MARKAL model. The Indian Stochastic MARKAL model (Shukla and Kanudia, 1996; Shukla, 1997) uses a multi-stage recourse framework (Loulou et al, 1997). The stochastic MARKAL model minimizes the discounted expected cost of the energy system. The uncertainties are modeled for three parameters - economic growth, price of natural gas and limitations on carbon emissions from India. The analysis suggests strategies for energy sector investments. Stochastic MARKAL also computes value of information, i.e. the value of resolving uncertainties, which is an important policy input.

3.2 Top-Down Models and Linkages

A most vital limitation of the bottom-up energy models is that the macro-economic feedbacks are exogenous to the model. For instance the end-use demands, which are the most important drivers of bottom-up energy models, are inelastic to changes in macro-economic parameters such as energy prices or changes in GDP resulting from tax or subsidy policies. In the scenario analysis, these macro-economic changes are required to be introduced exogenously. For the consistency of the scenario, those vital inputs to the bottom-up models that are influenced by the macro-economic parameters are required to be recomputed and specified exogenously. Top-down models are appropriate tools to endogenously derive the macro-economic indicators for a reference future. These models endogenously specify the economic variables such as the future investments and prices. Besides, these models can also compute the changes in macro-economic indicators over the reference scenario resulting from alternative scenario specifications. This information is essential to recompute some input parameters for the bottom-up models so as to make the results of top-down and bottom-up exercises constant.

We use two top-down models for energy and carbon mitigation analysis - i) Second Generation Model (SGM), and ii) Edmonds-Reilly-Barns (ERB) model. The SGM is used for national level analysis. ERB is a global energy systems partial equilibrium model with nine regions, where India is specified as a separate region. The ERB analysis provides a long-term energy and emissions trends (105 years horizon from 1990 to 2095) for India under different scenarios that are specified globally.

3.3 Other models

3.3.1 Inventory Estimation Model

The emissions inventories are traditionally reported on a cumulative national basis or for geographical grid dimensions. Although national level emissions for India would provide general guidelines for assessing mitigation alternatives, they fail to capture the regional and sectoral variability in Indian emissions. Districts reasonably capture this variability to a fine grid since 80% of these districts are smaller than $1^o x 1^o$ resolution with 60% being smaller than even $1/2^o x 1/2^o$. Moreover districts in India have well established administrative and institutional mechanisms that would be useful for implementing and monitoring mitigation measures. It should however be noted here that the mitigation policies are presently formulated at the national level and the implementation can be monitored at the district level using the existing institutional frameworks innovatively. Therefore district level emission estimates offer finer regional scale inventory covering the combined interests of the scientific community and policy makers.

The basic methodology to estimate the total emissions of a particular gas from the country uses the following equation, which is in line with the recommended Intergovernmental Panel on Climate Change methodology (IPCC, 1997):

$$\text{Total emissions} = \sum_{\text{Districts}} \sum_{\text{Source Categories}} \sum_{\text{Sectors}} (\text{Activity level} * \text{Emission coefficient})$$

3.3.2 Geographical Information System (GIS) Based Energy and Emissions Model

GIS is a computer-assisted system for the acquisition, storage, analysis and display of geographic data. GIS is a useful policy tool for regional analysis of energy use and emission patterns. The district level data has been linked to the district topology for India available in GIS package, converted into per unit area for each of the 466 districts and plotted (Garg et. al, 2000a and b). The analysis of regional and sector specific gas inventories contributes to effectiveness of emissions mitigation by indicating the hotspot locations and sectors where controls can lead to maximum benefits. GIS also assists in identifying energy and environment zones in India that would offer a mechanism to monitor these hotspots in future. These zones may be formed on the basis of dominant energy and emission forms, energy consumption per capita, total annual energy consumption and emissions, average annual concentrations, growth rates of emissions, mitigation possibilities etc (Garg, 2000).

3.3.3 Power Sector Linear Programming (LP) Model

The scenario analysis for grid integration and regional co-operation in power sector uses a LP model that determines the optimal combination of new plants needed to meet given levels of power demand (Shukla et. al., 1999). The modeling framework uses a detailed, bottom-up representation of technologies (figure 4). It allows constraints on fuel availability, emissions, investments, and technology improvements that mimic policy measures and set limits over which values can be obtained. The objective function of this least-cost optimization model minimizes the entire system cost including power generation costs, coal cleaning and transportation costs, electricity transmission costs, and pollution control internal and external costs. Representation of the separate regions captures the variation in energy availability, demand patterns, and fuel cost. Simulation begins with a base year (1995) and then determines the amount of new capacity from each type of power plant needed to meet demand over 5-year intervals till 2015.

3.3.4 Health Impact Model

The impacts of energy sector activities on human health are linked to the emissions of local air, water and solid pollutants. These emissions alter the existing ambient levels of local pollutants. Human populations, living species and even buildings exposed to these altered concentrations are effected in varying degrees. In the present work we analyze the human health impacts of local air pollutants, namely Suspended Particulate Matter (SPM), SO_2 and NO_X as these three cause the maximum damages among various air pollutants (WB, 1995 and 1997). These health impacts, also called the Burden of Disease (BOD), are estimated in terms of mortality (premature deaths) and morbidity (sickness and lower activity levels). These are modeled for representative new plants in power, cement, steel, aluminium, sugar and brick industries. These sectors are chosen since they have the highest emission levels among various sectors. These impacts are then extrapolated to national level under suitable assumptions.

This model estimates the emission loads from a new plant, converts them into changes in ambient concentration levels using a dispersion model, estimate the exposed human population, use dose-response functions to estimate incidences of mortality and morbidity, and then project health impact values based on their specific health cost estimations for various incidences of disease. In reality each of these are very complex processes. For example, the first two steps involve interaction between multiple factors like meteorological parameters (wind directions and speed, temperature, humidity, cloud cover, time of the day etc), stack height, existing ambient concentration levels etc. The modeling requirements are also therefore very site specific and stringent. A combination of widely accepted Gaussian Dispersion and Rectangular Box models is developed to take advantage of their inherent strengths as well as to keep the analytical framework simple (Garg, 2000). Gaussian Dispersion model is used to first determine the mass distribution profile of emissions as one move away from the emission source. Box model then converts these into average increase in ambient concentration levels (micro gm/mt^3) in various concentric circles up to 50 km away from the source. This two-step methodology of estimating emission load distribution

profile and change in particulate concentration levels accounts for the effects of varying wind circulation patterns.

We have so far discussed the methodological aspects and specific characteristics of the models used in the integrated modeling system. Table 3 summarizes these.

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3.4 Database requirements

Databases are an important component of Integrated modeling system providing a consistent link across diverse models. The databases are structured as economic, technology, energy resource (production and consumption), and emissions. The economic database consists of GDP, sectoral GVA, industrial production, population, energy prices and other related parameters. The technology database captures the technical, economic and environmental performance details of technologies for various sectors of the economy (table 2). The energy resource database captures the resource availability in the country, annual extraction details of different energy resources and their annual consumption. The extraction and consumption details are captured at district level for India for 1990 and 1995. In fact the consumption details are captured at the basic point source level for various sectors. These provide the base data for regional and sectoral inventory assessment that constitute the emissions database (Garg et. al., 2000a).

4 Results

The integrated modeling framework provides insights to the energy and environmental concerns expressed earlier. The top-down results are presented in this issue separately (Rana and Shukla, 2001). These are consistent with the bottom-up model results.

A typical output from the demand projection model is shown in figure 5 below. It projects the end-use demand for cement sector up to 2035. Such projections are input to AIM/ENDUSE and MARKAL models. The AIM/ENDUSE model optimizes the technology fuel mix for individual sectors. Figure 6 is a typical output indicating the technology selection for the Indian cement industry. These outputs are used to provide initial exogenous bounds in the MARKAL model as explained earlier. The technology selection under the carbon mitigation scenario is a MARKAL result and indicates higher penetration of less carbon intensive technologies when a carbon tax is employed. This figure also demonstrates the usefulness of integrated modeling system for policy analysis.

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The MARKAL model mainly provides energy system optimization results. Some important results include future projections for the Indian energy system indicating a three times increase in the energy demand in the reference scenario over a period of forty years. Coal continues to dominate the Indian energy sector, although its share in the commercial energy consumption reduces from above 60 percent in 1995 to 53 percent in 2035. However coal use becomes more efficient and cleaner due to higher penetration of clean coal technologies in future and it partly offsets reduction in coal share. The decline in coal share is mainly due to coal to gas substitution, mainly in the power sector, with the natural gas share rising from the present 7 percent to 12 percent in forty years.

The sectoral fuel consumption indicates continued dominance of power sector in coal use and transport in petroleum products with each having 70 percent share in 2035 (table 4). Power sector share in natural gas consumption increases to more than half from the present one fourth, caused by increasing competitiveness of Combined Cycle Gas Turbine technologies (CCGT) for electricity generation. Absolute gas consumption also rises in other industries like fertilizers and petro-chemicals. While the share of gas in primary energy still remains low, the trends suggest a rising penetration of natural gas that emerges as the main hedging option to coal in future. These are results from the MARKAL model.

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The emission inventory projections for emissions basket of GHGs and local pollutants are given in table 5. The carbon and local pollutant emissions are MARKAL outputs while those for methane and N2O are Inventory Estimation Model outputs since these two are mainly due to non-energy activities, mainly in the agriculture sector, that are not covered by MARKAL. While the carbon emissions grow by about 3.5 times over 1995-2035, those for local pollutants in general grow less than twice. Methane emissions grow along agriculture sector rate while N_2O trajectories follow those of nitrogen fertilizer use. The emissions growth rates follow a decreasing trend for almost all the gases and are in fact negative for some local pollutants in later years.

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The national 1995 emissions from the above models are calibrated with the district and sector level inventory estimates from the Inventory Estimates Model. The GIS interface of

the integrated modeling system provides regional distribution maps of emissions. Figure 7 is a typical output and gives the distribution for Carbon dioxide emissions across the country. This analysis also suggests that pollution control is not as horrendous as it appears. Concentrate on 70-point sources to tackle 50% of sulfur and carbon emissions. These include 50 power plants, 5 steel plants and 15 cement plants. The analysis of regional and sector specific gas inventories contributes to effectiveness of emissions mitigation by indicating the hotspot locations and sectors where controls can lead to maximum benefits (Garg et. al, 2000b). However measures like stricter enforcement of ESP norms at cement and power plants, sulfur reduction in petroleum oil products (especially diesel and fuel oil) through out the country and gradual replacement of older vehicles with at least Euro-II complaint stocks should continue simultaneously to speed up local air cleaning. These policies also constitute the priorities for reducing the adverse health impacts of local air pollution. Such comprehensive policy analysis is possible since we employ diverse models to probe the individual policy issues keeping a consistent integration across the models.

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The health impact model indicates that if the health impacts of various industries are compared based on per unit of energy used in production by each plant, brick and cement sector impacts are most pronounced. This indicates the relative damage potential to human health from these sectors. The policy implications are to have stricter monitoring of these industries for local pollutant emissions especially particulate. We may even consider placing these industries far away (more than 25 km) from human populations.

The grid integration results from the power sector LP model indicate a reduction in capacity requirements due to better performance of generation technologies and lower transmission and distribution losses (table 6). There is a 3 to 4 percent lowering of the electricity generation costs due to changes in the technology mix and better performance of the technologies. Grid integration results in both local and global environmental benefits caused by alterations in the energy mix. There are substantial savings in the investment requirements in generation capacity. However large additional investments will be needed in setting up of state-of-the-art technology in transmission and distribution and upgradation of the existing facilities.

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5 Conclusions

In this paper we describe the integrated modeling system for energy and environment policies. It integrates ten models in a consistent framework and demonstrates the methodological soundness of the analysis. The results of the models and scenario analysis generate information required for strategic policy analysis.

The improvements in the modeling system are possible by enlarging the model for an integrated analysis in the context of climate change. This will require linkages with models from other disciplines like atmospheric sciences, sea level rise and impacts assessment. The Integrated Assessment Models (IAMs) with such linkages are available (Edmonds et. al, 1994; Alcamo, 1994; Matsuoka et. al. 1995; Dowlatabadi, 1995; IPCC, 1996; Rotmans and Vries, 1997). However, the regional and sectoral specifications in these models are too aggregated to be useful for strategy analysis at a national level. The approach we are following in India over the past two years is to develop a regionally sensitive IAM that suits needs of strategy formulation for the region. The aim is to develop a network of interdisciplinary team of modelers working in different institutions across the country in close interface with policy makers.

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Table 1: Characteristics of models used in Integrated Modeling Framework

Model	Objective	Output	Policy Analysis
Bottom-Up Models			
End-Use Demand Projection	Demand Projections consistent with macroeconomic scenario	End-use Sector Demand Trajectory	Sectoral investment, technology and infrastructure policies
AIM/ENDUSE	Minimize discounted sectoral cost	Sectoral energy, and technology mix, investments and emissions	Sectoral technology, energy, investment and emissions control policies
MARKAL	Minimize discounted Energy system cost	National energy and technology mix, energy system investments, and emissions	Energy sector policies like energy taxes and subsidies; energy efficiency; emissions taxes and targets
Stochastic-MARKAL	Minimize expected value of discounted system cost	Energy and technology mix under uncertain future, Value of information	Hedging strategies for energy system investments; identify information needs
Top-Down Models			
SGM	Determine market clearing prices for economic sector outputs	GDP and consumption trajectories;, prices of sectoral outputs and energy; sectoral investment patterns	Macro-economic impacts of policy interventions such as energy tax / subsidies; emissions limitations
ERB	Determine Global / Regional Energy Prices and Energy Use	Long-term global and regional energy prices, energy mix and emissions	Implications of very long-term global energy resource, tech. expectations
Other Models			
Inventory Estimation Model	Estimate national emission inventory for various gases	National emission inventory	Regional and sectoral emission variability, bench-marking, emission hot-spot assessment
GIS Based Energy and Emission Model	Determine regional spread of energy and emissions	Regional maps	Linking energy and environment policies across time and space
Power Sector LP Model	Minimize discounted Power sector cost	Power plant capacity and generation mix, emissions profile, total costs	Power sector technology, energy, investment, emissions control policies
Health Impact Model	Estimate local pollutant emission impacts on human health	Impact of individual plants, per capita and total national human health impacts, sensitivity analysis	Plant location and stack height policies, emission norm analysis, enforcement policy assessment

Table 2: Technology specification in bottom-up models

Sectors	Sub-Sectors	Technologies	Grades
Industrial	11	152	276
Residential	3	21	46
Agricultural	3	8	14
Transport	4	25	46
Commercial	3	6	9
Power Sector	6	22	93
Oil Refinery	1	1	2
Total	31	235	486

Table 4: A typical analysis using MARKAL model: Sectoral fuel consumption shares (%)

Fuel (PJ)	Sector	2000	2010	2020	2035
Coal products	Power	64	65	66	70
	Steel	17	16	15	12
	Cement	5	6	6	5
	Brick	2	2	3	4
	Paper	1	1	1	1
	Textile	1	1	1	1
	Transport	0	0	0	0
	Residential	1	1	1	1
Petroleum products	Transport	53	63	70	71
	Industry	32	25	20	19
Natural gas	Power	28	44	52	51
	Fertilizer	13	14	11	11
	Non-energy	48	37	32	33

Table 5: Emission inventory projections for India

Emissions (MT)	1995	2000	2010	2020	2035	CAGR*
Carbon	212	253	411	572	738	3.14
Methane	18.6	19.5	21.5	23.2	25.7	0.95
N_2O	0.251	0.251	0.405	0.610	0.838	3.48
CO_2 equivalent GHG	1219	1424	2063	2752	3504	2.67
SO_2	4.76	5.58	6.46	8.09	7.39	1.11
NO_X	4.66	5.57	6.08	7.64	8.66	1.87
Particulate	3.10	4.10	4.70	4.26	3.03	-0.06
CO	37.1	39.3	40.8	42.7	43.5	0.40

** Compounded Annual Growth Rate over 1995-2035 (%)*

Table 3: Computational details of the models

Model	Scaling: Time, Space and Sector	Computation Method
Bottom-Up Models		
End-Use Demand Projection	Horizon: 40 years Space: National Sector: End-Use	Logistic regression
AIM/ENDUSE	Horizon: 40 years Space: National Sector: End-Use	Linear programming (with step-wise linearization of non-linear functions)
MARKAL	Horizon: 40 years Space: National Sector: Energy	Linear programming (with step-wise linearization of non-linear functions)
Stochastic-MARKAL	Horizon: 40 years Space: National Sector: Energy	Stochastic-Linear Programming
Top-Down Models		
SGM	Horizon: 60 years Space: National Sector: Economy	Computable General Equilibrium
ERB	Horizon: 105 years Space: Global Sector : Energy	Non-linear Energy System Partial Equilibrium
Other Models		
Inventory Estimation Model	Horizon: Annual Space: National Sector : All	Linear summation
GIS Based Energy and Emission Model	Horizon: Annual Space: National Sector : All	Software packages
Power Sector LP Model	Horizon: 20 years Space: National Sector : Power	Linear programming
Health Impact Model	Horizon: Annual Space: Plant level Sector : All	Combination of Gaussian Dispersion and Cylindrical Box models

Table 6: Implications of Grid Integration

Parameter	**2005**	**2010**	**2015**
Generation capacity (GW) reduction*	148.4 (4.1)	187.4 (5)	229 (5.8)
Generation cost (Rs/kWh) reduction	2.05 (2.7)	2.01 (3.6)	1.95 (4)
SO_X Emissions (MT) reduction	4.2 (3.7)	5 (4.1)	5.6 (5.4)
Carbon Emissions (MT) reduction	137.6 (2.7)	175.2 (3.6)	207 (4.8)
Reduction in generation capacity investments	6.4	7	8

* The reduction for each variable (in brackets) represents the % reduction over the reference scenario

Figure 1: Soft-linked Integrated Modeling Framework

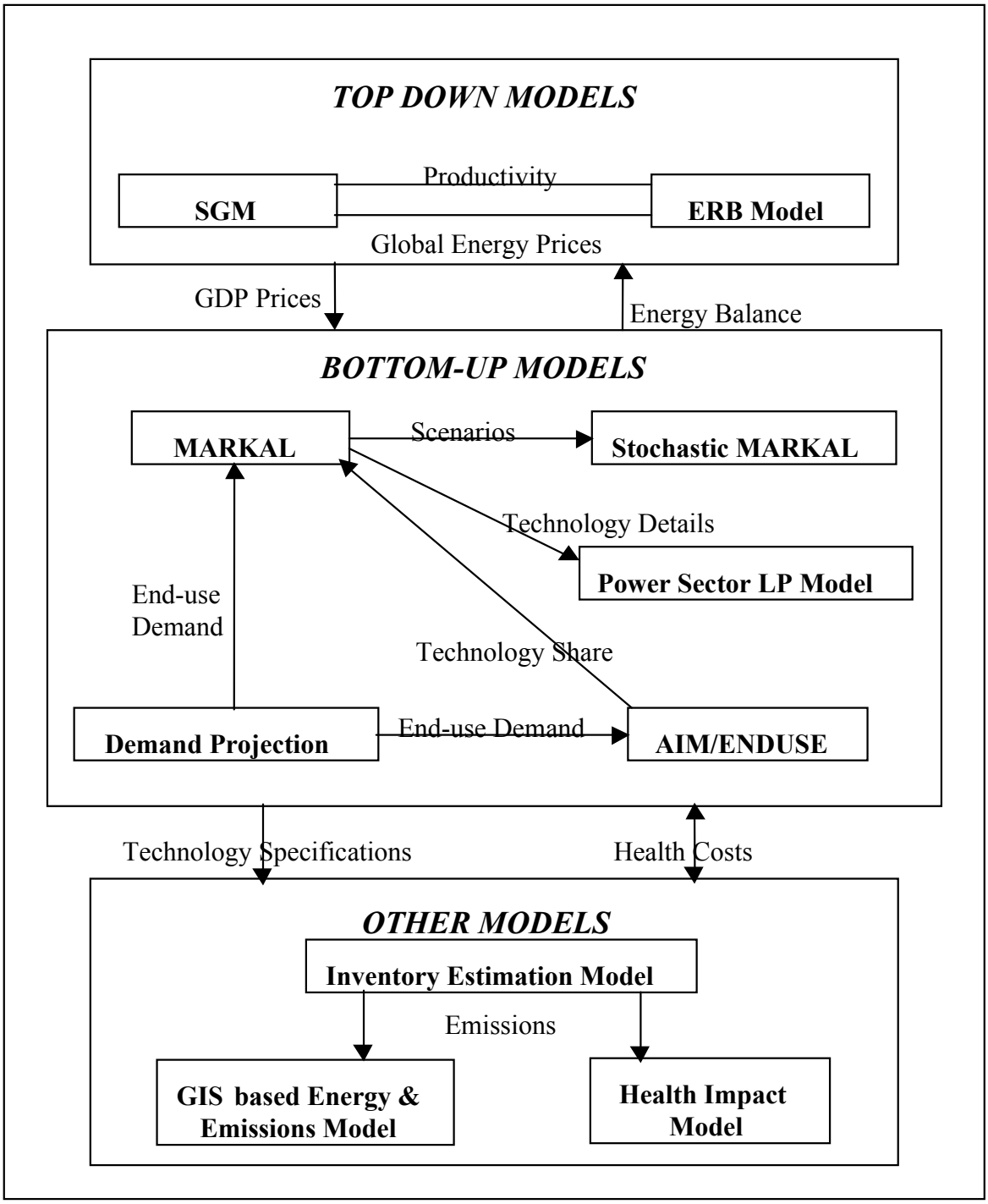

Figure 2: Soft-linked Bottom-up module

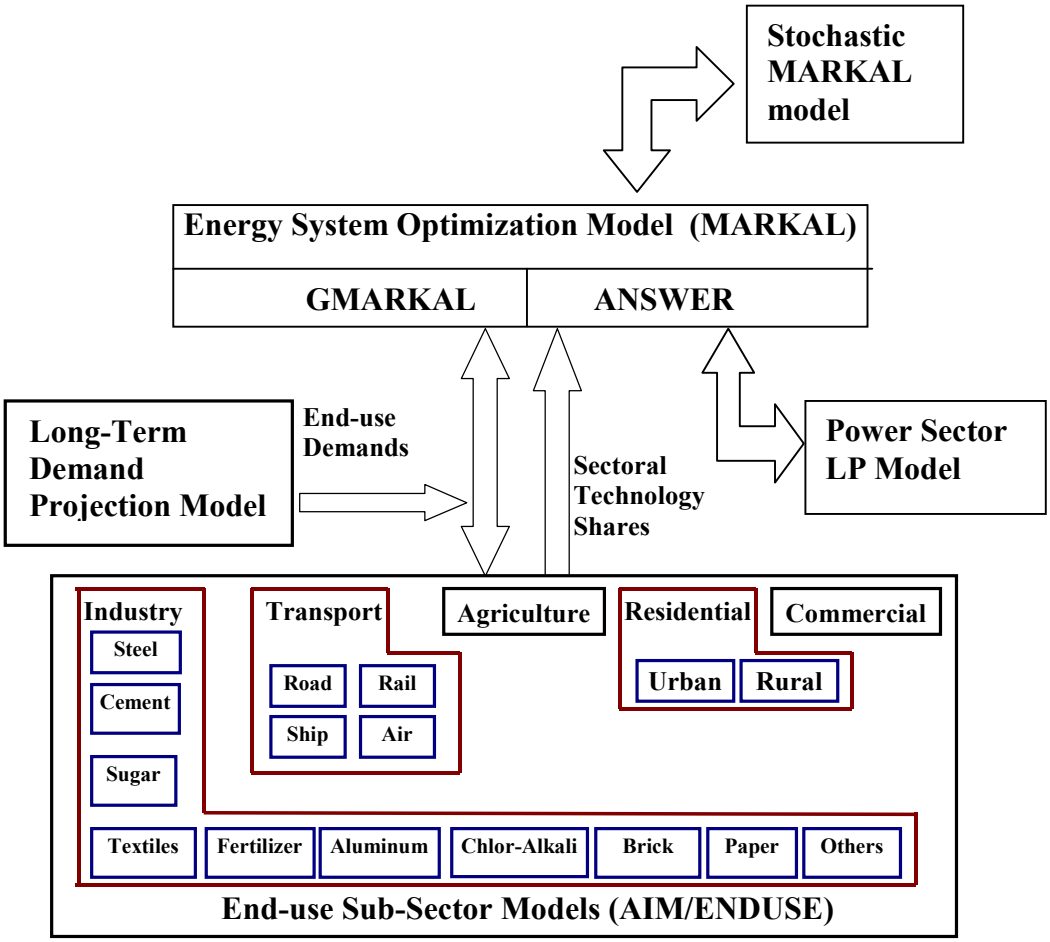

Figure 3: **Integrating the "bottom-up" and "other model" modules**

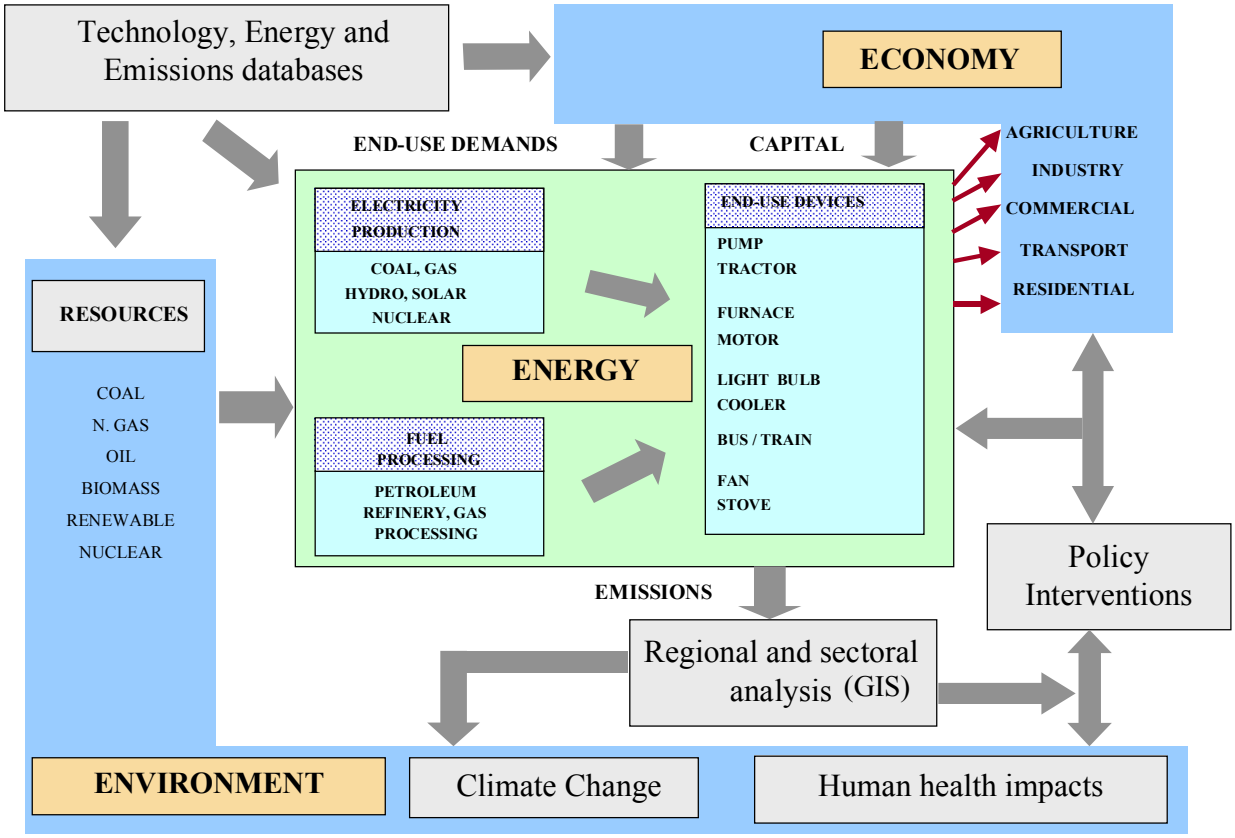

Figure 4: The Power Sector Linear Programming Model

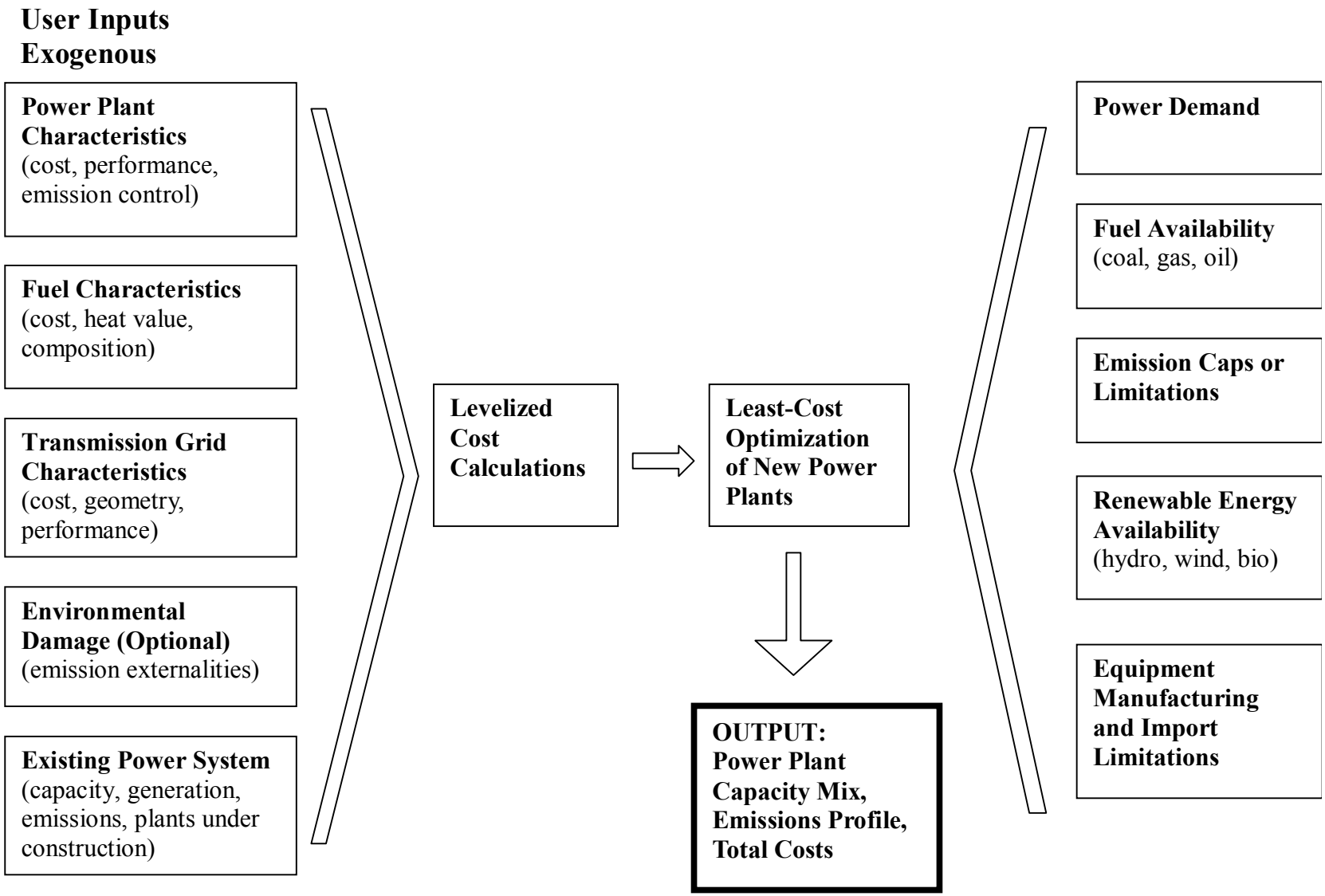
User Inputs
Exogenous
Power Plant Characteristics (cost, performance, emission control)
Fuel Characteristics (cost, heat value, composition)
Transmission Grid Characteristics (cost, geometry, performance)
Environmental Damage (Optional) (emission externalities)
Existing Power System (capacity, generation, emissions, plants under construction)
Levelized Cost Calculations
Least-Cost Optimization of New Power Plants
OUTPUT: Power Plant Capacity Mix, Emissions Profile, Total Costs
Power Demand
Fuel Availability (coal, gas, oil)
Emission Caps or Limitations
Renewable Energy Availability (hydro, wind, bio)
Equipment Manufacturing and Import Limitations

Figure 5: Cement sector demand projections in million tons/year

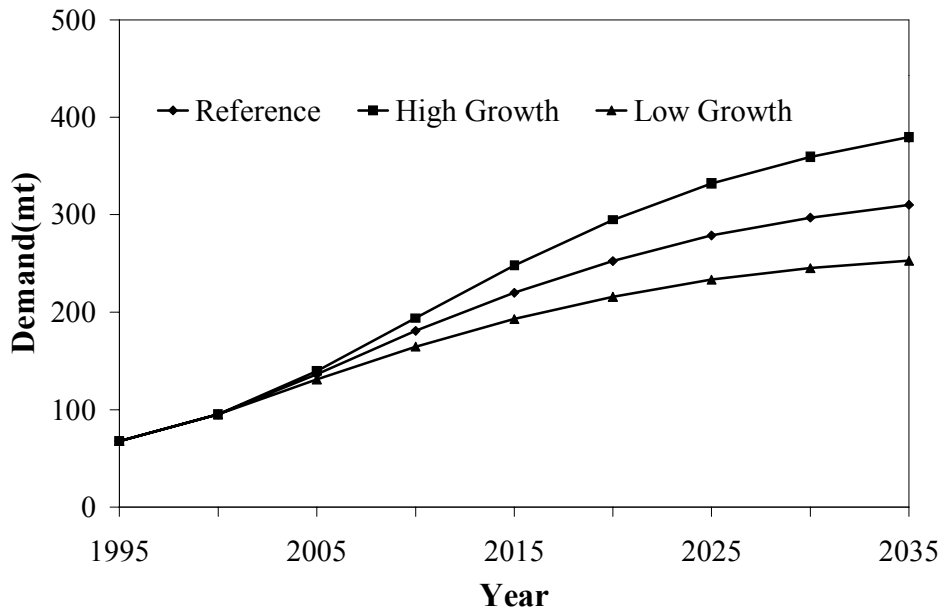

Figure 6: Technology selection dynamics in cement industry under different carbon mitigation scenarios

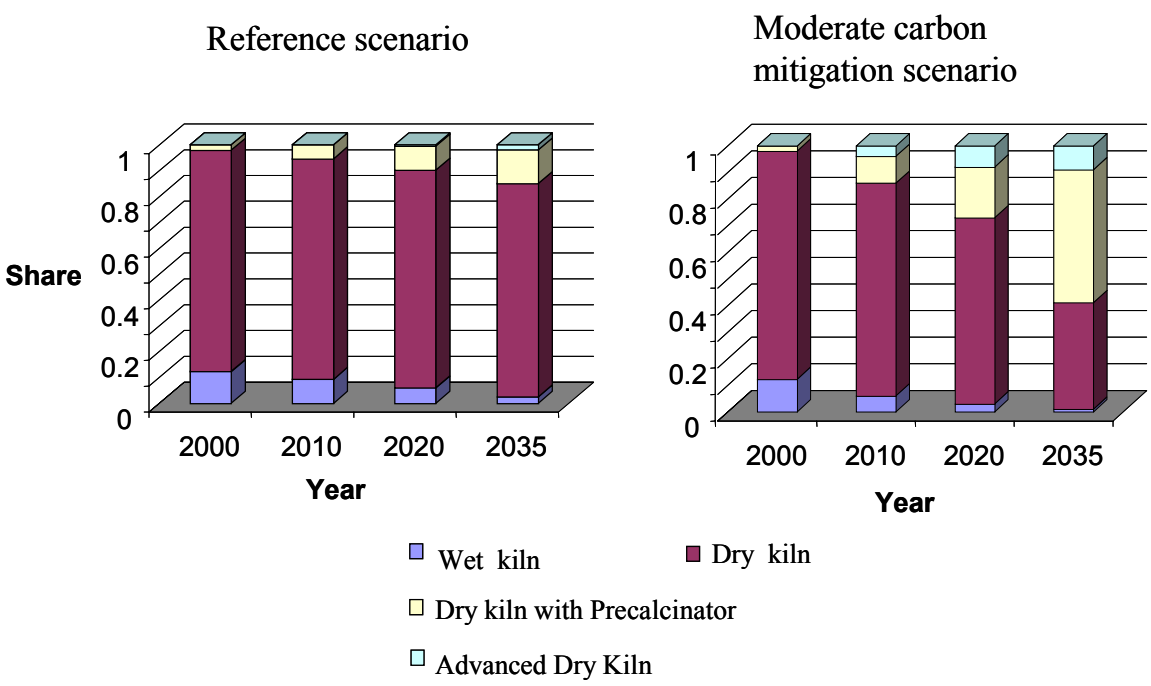
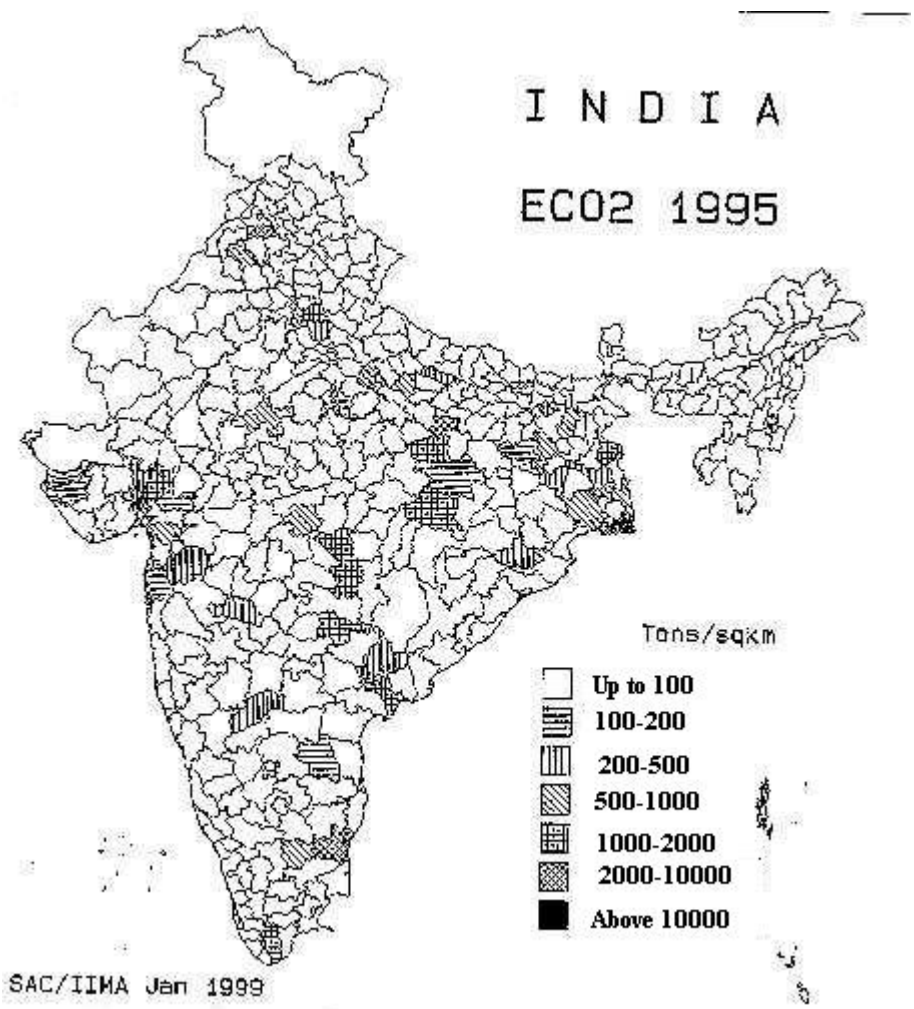
Figure 7: Regional spread of CO_2 emissions for India in 1995