Chapter 2
Methodology: An Integrated Modeling Approach

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 behavior.

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 behavior, 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.

2.1 The Integrated Modeling Framework

The analysis in the case studies that follow utilize an integrated modeling framework. The integrated modeling framework for energy, economy and emissions mitigation analysis is shown in figure 2.1. 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.

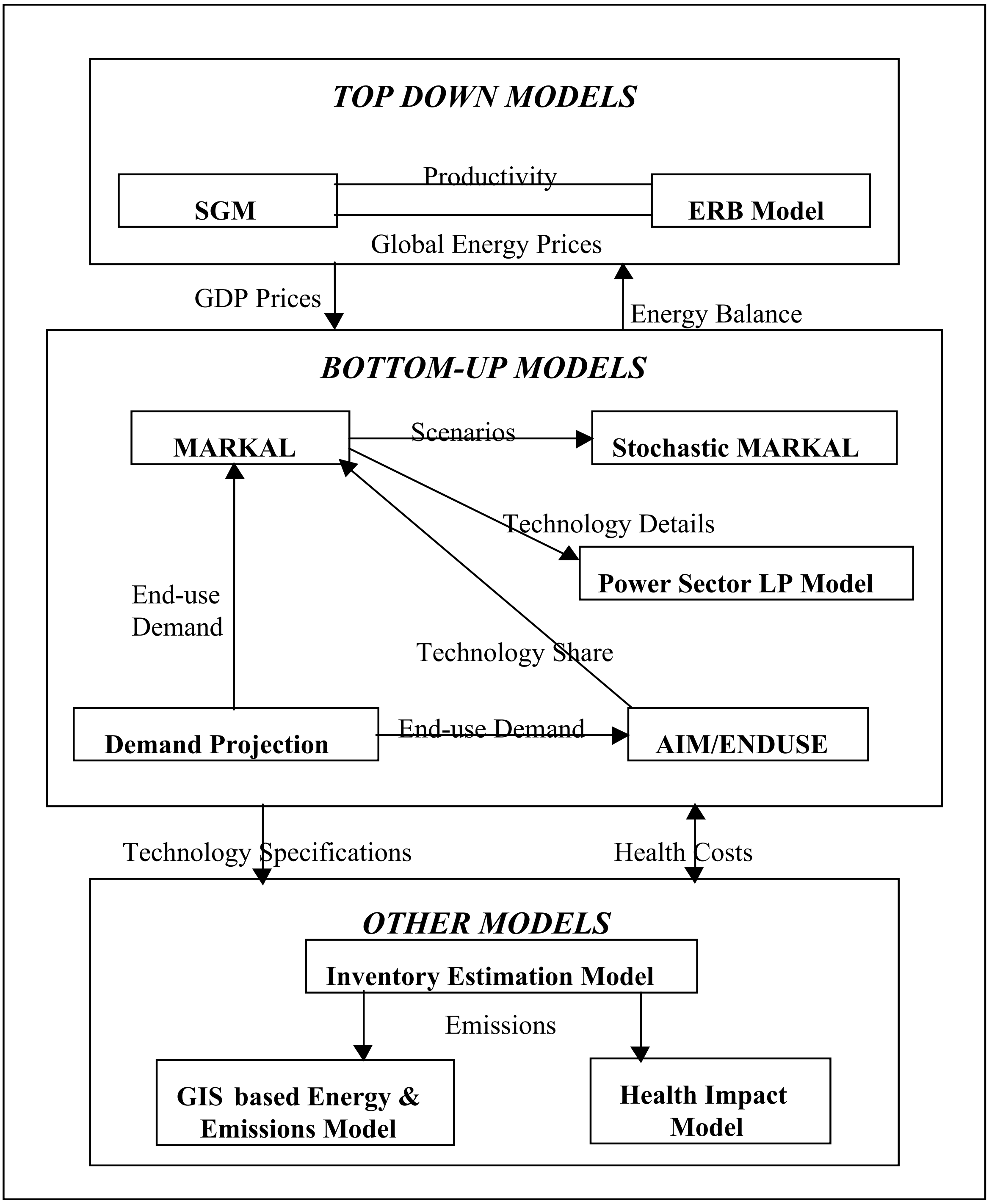

Figure 2.1: Soft-linked Integrated Modeling Framework

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.

2.2 Bottom-Up Model Integration

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.

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.

2.2.1 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.

2.2.2 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. 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.

2.2.3 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).

2.2.4 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.

2.3 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.

The two top-down models used for energy and carbon mitigation analysis are - 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 for India under different scenarios that are specified globally.

2.4 Other models

2.4.1 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):

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

2.4.2 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 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.

2.4.3 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. 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.

2.4.4 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. 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.