Energy Economy Model Applications for India: Long-term GHG Trends and Mitigation Costs

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1. Introduction

Notwithstanding the improvements in the efficiency of energy technologies, the consumption of commercial energy (Shukla et. al, 1999) and emissions of greenhouse gases (GHGs) in India during past three decades have grown at rates that are higher than the growth rate of gross domestic product (GDP). This is primarily due to the structural transformations of three kinds. First, decline in the share of agriculture in total GDP and the enhanced share of industry and services sectors. Second, shift in transport sector from rail to road, and from mass transport to personal transport vehicles. Third, enhanced share of commercial fuels in the households sector at the expense of traditional biomass fuels. In a structurally transforming economy, assessing the long-term trends of energy and emissions is a complex exercise requiring modelling of the transforming dynamics.

Although under the Kyoto Protocol (UNFCCC, 1997) to the United Nations Framework Convention on Climate Change (UNFCCC, 1992) there are no binding GHG emissions limitation commitments on India, her growing energy and emissions trajectories are attracting attention due to rising future global shares. This makes India a vital country subject to the pressures such as from the doctrine of 'meaningful participation' of developing countries in emissions mitigation as advocated by the Congress of the United States of America. In the next phase of global climate change negotiations, the pressures on developing countries to join emissions limitations (Jacoby, 2000) will be more intense to bridge "the chasm between the United States and developing countries" (Frankel, 2000).

The indigenous studies on the long-term GHG trends from developing countries are therefore important to address the issues before the global negotiations. This paper presents the work of the authors on energy-economy models together with an analysis of future energy, economy and emissions trajectories in baseline scenarios and the mitigation costs under different policy options.

1.1 Integrated Modelling Framework

For the energy, economy and emissions mitigation analysis, we use an integrated modelling framework that includes bottom-up and top-down energy and economy models

(Figure 1). Bottom-up models contain detailed representation of the energy resources, technologies, and end-use demand categories. A typical bottom-up model helps in evaluating specific technology and fuel options within a sector. It concentrates on substitution possibilities available to mitigate the effects of increases in the prices of energy inputs under external structural constraints and macroeconomic assumptions about growth. The absence of interconnections with other sectors of the economy is the major limitation of this set of models. Compared to bottom-up models, top-down models have higher sectoral aggregation, but better characterization of impacts on economic growth, feedback of prices, and trade. These models represent the macroeconomic interlinkages between the aggregate production sectors of an economy, consumers, and the government. Conceptually, top-down and bottom-up models can be linked together to utilize the outputs from one into another for finer depiction of the exogenous inputs.

The bottom-up models included are: 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 fifteen end-use sectors, and iii) a demand model which projects demands for each of the thirty seven end use services. The overall bottom-up model specification includes 22 electricity generation and 86 demand technologies. 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 modelling exercise is exogenously passed to the MARKAL model as an input. The analysis, which spans four decades, examines a reference scenario and several carbon mitigation scenarios, and provides insights into the implications of mitigation commitments on energy and technology mix, energy costs, mitigation costs and competitiveness of Indian industries.

The national level top-down analysis uses the Second Generation Model: SGM (Edmonds et. al, 1993; Fisher-Vanden et al, 1997). SGM is a computable general equilibrium (CGE) model. The long-term analysis of India's energy and emissions profiles is done using the global Edmonds-Reily-Barnes (ERB) model (Edmonds and Reilly, 1983; Reilly et al., 1987; Edmonds and Barns, 1992). The global model depicts

India in the global economy and the national model depicts dynamics of domestic markets in a more detailed fashion. The aim is to consolidate the calibration of these two models with results of each other as well as with those of bottom-up models, so as to increase the confidence in the insights that each of these models provide independently. These models also have soft linkage, in the sense that consistency is pursued by reconciling the scenario inputs for each model. Further, the linkage between the set of top-down models and the bottom-up models is through the end-use demands and energy balances. End-use demands, which are used as inputs for bottom-up models are projected using the sectoral GDP projections from SGM and the energy balances obtained from the bottom-up exercises are used to recalibrate the top-down models. The models are however not hard-linked.

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Insert Figure 1 around here

Figure 1: Integrated Modelling Framework

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1.2 Model Integration with Soft Linkages

While we use multiple models for energy and GHG mitigation analysis, these models are only soft linked. The hard linking, i.e. integrating model codes and runs is a very complex process. This corresponds with state-of-the-art energy and emissions modelling 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. As such, it is acknowledged in the literature that building a single model capable of addressing all the nuances of the climate change problem is not possible (Dowlatabadi, 1995). Although various Integrated Assessment Models (IAMs) have been developed and used for analysis (IPCC, 1996). While IAMs have some success with respect to linking economic models with impacts and atmospheric models, it is observed that when creating mitigation scenarios, policy introduction in most of the models is handled in too simplistic a fashion (Rana and Morita, 2000) pointing to the fact that even hard-linked or

integrated models are weak in certain respects.

Therefore, we have preferred the soft linkage route while using strong top-down and bottom-up models for macro- and micro-level analyses respectively. 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 meticulously scenario specifications and cross checks. Soft linkage belongs to the art of modelling, 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.

The discussion in this paper is restricted to the application of the top-down models. Bottom-up models are discussed in Shukla, Garg and Ghosh (this volume).

2. Brief Description of ERB Model

ERB is a well-documented (Edmonds and Reilly, 1985; Reilly et al., 1987; Edmonds and Barns, 1992), behavioral, long-term model of global energy and greenhouse gas emissions. The world is divided in the model in nine regions - US, OECD West, Europe, Africa, Russia, Middle East, Japan-Australia-New Zealand, China and Asia (excluding India), and India. The model has four components: supply, demand, energy balance, and greenhouse gas emissions.

The supply module projects future supplies and prices of six major primary energy categories-conventional oil, conventional natural gas, coal, nuclear power, hydroelectric power, and solar electric power-for each of the nine regions in a given period. Energy supply is disaggregated into renewable and non-renewable sources. Fossil fuel energy supplies are related to the resource base by grade of the resource, cost of production, and historic production capacity. For each fuel, different technological progress is specified. The demand module computes primary fuel requirements. Demand for each fuel is computed from population, labour productivity, energy end-use intensity,

and energy prices. Energy end-use intensity is a time dependent index of energy productivity. Regional prices of primary and secondary fuels are first computed followed by computation of energy service price for each end-use sector. Regional prices of primary fuels are in turn governed by respective world price of each, energy taxes, subsidies and tariffs. Demand for energy services in each region's end-use sectors is determined by the cost of providing these services, income and population. For all regions, energy demand is disaggregated into residential/commercial, industrial and transport sectors.

The energy balance module ensures market equilibrium, given assumptions on technologies and income and price elasticities and other factors such as resource availability. The greenhouse gas emissions module is a set of three post-processors which calculate the energy-related emissions of carbon dioxide, methane, and nitrous oxide, essentially by applying appropriate emission coefficients. The model horizon is 105 years, from 1990 to 2095 with eight benchmark years separated by 15 years interval.

We have set up the ERB model for the India region, while keeping the balances for the other regions as specified in the original ERB model. In this manner, the global model depicts India in the global economy. Global specification of the model ensures the consistency of results for India with the rest of the world. The reference case assumptions follow the IS92a scenario paths[1] (Pepper et. al, 1992; Legget et. al, 1992) for rest of the regions. Two separate cases of high growth and low growth scenarios for India are created as departure from the reference case. For the policy analysis, a range of carbon tax scenarios for mitigation is created. The long-term results from ERB model, like the global energy prices, energy mix and emissions are used as inputs and benchmark for other models - i.e. SGM as well as the bottom-up models.

3. Brief Description of SGM

The Second Generation Model (SGM), a computable general equilibrium (CGE) model (Edmonds et. al, 1993), is used for the top-down analysis. SGM can be used as global model with several regions (Sands et al, 1998) as well as national model for specific country

[1] Six IS92 scenarios (IS92 a-f) were developed for Intergovernmental Panel for Climate Change in 1992. The IS92a scenario is one of the five no-policy scenarios and is based on the moderate population and

analysis (Fisher van-dan et al, 1997; Hibiki and Sands, 1998). We use it as the national model for India. SGM analysis is calibrated for the year 1990. The analysis spans sixty years, from 1990 to 2050. The Indian economy is represented by nine producing sectors (including seven energy sectors), four final demand sectors and three factors of production. A sector consists of several sub-sectors, each using a different set of technologies and fuel grades. For instance, there are six sub-sectors in the electricity sector. Each sub-sector within a sector produces a homogenous good. There are twenty sub-sectors in total. Production relations are represented by constant elasticity of substitution (CES) functions. Technological change is assumed to be "Hicks Neutral" and is exogenously introduced as change in total factor productivity. If the efficiency of all inputs to a given production process is changing at the same rate, then technical change is said to be neutral. Technological progress also results from the selection of new technologies. Economic growth occurs through enhanced factor supply and improved productivity, i.e. technological progress.

Investment in a sector (or sub-sector) in each period depends on the savings in the economy and expected profit in the sector. Investment allocation among subsectors is determined by a logit function; investment shares sum to 1. Subsectors with the highest profit rate receive the largest share of that sector's investment. Capital is assumed to be "putty-clay" type, that is, once the investment occurs the technology cannot be changed. Capital is modelled using a vintage approach and investments operate for life or till they cover operating expenses. Data required are input-output table for 1990, past capital investment pattern, energy flows in the economy at sub-sector and technology level, reserves of resources, land supply, and current emissions. Input-Output Table provided by Central Statistical Organization, consumption and value added data was taken from National Accounts Statistics, capital stock data from National Accounts Statistics with consolidation from data of Annual Survey of Industries, and energy data from Center for Monitoring Indian Economy and TERI Energy Data Directory Yearbook were employed. Labour supply is estimated using a separate demographic model. Both renewable and natural resources are explicitly treated. Only commercial energy sources are considered. Traditional

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economic growth assumptions and produce mid-level energy consumption and GHG emissions.

biomass fuels are ignored since national accounts and official input-output data do not include their value.

The energy balances and trajectories for the reference scenario of SGM are reconciled with the MARKAL reference case. Carbon tax is modelled as an additive tax per ton of carbon content of fossil fuels. Revenue from carbon tax is recycled to households by adding lump sum to income. In SGM, the influence of carbon tax pervades to alter the macro-economy. The SGM endogenously generates the macroeconomic information such as energy prices and loss of sectoral GDP and consumption. This information, besides its direct utility, is also necessary to modify the inputs for equivalent scenarios in bottom-up models.

4. Future trends and mitigation costs

4.1 Long-term trends from ERB: Baseline scenario

The primary energy demand in India rises at a rate of 2.6 percent per year in the model period. Total primary energy demand rises to 123 EJ in 2095 (Figure 2a). Between 1990 and 2050, the annual energy consumption grows at 3 percent, reaching 48.3 EJ in 2050. Coal remains the dominant fuel and accounts for over a half of energy consumption throughout the model period. Coal consumption rises from 4.76 EJ in 1990 to 25 EJ in 2050 and 64 EJ in 2095 (Figure 2c). Oil consumption, which stood at 2.3 EJ in 1990, increases to 9.84 EJ in 2035 and subsequently falls to 5 EJ in 2095 (Figure 2b). After 2035, the rising prices of depleting global fossil oil and gas resources lead to higher penetration of biomass, nuclear and solar energy. Solar energy penetration jumps 26 EJ in 2095 from a meager 0.9 EJ in 2035. Similarly, penetration of nuclear energy increases from 2 EJ in 2035 to 15.4 EJ in 2095. In the baseline scenario, coal remains the most dominant fuel throughout the next century with a 57 percent share in 2095, followed by solar with 21 percent and nuclear with 12.5 percent.

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Insert Figure 2 around here

Figure 2: Energy and emission results for India from ERB Model

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The baseline trends suggest an increasing gap between energy demand and domestic supply. India therefore continues to be net energy importer during the next century. Most energy imports are for oil. The imports of oil quadruple by 2020 and after that the value of oil imports shoots up due to steep increase in oil prices. Share of energy import in GNP rises to 13 percent in 2035, thereafter falling due to increased substitution of imported oil.

ERB model is a market equilibrium model with trade taking place in three markets – oil, gas and coal. The global supply and demand in these markets yield the equilibrium price trajectories. These trajectories of prices reflect the scarcity of the respective fuel reserves. With oil reserves drying up, the equilibrium price of oil rises by nearly four times from 1990 to 2095 at 1990 prices, implying extraction from higher cost marginal oil fields in later periods. Similarly a four-fold increase in gas price is observed with price of $2.4 per GJ in 1990 rising to $9.8 in 2095. Relatively, the rise in price of coal is lower, from $1.4 in 1990 to $3.2 in 2095.

Carbon emissions are a function of economic activity and population in a region, through the energy end use demand. The carbon emissions for India for the base case are shown in Figure 2d. The global carbon dioxide emissions rise from 6.1 billion tons carbon (BtC) in 1990 to 23.4 BtC in 2095. India contributes 3 percent to global emissions in 1990. With rising economic growth, under the baseline scenario, this share will rise to 10 percent towards the end of next century. The analysis thus points to a need for mitigation of these rising emissions.

4.2 Long-term trends from ERB: Mitigation scenarios

We analyze the mitigation using carbon tax as the primary mitigation policy instrument. Carbon tax scenarios consider uniform tax ranging from $10 to $150 per ton of carbon beginning from 2005. The reference case assumes 'no carbon tax' for the entire model horizon. The reduction in carbon emissions over the reference case (Figure 2d) due to imposition of tax for India, follow a pattern similar to that for reduction in global emissions2. The carbon tax achieves mitigation primarily by fuel switching, whereby coal is initially substituted by oil and gas and later by carbon free renewable and nuclear energy.

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[2] The average reduction in global carbon emissions is 5 % over the reference case for $10 tax, 12 % in $25 tax case, 24 % in $50 tax case, 40 % under a $100 tax, and 49 % in the $150 tax case (Rana et. al, 2000).

Under a $100 tax, the emissions grow annually at a 1.9 percent rate, compared to 2.5 percent in the reference case. In the short run, a tax of $150 causes the emission reduction of 38 percent in 2005 and 33 percent in 2035. For lower tax levels, emissions reductions are delayed. Besides fuel switching, some emissions mitigation also occur due to the decline in energy consumption. The primary energy consumption falls by 2 percent in $10 tax case and by 20 percent in case of $150 tax (Figure 2a).

Coal remains dominant fuel in India even at $50/tC tax, though its share declines to 39 percent in the year 2095 as compared to 52 per cent under reference case. It is only under a more severe tax of $150 that the share of coal drops to below 30 percent in the terminal period. The share of oil falls to 4 percent in 2095 under all the cases. In 2035, the share of oil, which is 26 percent for the reference case, rises to 31 percent for a $50 tax case. In 2095, the share of solar energy increases from 21 percent for the reference case to 35 percent for $150 tax case, where as the share of nuclear energy rises from 12.5 for reference case to 20 percent under $150 tax case. A most prominent economic concern of the emerging fuel mix scenario is a very high commitment of foreign exchange for energy imports and high up-front investments needed for nuclear and solar plants.

4.3 Future trends from SGM: Baseline scenario

The trajectories of primary energy consumption in SGM are similar to those of ERB and MARKAL because of the soft linkages between these models. The SGM baseline scenario presumes no climate change intervention. In this scenario, the overall growth of total primary (commercial) energy consumption is 3.5 percent per annum between 1990 and 2050. Coal remains the most consumed fuel throughout the model horizon. Gas consumption grows at a rate higher than that for the total energy, thus indicating the increased preference for gas. The discussion on SGM here is limited to the results for which SGM is eminently suited, namely the endogenous determination of GNP, investments, price of fuels (other than oil and gas which are exogenous inputs for the national model), and energy imports.

For the baseline case, real GNP is projected to grow rapidly in the initial years, at an annual rate of 6 percent between 2000 and 2005. Growth rates decline thereafter and stabilize at around 3.6 percent per annum towards the end of model horizon. Average

growth rate is 4.6 percent per annum over the period 1990 to 2050 increasing from $305 billion in 1990 to $4380 billion by 2050 at constant prices (Figure 3a). Among the components of GNP, government spending increases at 4.9 percent per year, total investment at 4.6 percent and consumption spending at 4.4 percent. The share of government spending in total GNP increases from 11 to 14 percent. The share of consumption spending decreases from around 72 to 64 percent while share of investment rises marginally from 20 to 22 percent. Net exports remain negative during the large part of the model horizon and become positive in the second half of the model horizon. Per capita real GNP increases at an average rate of 3.2 percent per year over the sixty-year period.

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Figure 3: GNP Trajectory for SGM Base Case and Losses due to Mitigation

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Investment distribution among sectors is a function of relative expected profitability of the sectors, which in turn depends upon the technology parameters. The large ETE (Everything Else, i.e. rest of the economy) sector takes up 70 to 78 percent of the investment in various periods. Of the remaining, agriculture gets 10 to 15 percent and the rest is shared by the energy sector. Investment projections for energy sectors for selective years are shown in Table 1. Share of electricity sector is highest, followed by refinery oil and coal sectors in all periods. No new investment is undertaken in the crude oil and gas sector after 2010 because of the exhaustion of reserves. Substantial investments are however projected for electricity, oil refining and gas transport sectors.

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Insert Table 1 around here

Table 1: Investment requirement in energy sectors (Billion US$, 1990 prices)

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Under baseline scenario, coal remains relatively cheaper than gas throughout the model period (Figure 4). Hence very little substitution of coal by gas is observed. The rising electricity demand pushes the electricity price higher than all other sources of energy.

Another reason for high electricity prices is more demand for costlier gas-based electricity in later years of the model. Dependence on oil and gas imports increase over the next half-century.

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Figure 4: Energy Prices (index 1990 =1) in SGM

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Carbon dioxide emissions from the energy system increase by seven times and reach 1225 MtC over the 60 years. Coal and oil contribute 67 and 27 percent to carbon emissions in 1990. These shares change to 57 percent for coal and 39 percent for oil in 2030. Share of emissions from gas remains nearly same in this period. The rising carbon emissions prompts the mitigation analysis, discussed next.

4.4 Future trends from SGM: Mitigation scenarios

The three carbon mitigation scenarios assume carbon tax levels of $25, $50 and $100 per ton of carbon beginning from year 2000. A direct consequence of carbon tax is the decline in energy consumption. Under $25, $50 and $100 tax cases, the growth rate of energy consumption decline to 3.2, 3 and 2.8 percent per annum over the period 1990 to 2050 respectively as compared to 3.5 percent for the base case. Primary energy consumption declines, as compared to base case, by 18, 28 and 37 percent under $25, $50 and $100 tax cases respectively for the year 2050. The decline is due to two reasons - first the slow down in economy, which result in the decline in the growth of the GNP and second the substitution of less efficient coal technologies by more efficient technologies.

The impact of carbon taxes on the real GNP is severe for high tax rates (Figure 3b). At $25 tax, real GNP declines initially by 1 percent in 2010, but later stabilizes to 0.45 percent. In case of $50 tax, the GNP decline by 1.5 percent initially and stabilizes at 0.75 percent decline. The GNP loss is very high for the $100 tax case, where a 3.5 percent decline occurs in 2005. The GNP loss then stabilizes to 1.3 percent level. The high GNP loss in early periods occurs due to the investments for quick capital stock turnover and partly due to the stranded assets in case of high tax. While the percent GDP loss stabilizes, the loss in

real dollar terms continues to rise following the rising GNP (Figure 3c). For the $100 tax case, the annual GDP loss remains around $30 billion during the period 2005 to 2020 and later sets on a rising trajectory and reaches $60 billion in 2050. This amply indicates very high stakes for India in the global carbon mitigation negotiations.

Among the components of GNP, private consumption spending declines to stabilize at 1.4 percent, 2.4 percent and 4 percent in $25 tax, $50 tax and $100 tax case respectively (Figure 3d). The consumption losses are very high in the initial periods. This level of reduction in consumption spending suggests considerable deterioration of welfare of Indian households. The total investment spending also decline and stabilizes at a 1.6, 2.5 and 4.5 percent below the base case for the low to high tax cases respectively.

In the year 2050, the carbon emissions decline by 23 percent, 37 percent and 48 percent in $25, $50 and $100 tax cases respectively relative to the base case (Figure 5). The share of coal in emissions reduces, from 56 percent of total emissions in the base case in 2030, to 44 percent in $25 tax case, 40 percent in $50 tax case and 37 percent in $100 tax case. These results suggest the effectiveness of the carbon tax as an instrument for mitigation. However, the impressive relative decline in emissions for tax cases compared to the base case seems inadequate as the absolute emissions maintain a high trajectory even under the high tax case and rise to three times the 1990 level in 2050 (Figure 5). The global tax levels or alternatively permit prices therefore shall have to be very high to reverse the rising emissions trend from India in the long run.

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Insert Figure 5 around here

Figure 5: Mitigation Scenarios in SGM - Carbon Emissions

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Phased-in tax scenarios were also developed but they are not reported here. The main results from phased-in tax scenarios (Rana, 1999) are that the same amount of reduction is achieved by moderate tax levels as by severe taxes with the advantage of less damage to real GNP and less constraints on energy consumption.

5. Conclusions

In this paper, we have presented the application of macroeconomic models for India to study policies to combat the problem of emissions from energy sector within an integrated modelling framework that includes bottom-up and top-down energy and economy models. We use two models - a global and a national level CGE models - to comprehend international dynamics as well as domestic dynamics of the markets.

The long-term trends of the GHG emissions, economic growth and changes in energy sector are tracked in the baseline scenarios and through introduction of mitigation policies embodied within carbon tax scenarios. The main conclusion drawn from the analysis is that future CO_2 emissions from India are likely to grow rapidly and under a non-intervention scenario its share would be around 10 percent in the global CO_2 emissions by end of the 21st century. This is alarming but at the same time it is vital to bear in mind that India's per capita emissions will still be low compared to those of developed countries for several decades to come. The other important result of this analysis is that under a mitigation regime India shall have significant real GNP loss. Under a severe tax regime, the real GNP loss for the economy initially would be as high as 3.5 percent that will gradually level off to lower levels. In monetary terms this would mean bearing annual costs of $60 billion in 2050.

In a nutshell, in mitigation of GHG emissions, the costs that India would have to bear are very high if a severe tax regime or its equivalent is enforced globally. A meaningful participation by India into the mitigation regime shall require developing a burden-sharing regime that can minimize the welfare losses. To begin with these mechanisms could be of the form of CDM, under which the industry can recover the cost of mitigation and also benefit by technology transfer, or direct technology strategy interventions such as promotion of cleaner fuels and efficient technologies. India's participation in GHG mitigation shall enhance the cost-effectiveness of the global mitigation regime, however global fairness (Shukla, 1999) and India's willingness would be best served only if appropriate burden sharing rules are developed.

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Figure 1: Integrated Modelling Framework

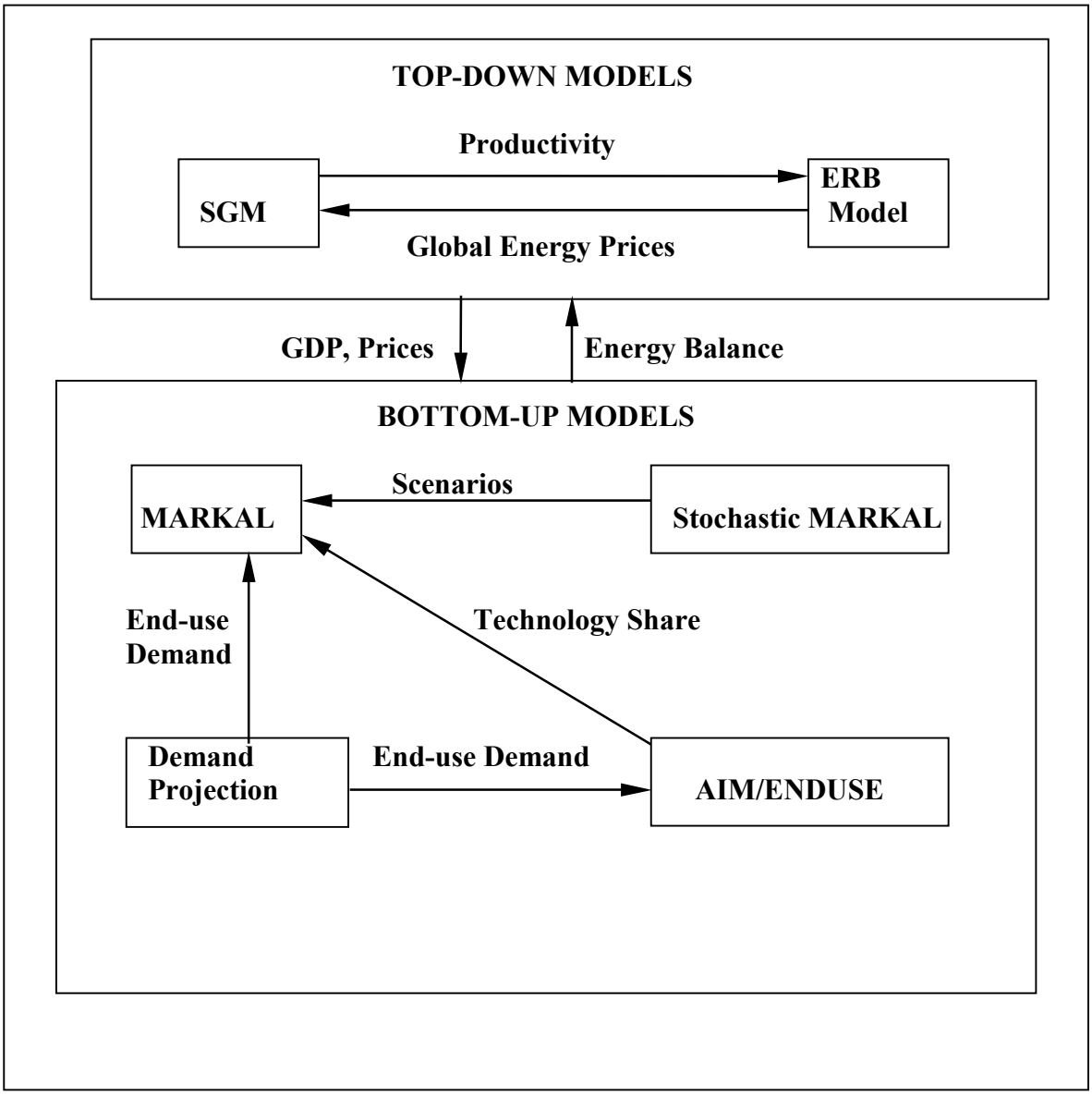

Figure 2: Energy and emission results for India from ERB Model

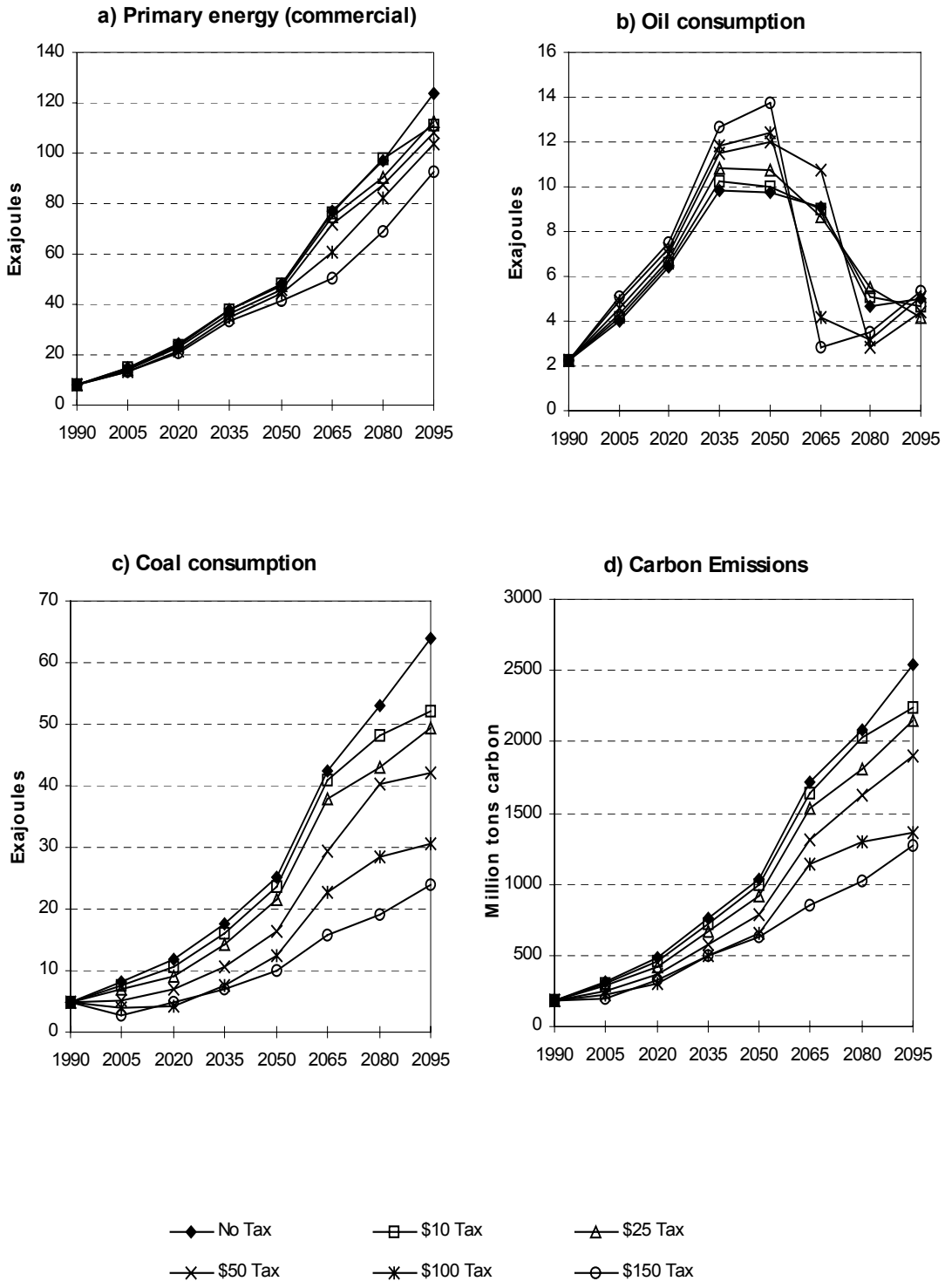

Figure 3: GNP Trajectory for SGM Base Case and Losses due to Mitigation

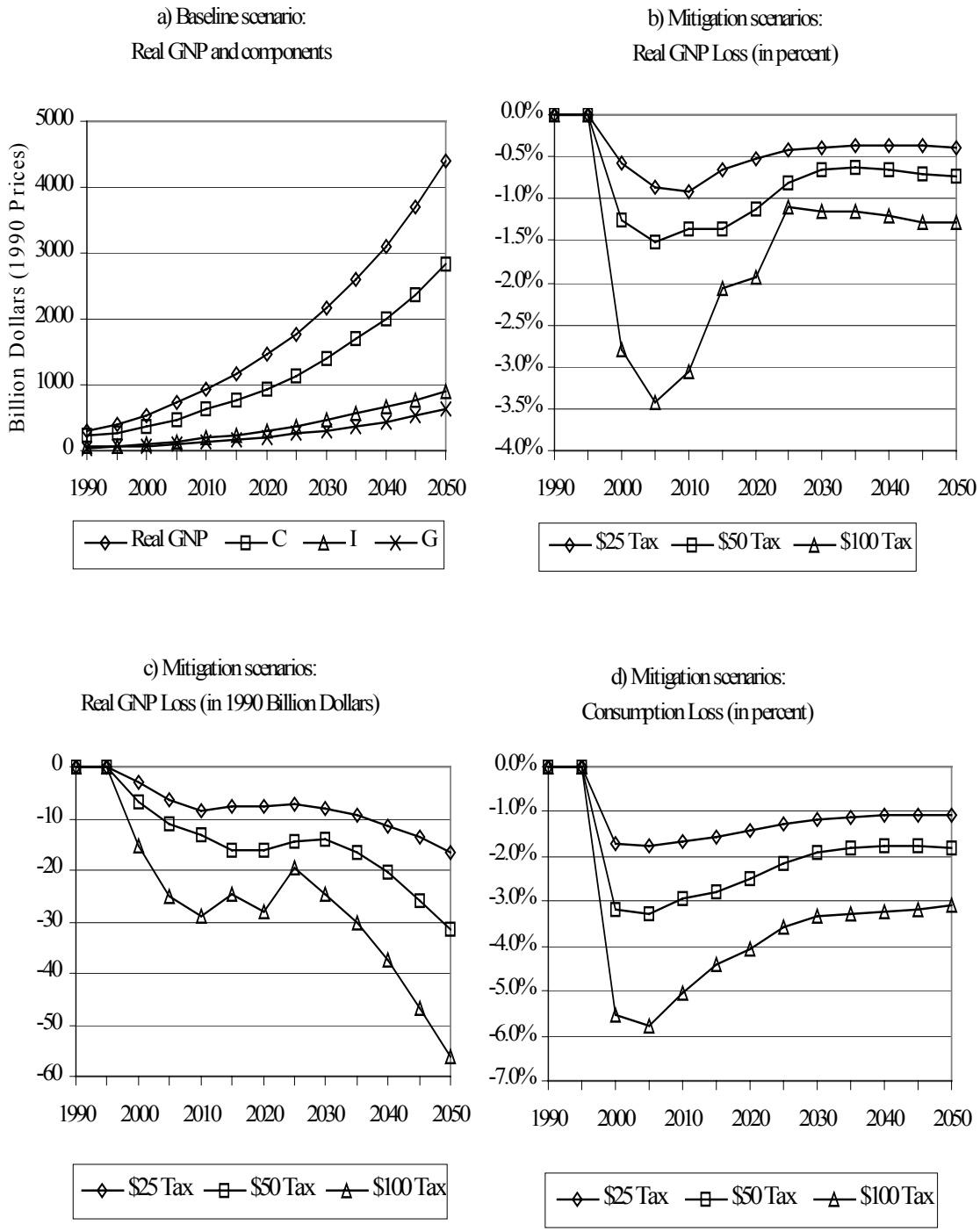

Figure 4: Energy Prices (index 1990 =1) in SGM

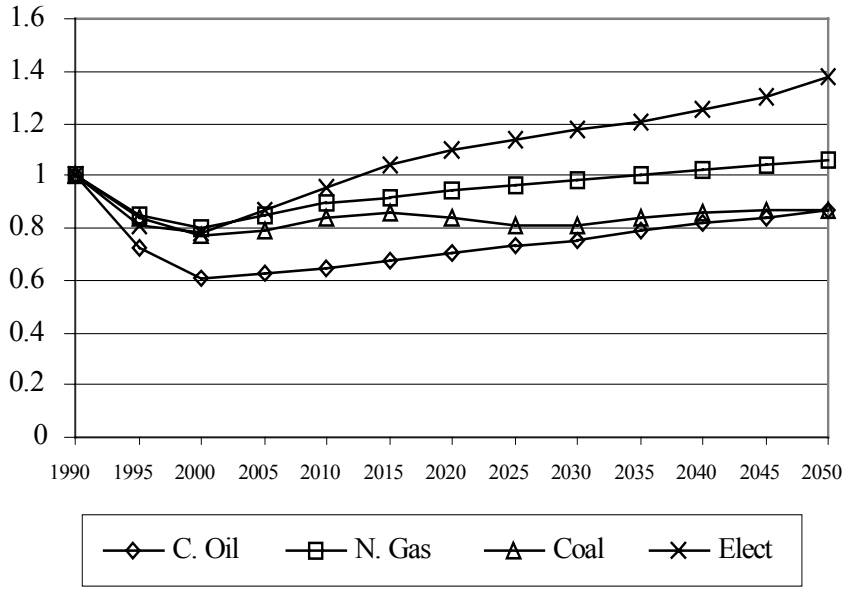

Figure 5: Mitigation Scenarios in SGM - Carbon Emissions

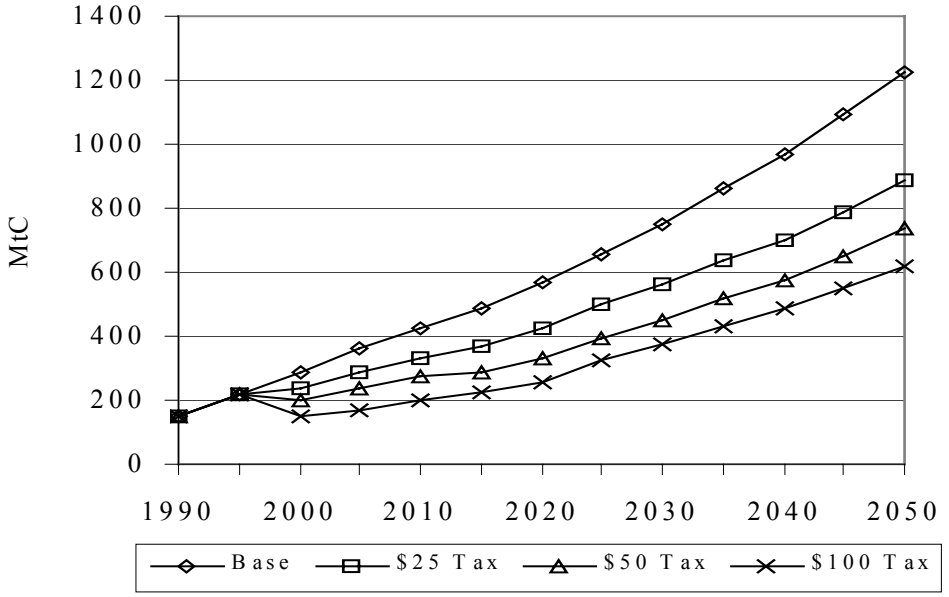

Table 1: Investment requirement in energy sectors (Billion US$, 1990 prices)

Sectors	1990	2005	2020	2035	2050
C. Oil and Gas	1.69	0.91	0	0	0
Coal	1.29	1.25	2.56	3.12	4.79
Electricity	7.63	4.21	7.92	18.30	26.79
Oil Refinery	0.57	0.80	2.87	3.12	7.03
Gas Transport	0.18	0.44	0.58	0.78	1.30