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Macroeconomic Models for Long-term Energy and Emissions in India

Ashish Rana
National Institute for Environmental Studies, Japan

P. R. Shukla
Indian Institute of Management, Ahmedabad, India

Address for Correspondence:
Ashish Rana
STA Fellow
Social and Environmental Systems Division
National Institute for Environmental Studies
16-2 Onogawa, Tsukuba 305-0053
Ibaraki. JAPAN
Email: ashish.rana@nies.go.jp

Abstract

The complex dynamics between energy, emissions and economy have increasingly attracted modelling studies over the past decade. In this paper, we briefly describe two top-down models that were adapted for India and show some key results from them. Working with more than one model gives us a better understanding of the differences in model structures and puts us in a good position for appreciating the differences in results from these models due to this fact. We project the long-term energy and emission trajectories from the global model (ERB) and the national model (SGM) and come to a conclusion that India's energy system will remain largely dependent on coal in BAU case and is open to change under a regime of carbon taxes towards less carbon-emitting fuels like gas and renewables. Carbon tax reduces carbon dioxide emissions but there is also a loss of GDP.

Keywords: Models, Energy, Emissions, Top-down, Macroeconomic

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1 INTRODUCTION

It is a well-known fact that the most significant negative consequences of increased fossil fuel use, from a macroeconomic perspective, are: (a) stress on scarce energy resources and, (b) emission of harmful gases like carbon dioxide, through burning of fossil fuels. Higher growth paths, that the developing countries would want to chart, mean more use of fossil fuels and consequently more emissions. While India and many other developing countries need to worry about the scarce energy resources, increased pressure for participation in restricting global emission levels has raised several issues in the recent past (e.g, see [24]). Also in this context, policy makers face a situation where formulating policies for high growth could also lead to a rising emissions trajectory. On the other hand, adopting policies, such as carbon tax, aimed at controlling carbon emissions could change the fuel consumption patterns of the economy and also have an overall negative impact on the economy.

The complex dynamics between energy, emissions and economy have increasingly attracted modelling studies over the past decade. A variety of models that deal with emissions at global and/or regional and national level, such as many integrated assessment models (IAMs), various bottom-up models and a number of top-down models now exist. For reviews of IAMs see Dowlatabadi (1995)[3], Rotmans et al. (1995)[21], IPCC (1996)[12], Weyant (1997)[25], and Rana and Morita (2000)[19]. Market Allocation (MARKAL) model [7] and Asia-Pacific Integrated Model (AIM) [17], are examples of bottom-up models. Second Generation Model [9], GLOBAL 2100 [16], Dynamic General Equilibrium Model [13], are examples of top-down models.

Compared to bottom-up models, top-down models have higher sectoral aggregation, but better characterisation of impacts on economic growth, feedback of prices, and trade [11]. These models represent the macroeconomic interlinkages between the aggregate production sectors of an economy, consumers, and the government. Most top-down models base on the general equilibrium framework. A typical top-down model helps the policy maker in assessing the macroeconomic impacts (overall change in

GDP, consumption, investments, imports and foreign exchange) of particular market instruments like carbon tax. Major advantage of top-down models in such analysis stems from the fact that, unlike bottom-up models, they have endogenous representation of most of the macroeconomic parameters like prices and demands. Clearly, if interdependence within the economy is pervasive and strong, as it is likely to be in a moderately complex economy, this approach becomes essential. However, the limitation is simple specification of these models due to sectoral aggregation, and data demands.

In this paper, we briefly describe two top-down models that were adapted for analysis of long-term energy and emission trajectories in India.

2 TWO TOP-DOWN MODELS ADAPTED FOR INDIA

2.1 ERB Model

2.1.1 Description and Key Assumptions

ERB ([6]; [20]; [5]) is a behavioural, long-term model of global energy and greenhouse gas emissions. This model serves as the economic module in the integrated MiniCAM model developed at Pacific-Northwest National Laboratory in USA. The world is divided in the model in nine regions (Table 1).

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The model has four components[1]: 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. Production for resource constrained exhaustible energy such as oil, gas and coal is determined by extrapolation model.

$$f(t) = \frac{e^{a+bt}}{1+e^{a+bt}} \quad \text{... 1}$$

where,

f(t) is the cumulative fraction of the total resource base that has been exploited
t denotes time elapsed from the initial period, and
a and *b* are parameters defining the shape of the curve.

Total amount of resource $Q_s(t)$ by time *t* is then given by.

$$Q_s(t) = f(t) \cdot \left(1 - f(t)\right) \cdot bR \quad \text{... 2}$$

where,

R is the initial resource base.

The resource constrained renewable energy, on the other hand, is modelled as being phased in over time as determined by a logistic curve.

$$Q_s(t) = \frac{e^{a+bt}}{1+e^{a+bt}} R \quad \text{... 3}$$

where,

$Q_s(t)$ is the production in period *t*,
R is the total resource, and
a and *b* are parameters defining the shape of the curve.

The demand module computes primary fuel requirements. Demand for each fuel is derived from population, labour productivity, energy end-use intensity, energy prices, energy taxes, subsidies and tariffs. Energy end-use intensity is a time dependent index of energy productivity.

For all regions, energy demand is disaggregated into residential/commercial, industrial and transport sectors. Demand for energy services, ES_k, in each end-use sector is determined by the cost of providing these services, and by income and population.

$$ES_k = P_k^{r_{pk}} \cdot X^{r_{yk}} \cdot Y \quad \text{... 4}$$

where,

k indexes to end-use sector,
X is a per capita GNP index,
r_{pk} is energy service price elasticity,
P_k is the energy service price for the end-use sector *k*
r_{yk} is income elasticity.
and *Y* is the adjusted GNP given by

$$Y = GNP \cdot PS^{r_y} \quad \text{... 5}$$

where,

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[1] Description given here is adapted from [6].

r_y is the percentage change in the GNP resulting from a 1% increase in the cost of providing energy services, and
PS is the overall energy service price, calculated in a detailed fashion in a separate module.

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. 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 such that India is treated as a separate region whereas earlier India was a part of South-East Asia region. This is important because we want to study the impact of the global process of climate change mitigation specifically on India. In this process, care has been taken to keep the global balances as specified in the original ERB model. The reference case assumptions follow the IS92a scenario paths [14] for rest of the regions. For the policy analysis, scenarios for mitigation are created with a range of carbon tax. Global specification of the model ensures the consistency of results for India with the rest of the world.

The reference scenario depicts dynamics-as-usual for population and labour productivity for India while the growth figures for other regions follow the assumptions of IS92a scenario of IPCC. The world GDP is assumed to grow at 2.6 percent per annum in the 60-year period from 1990 to 2050 while GDP for India shall grow at a rate of 5 percent per annum during the same period. The GDP growth follows a declining path over time (Table 2) and the GDP growth for India over the model horizon is 4.2 percent per annum.

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The population projections are taken from studies done at World Bank [1]. India's population is assumed to grow at 1.1 percent per annum between 1990 and 2050. Labour productivity is assumed to grow at 4 percent per annum during the same period. There is an autonomous energy efficiency improvement of 2 per cent during the model period.

2.2 SECOND GENERATION MODEL

2.2.1 Model Description[2] and Key Assumptions

The Second Generation Model (SGM), a computable general equilibrium (CGE) model [4], is used for the top-down analysis. It can be used in global mode [22] as well as national mode ([8]; [10]). We use it in national mode. SGM is calibrated for the year 1990. The analysis spans sixty years, from 1990 to 2050. The economy is represented by 22 producing sectors (including six energy sectors), four final demand sectors and three factors of production. A sector can consist 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. Production relations are represented by constant elasticity of substitution (CES) functions.

$$X_s = \alpha_o \left(\sum_{i=1}^{N} \alpha_i X_i^{\rho} \right)^{(1/\rho)} \qquad \ldots 6$$

where,
X_s = gross output of the process,
X_i = the use of input factor i,
α_o = scale coefficient,
α_i = individual factor coefficients, and
ρ = elasticity of substitution parameter.

Technological change is assumed to be "Hicks Neutral" and is exogenously introduced as change in total factor productivity. Technological progress also results from the selection of new technologies. Economic growth occurs through enhanced factor supply and improved productivity, i.e. technological progress.

Aggregate sector investment levels are determined by using an accelerator from the previous period's total investment. Specifically,

$$I_{t,s} = \alpha_0 I_{t-1,s} (baserate)^{\alpha_1} f(\exp(\pi_{t,s}))^{\alpha_2} \qquad \ldots 7$$

where
$I_{t,s}$ = annual level of investment in sector s at time t
$I_{t-1,s}$ = annual level of investment in sector s at time t-1
baserate = underlying growth in the economy affecting investment
$f(\exp(\pi_{t,s}))$ = a function of expected profit rate
α_0 = scale coefficient
α_1, α_2 = sensitivity parameters

[2] Description given here is adapted from Edmonds et al, 1993[4]. Key equations of the model are given here. For details see [4]. In a previous paper [23], SGM with eight producing sector was applied. The results presented in this paper employ an extended version of the model with 22 producing sectors.

Base rate is given by growth in potential employment and growth in lagged productivity, while $f(\exp(\pi_{t+1}))$ is given by present value of expected profits over the lifetime of capital investment.

Investment allocation among subsectors is determined by a logit function. 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 1989-90, past capital investment pattern, energy flows in the economy at sub-sector and technology level, reserves of resources, land supply, and current emissions. Labour supply is governed by population given exogenously. Both renewable and natural resources are explicitly treated. Only commercial energy sources are considered. Traditional biomass fuels are ignored since national accounts and official input-output data do not include their value.

Consumption of any final product can then be computed using price and income elasticities and an income expenditure normalization via,

$$Xd_{i,hh} = \alpha_{i,hh} P_i^{\beta_{i,hh}} Y_c^{\gamma_{i,hh}} \left(\frac{1}{\lambda}\right) \qquad \ldots 8$$

where,

$Xd_{i,hh}$	=	demand for good i by the household sector,
$\alpha_{i,hh}$	=	the household demand intensity factor for good i,
P_i	=	Price of good i
$\beta_{i,hh}$	=	the price elasticity of demand by households for good i,
Y_c	=	income for consumption
$\gamma_{i,hh}$	=	the income elasticity of demand by households for good i, and

$$\lambda = \sum_{i=1}^{NS} \alpha_{i,hh} P_i^{\beta_{i,hh}+1} Y_c^{\gamma_{i,hh}-1} \qquad \ldots 9$$

Each good is assumed to have an income and a price elasticity of demand.

For arriving at the equilibrium solution, the model calculates the price vector that reduces the excess demand in sectors to zero, following the Walras' Law. For each commodity, an excess demand can be calculated by

$$e_i = \sum_{s=1}^{Ns} \sum_{ss=1}^{Nss_{i,n}} \sum_{tech=1}^{Ntech_{i,ss,n}} (Xd_{i,s,ss,tech} - Xs_{i,s,ss,tech}) \qquad \ldots 10$$

According to Walras' law,

$$\sum_{i=1}^{N} e_i P_i = 0 \qquad \ldots 11$$

The energy balances and trajectories for the reference scenario of SGM are reconciled with the MARKAL reference case [15]. 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 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.

Assumptions

a) Demographic assumptions

One of the main drivers of economic growth and energy consumption is population growth, given exogenously to the model. We use the projections of Government of India [9]. This technical report gives annual projections till 2016. For periods after 2015, projections are extrapolated taking the linear trend. Total population grows at 1.17 percent per annum from 1990 to 2030. The growth rate of population decreases over the model horizon.

b) Total factor productivity improvement

Each CES production function has a multiplicative parameter, which can be increased over time to allow for Hicks-neutral, or disembodied, technical change. This type of technical change is neutral because it is not tied to, or embodied in, any input. This parameter is also an index of total factor productivity. If this increases by 10 percent, then 10 percent more output can be produced using the same quantities of inputs.

A rate of 2 percent per annum is used for the large ETE sector, which comprises mainly the tertiary sectors of the economy. This number is worked out from Dholakia's estimates [2]. TFP growth rates for energy transformation sectors, that is, electricity generation, refinery oil and gas transmission and distribution, are set to 0 percent to maintain energy balances between inputs and outputs. These sectors use large quantities of energy as inputs, and much of this energy is passed through as output instead of being consumed. For example, the amount of energy leaving the gas distribution sector is nearly equal to the energy coming in, with almost no opportunity for improvement in the ratio of energy output to energy input.

c) New technologies

Technical change can also occur through the incorporation of new technologies in the system. New technologies can become viable alternatives when the relative prices of other fuels increase due to taxes or resource constraints. In this model we use solar electricity to depict alternative source of electricity generation to thermal and hydro electricity. It is introduced in the model from the starting period but it starts penetrating the market only after third period because of relatively high initial cost.

d) Energy sources

Among various energy sources, crude oil, natural gas and coal are depletable resources and assumption about the total availability is important in shaping the future trajectories of their supply and demand. Energy resources are differentiated from reserves. Reserves are considered as the proven sources that are profitable to produce at current prices. Energy resources are then the ultimately recoverable energy sources yet to be exploited. In the model, when an investment is made in a depletable energy source, the invested amount is taken from the resource base and placed into reserves. Energy that is produced is then taken from the reserves. The assumptions of resources for purpose of model are shown in Table 3.

An important assumption about resources is that they are assumed not to grow over time, regardless of policy.

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2.3 Comparison of the two models

Naturally, being models for differentiated purposes there are bound to be differences among them. Working with more than one model gives us a better understanding of the differences in model structures and puts us in a good position for appreciating the differences in results from these models due to this fact. The salient points on which these models differ are presented in the Table 4.

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2.4 Mitigation scenarios

The mitigation scenarios in both the models were built with varying assumption of carbon tax. Carbon tax can be applied directly or it can be implicit in any other form of mitigation policy such as the permit price in emissions permit trading. Thus carbon tax as a policy variable is used independent of what mitigation regime comes into effect, liberating us from debate on pros and cons of different mitigation instruments. In carbon tax scenarios in ERB, a uniform carbon tax of $10, $25, $50, $100 and $150 per ton of carbon released is imposed in each region from year 2005 and the resultant energy, economy and emissions trajectories are compared with the reference case. The reference case is the 'No Tax' case. As compared to ERB, in SGM cases of very low tax of $10 and very high tax of $150 are not studied. The reason for this is that a very low tax of the order of $10 throughout the model period is not perceived to result in significant shifts in energy use pattern or in economic growth and a very high tax, above $100, may result in such structural shifts that may be unpractical and unsustainable, within the domestic dynamics of India's economy. In global model, such low and high taxes do have impacts because tax is imposed on all regions thus the effects are distributed accordingly.

3 RESULTS

3.1 ERB Results

Using ERB model we obtain results for all the regions. These are provided in Rana (1999)[18] in detail. Here we provide some key results pertaining to India keeping in mind that these are in global context.

3.1.1 Reference scenario

India's primary energy demand rises from 8.3 EJ in 1990 to 123 EJ in 2095 at a rate of 2.6 percent per year while the GDP growth rate during the same period is 4.2 per cent per year (Table 5). Between 1990 and 2050, the growth in energy consumption is 3 percent per annum reaching 48.3 EJ in 2050 while the GDP grows at 5 percent during this period as noted earlier. Coal remains the dominant fuel in the Indian energy scene accounting for at least half of the total consumption throughout the model period. In the terminal year, coal still remains dominant fuel comprising 57 percent followed by solar with 21 percent and nuclear with 12.5 percent of the total consumption. After 2035, because of depleting oil and gas

resources, consumption of bio energy, nuclear and solar picks up. Solar rises at 5.7 percent per annum and nuclear increases at 3.4 percent per annum between 2035 and 2095. These growth rates exceed significantly than growth of other fuels.

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The supply of primary energy from domestic production grows at a rate lower than that of growth in energy demand. The increasing gap between energy demand and supply suggests growing dependence of India on energy imports during the next century. Oil remains the main component of total energy imports with 57 percent share. Oil imports increase at a rate of 2.8 percent per annum and the level of oil imports in 2095 is 17 times the level in 1990. Import requirements of gas and coal are also increasing over the same period at the rates of 1.6 and 2.7 percent per annum respectively. In 1990, at constant prices, oil imports are $17.4 billion. Oil imports quadruple by 2020 and after that the value of oil imports shoots up because of steep increase in oil prices. Share of energy import in GNP is in the range of 8 to 13 percent. It shows a rising trend till 2035 and then falls till the terminal year. The value of oil imports comprises 6 to 10 percent of GNP while coal and gas are 1 to 2 percent of GNP.

As seen in Figure 1, commercial energy intensity for India declines from 27 MJ/$ of GNP in 1990 to 5 MJ/$ of GNP in 2095. This means that as the economy develops, energy is used more efficiently. Fall in energy intensity combined with fall in carbon intensity of energy lead to a decline in carbon intensities of GNP for India over the model period.

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Insert Figure 1 around here

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3.1.2 Mitigation scenarios

Under different tax regimes, the emission mitigation in India over the reference case follows a similar pattern as global emission mitigation (Table 6). The emissions from India grow at 1.9 percent per annum under $100 tax as compared to 2.5 percent per year growth in the reference case. In the short run, a

tax of $150/tC causes the emission reduction of 38 percent in 2005 and 33 percent in 2035 over the reference case while the reduction achieved by any lower tax is more in 2035 than in 2020. Thus we can reason that a more severe tax results in faster readjustments in the fuel consumption patterns.

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Insert Table 6 around here

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Insert Figure 2 around here

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The total primary commercial energy consumption in India falls only 2 percent on an average in $10 tax case while the average fall is 20 percent in $150 tax case (Figure 2). In the short run till 2020, the maximum fall in consumption is of the order of 10 to 12 percent, which is not significant in absolute terms. The fuel composition of the energy consumption changes in favour of oil in the initial years primarily due to the price of coal becoming high, laden with tax, and making oil relatively cheaper to consume. However, as in the case of global mix of fuel consumption, the oil is consumed heavily till the supplies last. As the oil resources start depleting, while tax on carbon is still there, solar and nuclear take larger shares in the total energy consumption.

Coal remains dominant in the Indian energy scene even with a tax of $25/tC though its proportion decreases in the year 2095 as compared to reference case in the same year (Table 7). It is only under a more severe tax that the share of coal drops to under 30 percent of the total in the terminal period. In the medium-term, oil consumption gains a substantial share under a sever carbon tax regime but in the long run due to depletion of resources, its share declines. Another important observation in the fuel composition is the high penetration levels of solar and nuclear energy by end of next century. The composition of the fuel mix has implications for the requirements of foreign exchange for import of oil and investments needed for setting up nuclear and solar plants.

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There is no significant impact on the energy intensity under different tax scenarios but the carbon intensity of the GDP falls to 0.053 TgC/GDP in the terminal year of $150 tax case as compared to 0.11 TgC/GDP in the terminal year of reference case. A maximum fall of carbon intensity (0.02 TgC/GDP) is observed when the tax is raised from $50 to $100.

3.2 SGM Results

3.2.1 Reference Scenario results

Real GNP is projected to grow at an overall rate of 4.55 percent per annum over the sixty-year period (Table 8).

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The total primary energy consumption increases from 7.8 EJ in 1990 to 67 EJ in 2050 (Figure 3) at a rate of 3.6 percent per annum. Consumption of crude oil increases at a rate of 4 percent per annum while that of coal increases at a rate of 3 percent per annum. Oil consumption is projected to grow almost nine folds between 1990 and 2050. Growth in consumption of natural gas, 4.2 percent per annum, is a little higher than that of oil consumption. Solar electricity is projected to grow very rapidly after it is introduced in 2005.

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Insert Figure 3 around here

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Coal remains the highest consumed fuel and comprises 52 percent of the total primary energy consumption in the year 1990. It remains the fuel with highest share in consumption but its share declines continuously till 2050 to 42 percent. Over the model horizon, a shift is observed towards increased share of consumption of oil and natural gas. Natural gas consumption increases its share from 8 percent to 13 percent by 2050. Share of oil increases from 30 percent in 1990 to 40 percent in 2050. The 9 percent combined share of nuclear, solar and hydro sectors in 1990 reduces to 5 percent in 2050.

Electricity demand increases from 0.8 EJ to 5.3 EJ during the model period. Figure 4 shows electricity demand by sub-sectors. Electricity using coal remains the predominant component of the total electricity demand. The share of gas-based electricity increases from the initial share of 4 percent in year 1990 to around 16 percent share by year 2050. Gas-based electricity demand rises at a growth rate of 6 percent per annum over the 60 years. Solar electricity enters in 2005 with 0.001 EJ and increases to 0.79 EJ by 2050. Its share in total demand in 2050 is around 14 percent. Shares of hydro electricity and nuclear electricity are projected to decrease in favour of solar electricity.

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Insert Figure 4 around here

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Total carbon dioxide emissions are projected to increase from 147 TgC to 1255 TgC over the 60 years. Emissions from coal have the largest share of 68 percent in 1990. This corresponds to its largest share in energy consumption. Oil emissions constitute another 26 percent and balance is from gas. As the composition of fuels in the consumption mix changes, their shares in emissions also change. Emissions from coal fall to 55 percent of total emissions in 2050. Share of emissions oil use increases from 26 percent in 1990 to 36 percent in 2050 while that of gas increase from 6 percent in 1990 to around 9 percent in 2050.

3.2.2 Mitigation scenarios

The first impact of imposition of tax that we study is a fall in the growth rate of energy consumption. Under $25, $50 and $100 tax cases, the growth rate of energy consumption is 3.5, 3.4 and 3.3 percent per annum respectively as compared to growth rate of 3.7 percent per year in the base case. Total primary energy consumption reduces by 6, 10 and 16 percent on an average over the model horizon under $25, $50 and $100 tax cases respectively. Comparative results of tax scenarios with the base case for the year 2050 are shown in Table 9.

In all the tax cases, oil and coal consumption in 2050 is lesser than consumption in base case while gas, hydro, solar and nuclear electricity consumption is higher than in base case. This is because growth rates of oil and coal are lower in tax cases than their respective growth rates in the base case while those of others are higher than their respective growth rates. Since coal and oil emit more carbon dioxide

than gas, the chief reason for their growth rates falling is an increase in their relative prices due to imposition of the carbon tax.

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The pattern of change in distribution of fuel shares over the model horizon period under tax scenarios is similar to that in the base case. Share of coal consumption reduces while that of oil and gas increases over the forty-year period. To recall the base case results, share of coal consumption between 1990 and 2050 falls from 52 percent to 42 percent, share of oil increases from 30 percent to 40 percent and share of gas increases from 8 percent to 13 percent. From Table 11, we see that in the terminal year, under $25 tax, share of coal is 42 percent while that of oil is 40 percent and share of gas is 13 percent. In case of $50 tax, share of coal is 37.5 percent while that of oil consumption is 41.4 percent and gas is 14.7 percent. Similarly, in $100 tax case, share of oil is 42.6 percent while coal has only 30 percent and gas has 17.4 percent share. Thus we observe that at the higher tax levels, in the terminal year, share of oil and gas is higher and share of coal is lower. Hydro share, 1.4 percent in the terminal year in base case, increases marginally to 1.5 percent and 1.6 percent in $25 and $50 tax cases respectively in the corresponding year while in $100 tax case it is 1.8 percent and balance is composed of nuclear and solar electricity. Solar electricity is seen to increase its share rapidly under the higher tax cases. This type of shift is caused by the burden of carbon tax making the carbon intensive options relatively more costly and unattractive.

The impact on real GNP is more when higher tax rates are applied, as can be seen in Figure 5. At $25/tC tax, real GNP is reduced by 0.25 percent on an average while the average reduction is 0.5 and 0.97 percent in case of $50 and $100/tC tax.

Cumulative emissions in the tax cases as compared to the base case are lower by 10%, 16% and 26% respectively under $25, $50 and $100 tax. The comparative picture of carbon dioxide emissions in different tax scenarios is shown in Figure 6. We saw in the base case results that emissions from coal reduce over the model horizon. Under tax cases, this reduction is even more drastic. Emissions from coal which form 55 percent of the total emissions in the base case in 2050, form 51 percent in $25 tax case, 48 percent in $50 tax case and 44 percent in $100 tax case.

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Insert Figure 6 around here

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4 CONCLUSIONS

In this paper we describe two macroeconomic models and employ them to examine, from a macroeconomic standpoint, India's energy system in the global context of mitigating carbon dioxide emissions. We first put to use the global energy-emissions model, ERB, treating India as a separate region in the world and find out the position of India's energy needs through the global market equilibrium framework. Next, we calibrate for India the Second Generation Model for the year 1990. Employing two different models adds to the depth of the analysis. 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. The results from the two models need not be, and should not be expected to be, identical in the absolute sense since the scope of the model and behavioural relationships differ.

We observe following main results from the two models. The abundance of coal in India and relative scarcity of other energy resources govern the predominant use of coal, under "business-as-usual" or reference scenario. The share of energy related carbon emissions from India in the global emissions increases to around 10 percent by the close of twenty first century. This is sensitive to reference case economic growth assumptions. Emissions can be controlled through application of a suitable carbon tax or an equivalent tradable permit regime. A carbon tax (or permit price) of $25 per ton of carbon achieves reduction of 12 percent in the cumulative emissions globally and 10 percent for India. A higher tax will result in increasing gains in emissions reduction till $100, beyond which there are diminishing returns to reduction of emissions. The reduction in emissions is accompanied by a change in the energy mix in favour of natural gas. Gas has 4 percent higher share under $25 tax compared to reference scenario, while share of coal is reduced by 12 percent. Substitution of coal by oil is also observed under low tax. Thus, lower level of tax around $25 or its equivalent is also effective for mitigation and has desirable results of energy mix

changes. High tax levels result in substantial penetration of renewables, for example solar energy rises to 36 percent share by 2095 under $150 tax.

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Table 1: Regions in ERB

S. No.	Regions in ERB	Short Name (used in Fig 1)
1	USA	US
2	OECD West	OECD West
3	Japan, Australia and New Zealand	JANZ
4	Africa	AFR
5	Eastern Europe and Former Soviet Union	EE/FSU
6	Latin America	LA
7	Middle East	MIDEAST
8	China and Asia (Excluding India)	ACENP
9	India	India

Table 2: GDP Growth Assumptions for India in ERB Reference Scenario

Year	GDP Growth
1990-2005	6.0%
2005-2020	5.3%
2020-2035	4.7%
2035-2050	3.5%
1990-2050	**5.0%**
1990-2095	**4.2%**

Table 3: Energy Resources (in EJ)

Crude Oil	68
Natural Gas	40.5
Coal	3640

Table 4: Comparing features of ERB and SGM models

S.No.	Dimension	ERB Model	SGM
1	Scale	Global	National
2	Equilibrium	Partial Equilibrium (Only Energy markets)	General Equilibrium (Neo-classical framework)
3	Model period	1990 – 2095; 15-year time steps	1990 – 2050; 5-year time steps
4	Sector detail	Limited	Wide
5	Production	Logistic functions	CES Production functions
6	Interaction of Energy sectors with other sectors	Not detailed	Detailed
7	Final Demands	Simple functions for demand of energy services	Based on elaborate functions of price, income and price and income elasticities for all goods and services
8	Price feedback to GNP	Included	General equilibrium nature
9	Capital and investment	Not detailed	Accelerator model for new investment
10	International trade	Present for major fuels like coal, oil and gas	Net exports fixed at base year values for all sectors except for oil, for which net exports covers the deficit of demand

			and supply

Table 5: ERB Model results of Reference scenario for India

	1990	2005	2035	2050	2065	2095
Primary Commercial Energy Consumption (Exajoules)	8.33	14.65	37.91	48.3	76.68	123.62
Oil	2.28	4.04	9.84	9.73	9.07	4.96
Gas	0.49	1.07	4.5	5.19	7.6	8.42
Coal	4.76	8.17	17.53	25.13	42.54	63.93
Renewables (Solar + Biomass)	0	0.01	2.85	3.45	8.53	27.8
Hydro	0.75	0.83	1.17	1.41	1.91	3.1
Nuclear	0.05	0.53	2.03	3.36	7.04	15.4
GDP (billion dollars 1990 pr)	305	729	3167	5306	9252	23509
Carbon emissions (TgC)	180	314	754	1041	1711	2535

Table 6: Cumulative mitigation of emissions and energy conservation (1990-2095) over the reference case

	Global		India	
Tax Level	Carbon mitigation (%)	Energy conservation (%)	Carbon mitigation (%)	Energy conservation (%)
$10	5	2	4	2
$25	12	5	10	4
$50	24	10	19	7
$100	40	19	30	12
$150	49	26	35	20

Table 7: Composition of Primary Energy Consumption in India (percent of total) under tax cases

	2035			2095		
Sources	Reference	$25 Tax	$150 Tax	Reference	$25 Tax	$150 Tax
Coal	46.2	38.0	20.6	51.7	45.3	26.4
Oil	26.0	28.8	38.1	4.0	3.8	5.9
Gas	11.9	13.3	18.1	6.8	8.0	9.2
Bio	5.2	7.6	4.3	1.5	2.4	1.0
Hydro	3.1	3.1	3.5	2.5	2.8	3.4
Solar	2.3	2.9	5.5	21.0	25.7	36.2
Nuclear	5.4	6.2	9.8	12.5	15.0	20.1

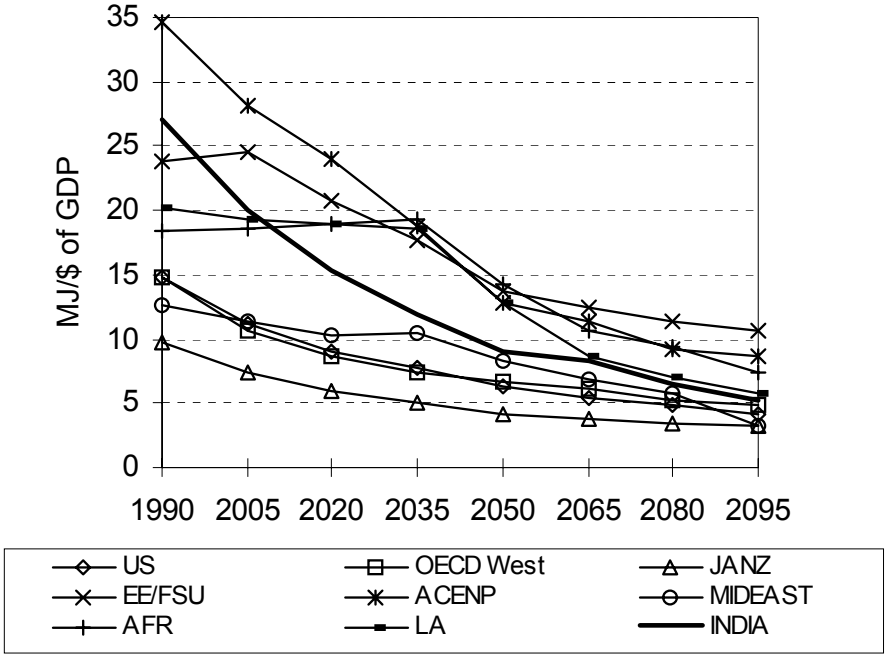
Table 8: Growth Rates (percent per annum)

Period	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040	2040-2050	**1990-2050**
GNP Growth	6.33	6.00	4.78	4.12	3.31	2.79	**4.55**

Table 9: SGM Tax cases: Primary commercial energy consumption (shares in percentage)

	1990	2050			
		Base case	$25 tax	$50 tax	$100 tax
Oil	30.2	40.1	41.4	42.2	42.6
Gas	8.3	13.0	14.7	15.9	17.4
Coal	52.4	41.8	37.5	34.3	29.8
Nuclear	0.7	0.1	0.1	0.1	0.2
Hydro	8.4	1.4	1.5	1.6	1.8
Solar	0.0	3.5	4.7	5.8	8.2
Total (in EJ)	7.8	67.4	62.4	58.9	54.5

Figure 1: ERB Reference Scenario: Energy Intensity in Regions



Note: For Legend details, see Table 1.

Figure 2: ERB Mitigation Scenarios: Primary Energy Consumption in India

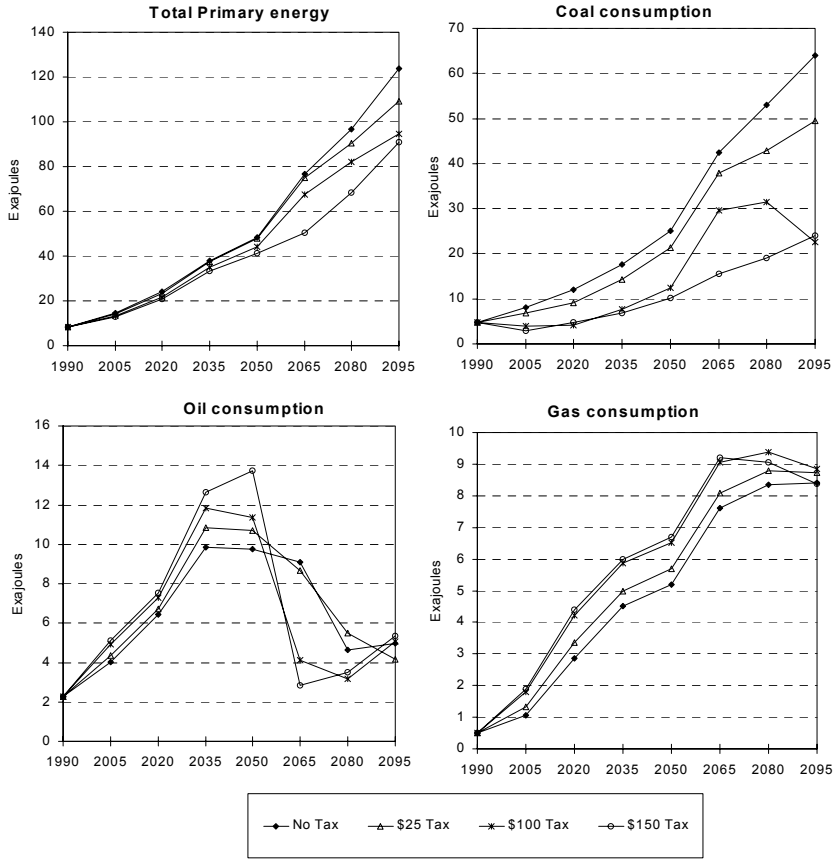


Figure 3: SGM Reference Scenario: Primary Energy Consumption

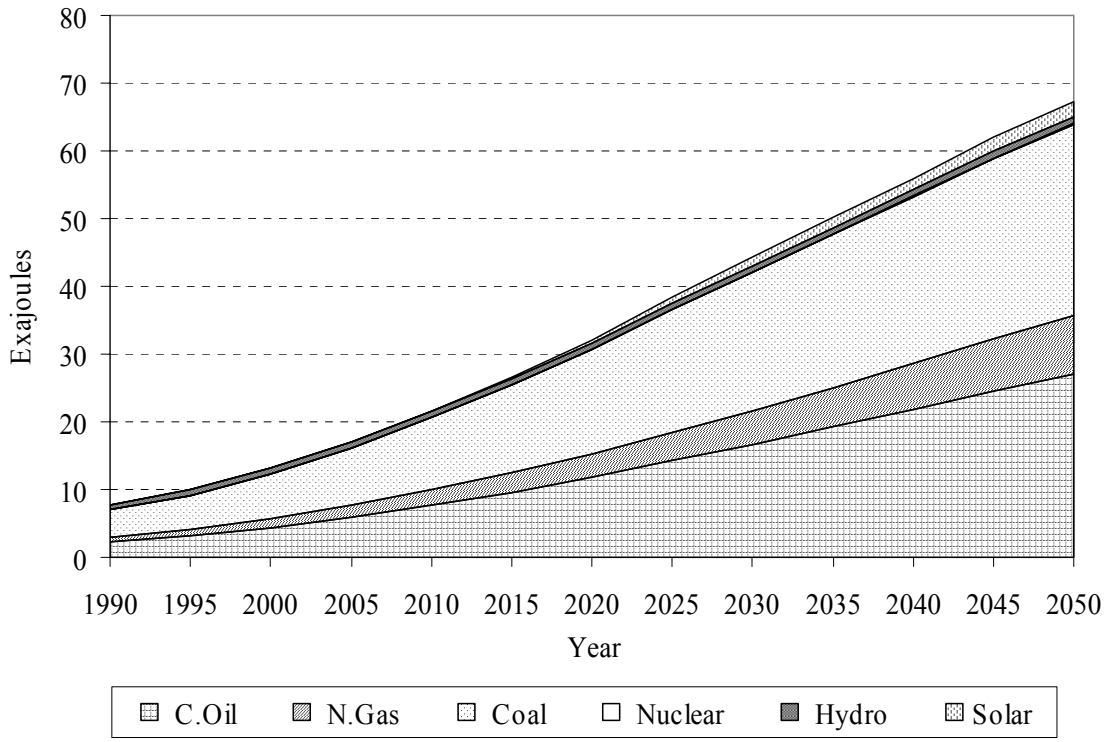


Figure 4: SGM Reference case: Electricity by sub-sector (in Exajoules)

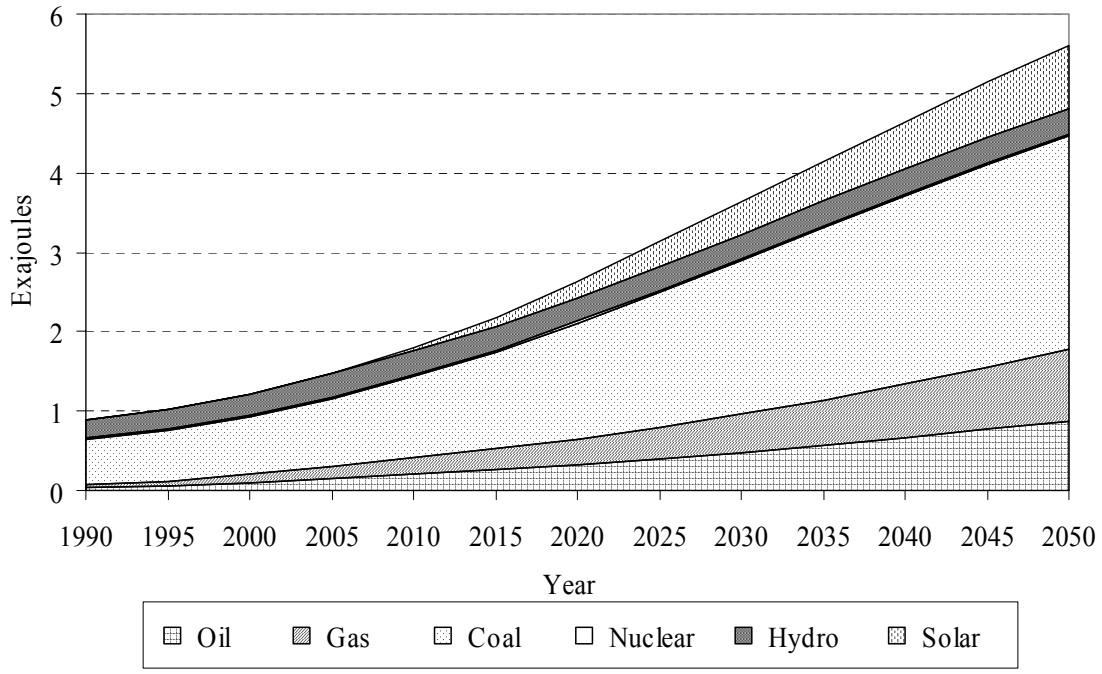


Figure 5: SGM Mitigation Scenarios: Change in Real GNP over reference case

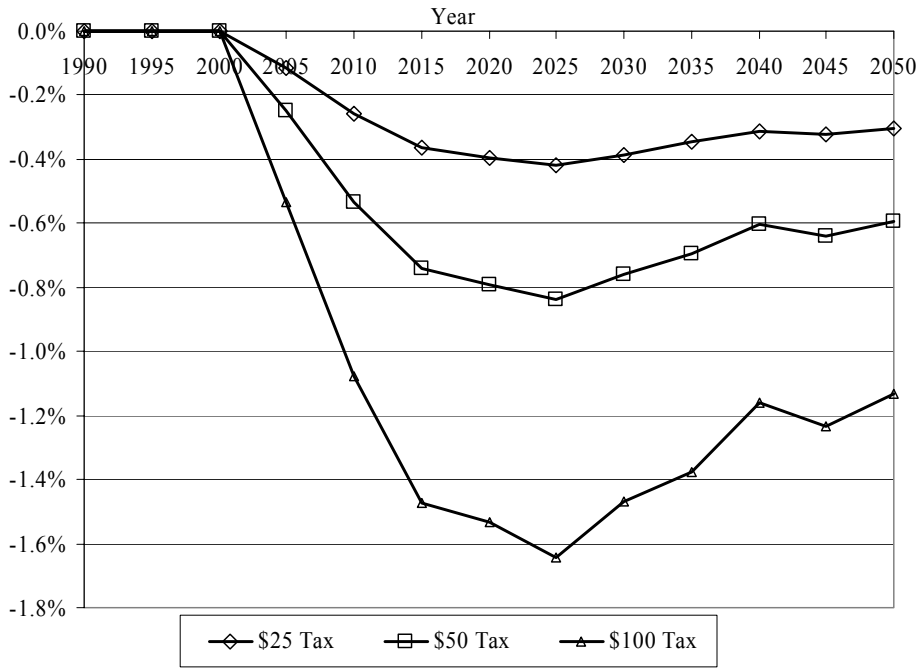
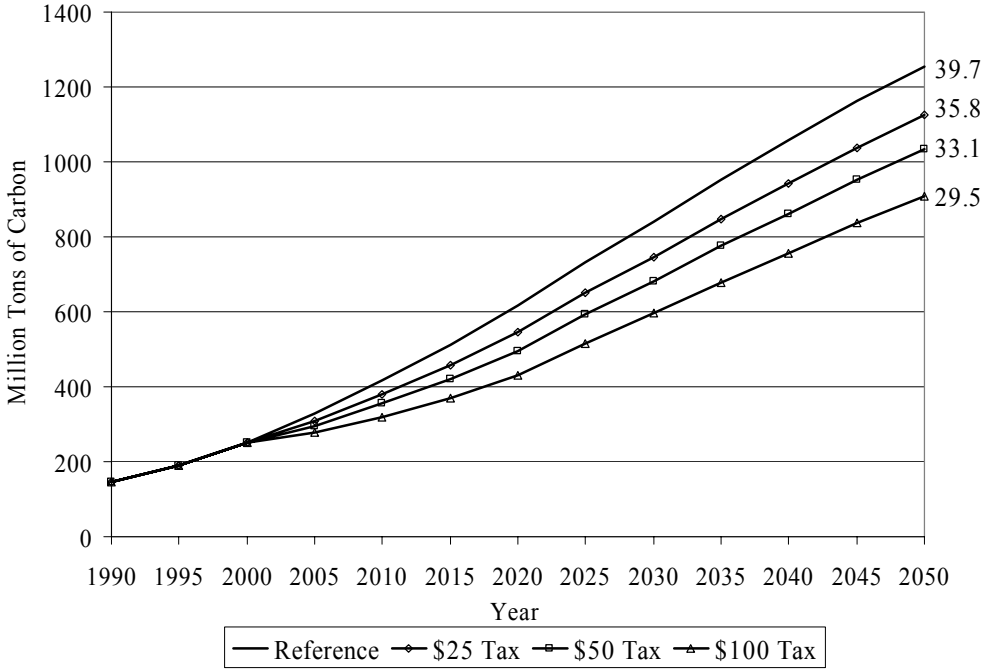


Figure 6: SGM Mitigation Scenarios: CO2 Emissions



Note: Numbers on the right show cumulative emissions in Billion Tons of Carbon