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Carbon taxes and India[1]

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Abstract

Using the Indian module of the Second Generation Model (SGM), we explore a reference case and three scenarios in which greenhouse gas emissions were controlled. Two alternative policy instruments (carbon taxes and tradable permits) were analyzed to determine comparative costs of stabilizing emissions at (1) 1990 levels (the 1X case), (2) two times the 1990 levels (the 2X case), and (3) three times the 1990 levels (the 3X case). The analysis takes into account India's rapidly growing population and the abundance of coal and biomass relative to other fuels.

We also explore the impacts of a global tradable permits market to stabilize global carbon emissions on the Indian economy under the following two emissions allowance allocation methods.

1. Grandfathered emissions: emissions allowances are allocated based on 1990 emissions.
2. Equal per capita emissions: emissions allowances are allocated based on share of global population.

Tradable permits represent a lower-cost method to stabilize Indian emissions than carbon taxes, i.e. global action would benefit India more than independent actions.

JEL classification: Q41

Keywords: Carbon taxes; Computable general equilibrium; Tradable permits

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1. Introduction

Greenhouse gas emissions from anthropogenic activities have emerged as a pressing global concern of our time. Accumulation of greenhouse gases (GHGs) in the atmosphere is expected to lead to undesirable changes in the global climate. As a global response, the Framework Convention on Climate Change (FCCC) was signed by 152 countries at the UN Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992. The framework convention aims to achieve stabilization of atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system (UNEP, 1992). The target of returning to the 1990 emission levels by the year 2000 was acknowledged by the developed nations.

The economic essence of global GHG emissions abatement policies is to achieve the desired future emission levels at the least cost of abatement and impacts. GHG abatement potential and costs vary in different nations and among different activities within the same nation. The least cost GHG abatement strategy therefore requires varying levels of abatement from anthropogenic activities spread all over the globe. Although the GHG emissions from the developing nations are relatively low at present, they are growing rapidly. Developing countries offer considerable potential for low cost abatement of future GHG emissions. India is a major developing nation contributing 3% of global GHG emissions.

The rapid development of India has important implications for its current and future contributions to the global change issue. Currently, India holds 15% (World Bank, 1992) of the world's population (three times that of the U.S.) and is growing at an annual rate of approximately 2% per year. This puts tremendous pressure on India's natural resources and energy use. India's energy consumption is currently growing at approximately 6% annually (three times its population growth) compared with 0.1% in industrial economies, and consists mainly of coal consumption. In addition, traditional biomass consumption for energy in rural areas accounts for approximately one-third of India's energy consumption. Although in the past biomass consumption in India has not been considered carbon neutral (e.g. WRI, 1992), recent literature has suggested carbon neutrality (Ravindranath and Somashekhar, 1995).[2] As India develops, much of this traditional biomass use will diminish, but will be replaced with fossil-fuel consumption (especially coal) which will perhaps increase India's emissions of carbon. For all of these reasons, India has a major stake in the global warming problem and solution.

Our discussion begins by describing the Indian economy and energy use, followed by a brief description of the model used in our analysis. We next describe the derivation of reference year parameters, proceed to develop reference case assumptions, describe the resultant reference case scenario, and then explore the costs and benefits of various policy mechanisms to reduce GHG emissions in India.

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[2] The authors thank an anonymous referee for pointing out this recent literature.

2. The Indian economy, energy and GHG emissions: past and present

2.1. An economic profile of India

India is a fast growing economy, as shown in Table 1. In the four decades prior to 1991, the Indian government followed a mixed economy model. Agriculture production and consumer product industries were developed in the private sector, whereas energy, infrastructure, and heavy industry were almost exclusively in the government sector. Government procured food and other essential commodities in bulk and marketed these through the public distribution system (PDS). Prices of energy products and essential commodities (like steel, cement, sugar, and food products in PDS) and services (e.g. transport and telecommunications) were administered on cost plus (minus) basis. The supply side of the economy had strong entry barriers through licensing of capacities. The foreign trade regime had severe tariff barriers and other restrictions. The Indian currency was not convertible and the exchange rate was fixed by the government, which priced Indian currency higher than the rate in the thriving unofficial currency market.

In 1991, the government of India initiated economic reforms for liberalizing the Indian economy. The reforms aim to give market orientation to the Indian economy and integrate it with the global economy. In terms of external trade and finance, the reforms are directed at reducing import tariffs, removing import restrictions, gradually making the Indian currency fully convertible and removing restrictions on foreign direct investment. Internally, the reforms are directed at removing the licensing of capacities, allowing private investment in sectors hitherto under the government monopoly control, and moving away from administered pricing to a market regime. The economic reforms also aim to give greater market orientation to the public distribution system. The post-reform economic dynamics are thus expected to be different than in the earlier period.

Table 1
Macroeconomic profile of India

Year	1970	1975	1980	1985	1990
GNP at factor cost[a] (Rs billion)	894.65	1046.60	1227.72	1553.65	2083.90
Annual growth rate[b] of GNP[a] (%)	5.1	3.2	3.2	4.8	6.0
Population (million)	541	607	679	754	837
GNP per capita[a] (Rs.)	1653.7	1724.2	1808.0	2061.0	2490.0
Gross domestic savings rate (%)	15.7	19.0	21.2	19.8	21.9
Employment (million)	179		223	288	307

Notes:
[a]At constant 1980–81 prices.
[b]Average growth rate over five years.
Sources: Central Statistical Organization (1989b, 1992), Centre for Monitoring Indian Economy (1992b).

2.2. Energy and GHG emissions: past trends

India's per capita commercial energy consumption increased from 9% of the world average in 1965 to 18.5% in 1989 (TERI, 1992). India's commercial energy demand is growing by nearly 7% (Centre for Monitoring Indian Economy, 1990) and electricity demand by 9% annually (Central Electricity Authority, 1991). The share of fuel cost in value added has increased from 20% in 1973–74 to 41.6% in 1987–88 (Centre for Monitoring Indian Economy, 1992a). India imported 19.5% of its commercial energy needs in 1991–92, the value of which was 26.8% of total Indian imports (Centre for Monitoring Indian Economy, 1994). India has relatively large reserves of coal, estimated at 196 billion tonnes gross (Centre for Monitoring Indian Economy, 1992a), but has meager oil and gas reserves. The energy system is therefore heavily coal based. The commercial energy consumption trend in India is shown in Table 2.

The impact of rapid economic development on the environment is apparent from the increased emission of GHGs, deterioration in the air quality of major cities from rising particulate and sulfur dioxide emissions, deforestation, and land degradation. One-third of the energy consumed in India comes from non-commercial sources, mainly biomass. The annual population growth rate in India has remained over 2% for several decades. The rapidly increasing population, the low purchasing capacity of the vast population to buy cleaner fuels, the unsustainable use of forest biomass by industries, and the increasing demand for land have led to tremendous pressure on forests. The WRI (1992) has attributed nearly 40% of carbon emissions from anthropogenic sources to land-use changes alone. The energy system is a major contributor to air pollution loads. The business-as-usual emissions projections point to alarmingly high rates of emissions growth, nearly a six-fold increase in carbon emissions between the years 1985 and 2025 (Sathaye and Ketoff, 1991).

Table 2
Energy consumption in India (petajoules)

Year	1970	1975	1980	1985	1990
Lignite	19	29	44	77	130
Coal	1466	1910	2222	3124	4201
Refined oil & LPG[a]	622	799	1082	1480	2035
Natural gas[a]	42	79	86	270	606
Biomass	2492	2821	3202	3518	3866
Hydropower[b]	258	334	484	540	723
Other[c]	25	33	32	49	74
Total	4923	6005	7152	9059	11636

Notes:
[a] Includes non-energy use of gas and fuel oil for fertilizer and petrochemical production.
[b] For hydro, nuclear, and renewables, energy is the coal equivalent for electricity generation.
[c] Includes nuclear, wind, solar, etc.
Source: authors' estimates based on Centre for Monitoring Indian Economy (1991), TERI (1992).

Energy and carbon emissions trends in the last two decades are shown in Table 3. Energy consumption has more than doubled in two decades, while net carbon emissions have tripled. This is owing to the decline in the use of sustainable biomass, a carbon neutral fuel. Net carbon emissions in Table 3 do not include indirect emissions because of deforestation. In fact, considerable deforestation has taken place in India, which according to the WRI (1992) contributed approximately 120 million tonnes (MT) to the carbon flux in 1989. Gross carbon emissions in Table 3 include carbon emissions from biomass, assuming present biomass use is not carbon neutral; however, more recent literature (Ravindranath and Somashekhar, 1995) suggests biomass use is carbon neutral.

Table 4 shows the contribution of major energy sources to total energy and gross carbon emissions in 1990. Biomass is still a major energy source, although its contribution to total energy has declined from 50% in 1970 to 39% and 33% in 1980 and 1990, respectively. Coal is the dominant energy source, accounting for

Table 3
Energy consumption and carbon emission trends

Year	1970	1975	1980	1985	1990
Energy consumption (PJ)	4923	6005	7152	9059	11636
Net carbon emission[a] (MT)	61.58	79.54	95.78	134.63	183.39
Gross carbon emission[b] (MT)	129.64	156.59	183.23	230.72	288.99

Notes:
[a] Net carbon emission excludes emissions from biomass combustion.
[b] Gross carbon emission includes emissions from biomass combustion.
Source: WRI (1992), authors' estimates.

Table 4
Contribution of energy sources in gross energy and carbon emission (1990)

Source	Energy contribution		Gross addition to carbon flux	
	Petajoules	%	MT of carbon	%
Coal/lignite	4331	37.3	129.57	44.8
Natural gas	606	5.2	8.38	2.9
Refined oil & LPG	2035	17.5	39.45	13.7
Biomass	3866	33.2	105.59	36.5
Hydro electricity[a]	723	6.2		
Other[b]	74	0.6		
Total	11636	100.0	288.99[c]	100.0

Notes:
[a] Equivalent energy generation using coal.
[b] Includes nuclear, wind, solar, etc.
[c] In addition to these sources, the total CO_2 flux also includes 5.98 MT of carbon (i.e. 2.1%) from cement production.
Source: WRI (1992), authors' estimates.

nearly 37% of total energy in 1990. The use of natural gas has increased rapidly in the last decade but it still contributes only 5% to total energy use. Consumption of refined oil products has tripled in two decades and at present contributes 17% to total energy use. Hydro energy contribution has stagnated at around 6%, and the nuclear and renewable energy contribution is marginal, below 1%. Although the contribution of refined oil and natural gas to total energy has increased lately, coal and biomass still remain major energy sources. The carbon intensity of energy use in 1990 is high: 16.3 tons of net carbon emissions and 24.9 tons of gross carbon emissions per terajoule of energy.

3. Assumptions about India into the next century: 1985–2030

We begin the analysis of carbon taxes to control India's GHG emissions by constructing a reference case against which to view policy-derived impacts. The reference case, in turn, rests on assumptions about the Indian economy and energy use. We firmly believe that no reference case that we could construct today is capable of representing the future. But the reference case does provide a consistent, reproducible foundation against which to test hypothetical changes in the energy tax structure of the Indian economy.

The Second Generation Model (SGM) India module requires input assumptions in five different areas: demographics, energy resources, productivity change, international trade, and fiscal policy. We discuss each in this section.

For a further description of the model structure, see Appendix A.

3.1. Demographic assumptions

The demographic module in SGM version 0.0 develops population estimates using exogenous fertility, survival, and migration rates. Population is differentiated by gender and five-year age group.

Fig. 1 shows the demographic profile of India for our benchmark year of 1985 (World Bank, 1990). The bulge in the chart for the younger age groups reflects the high fertility rates and population growth of the region.

Both the terminal values and the time to reach the terminal values can be specified by the user. We have specified initial values for these rates based on data for 1985. We also included a terminal value for each of these rates as a modeling parameter. Table 5 shows the values of the demographic rates, which are assumed to persist throughout the modeling period.

3.2. Depletable energy resources and reserves

By definition, the resource base is the total quantity of a resource which could be produced over time using any conceivable technology. It includes both discovered and undiscovered quantities. It is therefore a physical constraint on cumulative production. As discussed in Appendix A, we distinguish energy resources for oil,

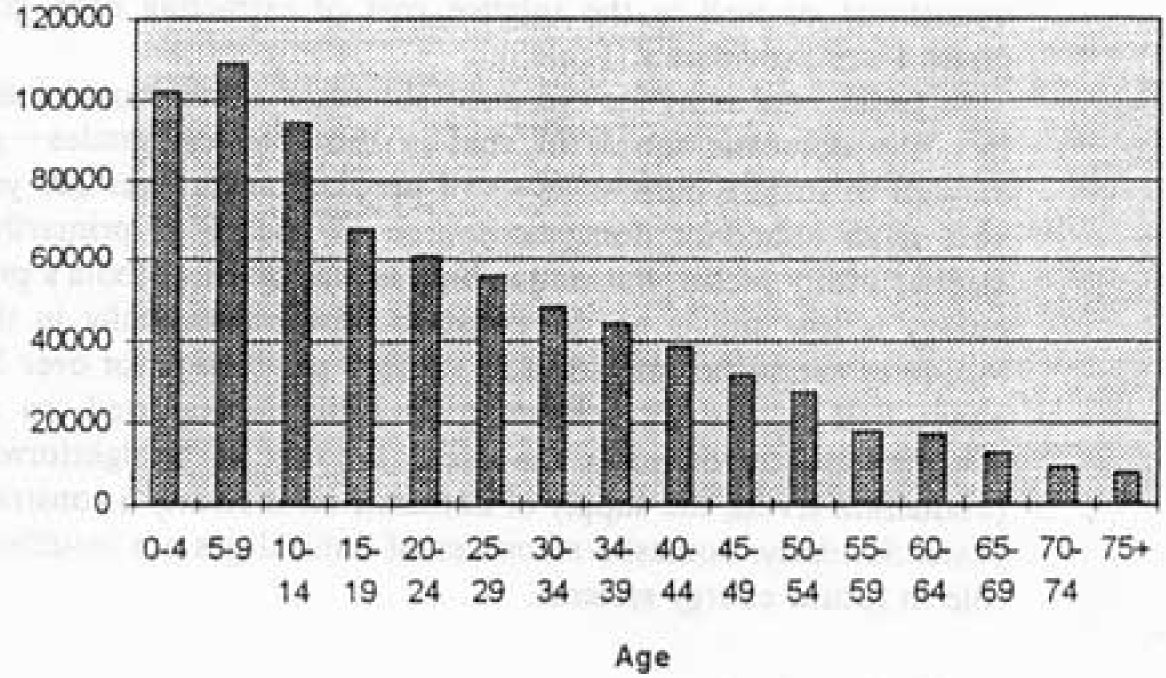

Fig. 1. Age-specific population of India.

Table 5
Demographic rates (per thousand people)

Age	Fertility rates	Male birth fraction	Female death rates	Male death rates	Migration rates
0–4	0.0	0.52	30.0	30.0	−0.2
5–9	0.0	0.52	4.4	5.1	−0.2
10–14	0.0	0.52	2.5	2.1	−0.2
15–19	68.13	0.52	3.2	2.5	−0.2
20–24	190.16	0.52	3.7	2.4	−0.2
25–29	209.11	0.52	4.6	1.7	−0.2
30–34	161.13	0.52	3.2	3.8	−0.2
34–39	108.08	0.52	4.2	1.0	−0.2
40–44	52.81	0.52	4.9	8.3	−0.2
45–49	0.0	0.52	4.7	5.4	−0.2
50–54	0.0	0.52	14.6	6.6	−0.2
55–59	0.0	0.52	5.8	12.3	−0.2
60–64	0.0	0.52	23.2	18.6	−0.2
65–69	0.0	0.52	20.3	35.9	−0.2
70–74	0.0	0.52	49.8	39.1	−0.2
75 +	0.0	0.52	56.2	85.8	−0.2

Source: United Nations (1990).

gas, and uranium by grades reflecting variation in the ease of extraction, which in turn drives costs. One to five grades are defined for this exercise. The estimates of the energy content available in each of the grades (excluding previously consumed quantities), as well as the relative cost of extracting each grade compared with grade 1 are provided in Table 6.

In India, coal is by far the most abundant conventional fossil fuel resource. In fact, the domestic supply of coal in the cheapest grades—grades 1 and 2—is enough to sustain current levels of production for over 200 years.[3] Uranium, the next most abundant domestic source of energy, is primarily consumed by the electric utility sector, but not at high levels, because India's production of nuclear energy is low and is not expected to grow substantially in the future. Uranium resources are sufficient to sustain current production for over 300 years. Currently, about half of the oil consumed in India is imported, so the implications of consumption on domestic resources are not as straightforward. Under current production levels, the supply of domestic oil is clearly a constraint over the next 50 years. Similarly, domestic resources of natural gas are insufficient to play a major role in future energy systems.

3.3. Productivity change

An important set of assumptions governs productivity change in a variety of human activities in the SGM. Productivity changes in the SGM can occur in either of two ways, through smooth changes in production function coefficients associated with new investment options, which we refer to as general productivity growth, or by the introduction of a new technology option at a specific point in time.[4]

Table 6
Indian energy resources remaining and relative costs by grade

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Crude oil (EJ)	68	0	0	0	0	68
Relative cost	1.0	N/A	N/A	N/A	N/A	
Natural gas (EJ)	6	33	4	1	0.5	44.5
Relative cost	1.0	2.75	5.5	7.92	33	
Coal (EJ)	30	633	337	333	333	1666
Relative cost	1.0	1.4	2.8	5.6	9.45	
Uranium (tons)	100	0	0	0	0	100
Relative cost	1.0	N/A	N/A	N/A	N/A	

Source: Authors' estimates based on WRI (1992).

[3]Coal resources were divided into the five grades in order to obtain stable coal prices throughout the modeling period.

[4]Similarly, the model can remove technologies from the available set, e.g. when new source performance standards are introduced.

Table 7
Assumptions of exogenous change in total factor productivity for new investments

Sector	Productivity growth assumption (%/year)
1. Agriculture	0.2
2. Crude oil production	1.0
3. Natural gas production	1.0
4. Coal production	0.2
5. Uranium production and refinement	1.0
6. Electric power generation	
Coal-fired	0.2
All others	0.0
7. Oil refining	0.2
8. Natural gas transformation	0.2
9. Other production	1.0

Assumed rates of change for general, Hicks neutral, productivity in new investments are given in Table 7.

Since the other production sector produces approximately 60% of total output, the productivity growth rate of this sector was adjusted to attain an average annual growth forecast of the Indian economy of approximately 4% between 1985 and 2030 (IMF, 1993). Lack of detailed knowledge of variations in future productivity growth between sectors resulted in the assumption of no variation in productivity growth rates between the crude oil, natural gas, and uranium sectors and the other production sector. Future versions of the SGM will incorporate current research in this area to better define variations in productivity growth between these sectors.

To reflect the expectation that coal mining will not experience the same level of productivity growth as the other primary energy sectors, and to keep the relative price of coal from dropping dramatically over time, a 0.2% productivity growth rate was assumed in this sector.

Productivity growth rates in two of the three energy transformation sectors are set to 0.2% per year to maintain energy balances between inputs and outputs. These three sectors—electric power generation, oil refining, and natural gas transformation—differ from the other producing sectors because they use large quantities of energy as inputs; most of which 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. In these sectors, changes in productivity could be modeled as discrete changes in available production functions over time.

Although productivity improvements in the electric power and agriculture sectors are handled mainly through the incorporation of new technologies in the SGM, small productivity improvements in the agriculture sector and in the coal-fired electricity subsector, resulting from changes in management practices, warrant the inclusion of a small neutral productivity growth assumption. This value (0.2%) was chosen in order to obtain reasonable results within the electric power sector (e.g. an average annual growth rate of approximately 3.3% between 1985 and 2030) and the agriculture sector (e.g. an average annual growth rate of approximately 3.9% between 1985 and 2030). In addition, these numbers are consistent with the neutral technological change growth rates experienced by these sectors in recent history.

3.4. International trade

Finally, the SGM requires assumptions about the region's interactions with the rest of the world. These are given in Table 8. The crude oil market is assumed to be open, and the model can import or export as much as is economically desirable at an exogenously specified price. (This price path is taken from Bradley et al., 1991). The nominal trade account is assumed to be balanced. This is accomplished by setting net exports of the other production sector, sector 9, equal to the negative of the sum of net exports from other sectors.

3.5. Fiscal policy

Budgets for all government activities taken together, including national and provincial, are assumed to be balanced.

4. The reference case

The assumptions discussed in the preceding section generate a reference case trajectory for the Indian economy, energy system, and GHG emissions. We discuss each in turn.

4.1. The reference case economy

We begin by discussing trends in population and economic activity. Fig. 2 shows

Table 8
Closure assumptions

Sector	Closure assumptions
1.Agriculture	1985 net exports fixed
2. Crude oil production	world price path given exogenously
3. Natural gas production	1985 net exports fixed
4. Coal production	1985 net exports fixed
5. Uranium production and refinement	1985 net exports fixed
6. Electric power generation	1985 net exports fixed
7. Oil refining	1985 net exports fixed
8. Natural gas transformation	1985 net exports fixed
9. Other production	set to balance nominal trade account

the real gross domestic product (GDP) divided into its three principal components: consumption, investment, and government spending (recall that net exports are zero by assumption). GDP grows throughout the period of analysis at an average annual rate of 4.1% between the years 1985 and 2030. We note, however, that the rate of growth slows after the year 1995. The rate of working age population growth slows to 1.67% per year after 2000 compared with the 3.09% per year at the start of the modeling period.

In order to understand the economic forces at work within the SGM, it is useful to examine why GDP growth falls from 1995 to 2030. This fall is due primarily to a slowdown in the growth of population and thus labor supply (Fig. 3 and Fig. 4). Although the average annual growth in the labor supply over the modeling period (2.5%) is larger than the average annual growth in population (1.6%), reflecting an increase in labor force participation (from 67% in 1985 to 87% in 2030), we still see a dramatic decrease in the growth of the labor supply by 2030. The growth in the labor supply is 1.46% per year by the year 2030 compared with 4.16% per year in 1990. This affects the economy not only through production but also in demand for goods and services.

Labor costs reflect this decrease in labor growth by almost tripling during the modeling period. As might be expected given the slowdown in labor supply, the capital/labor ratio increases over the modeling period from 22,821 rupees (Rs) per worker to 72,132 Rs per worker (Table 9). Correspondingly, we see a substitution away from labor into capital. This is seen in the decline in the ratio of labor to output, while the ratio of capital to output increases (Table 10).

The decline in the work age population has another route for affecting economic growth rates. A determinant of the demand for investment is the change in the rate

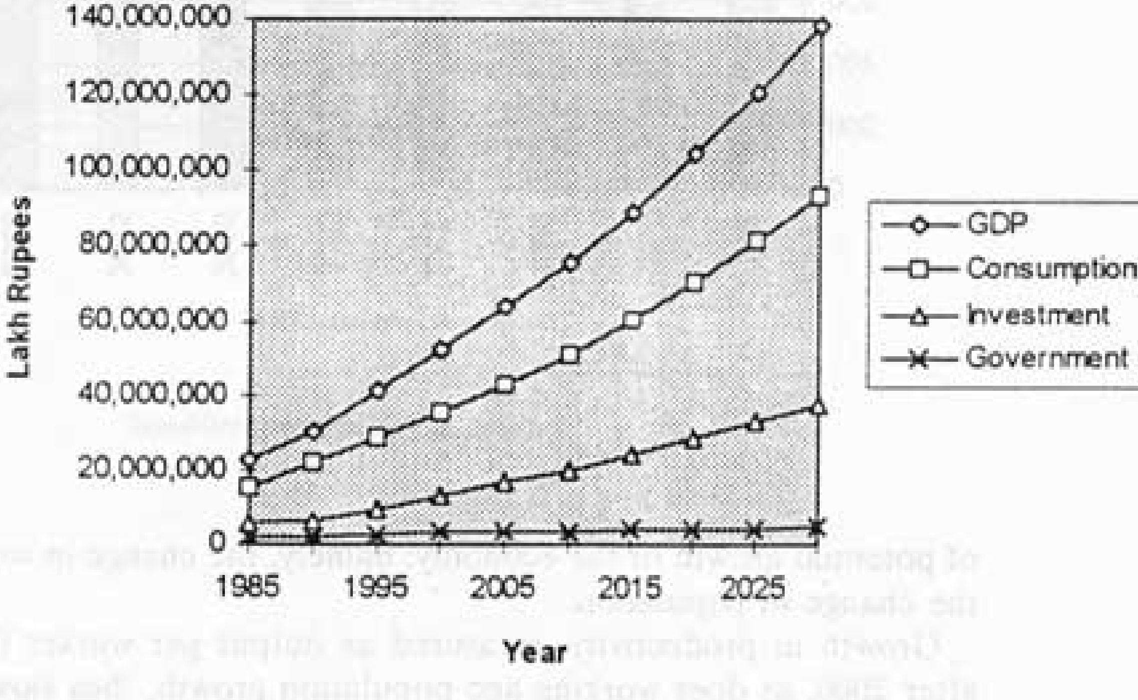

Fig. 2. Real GDP with components.

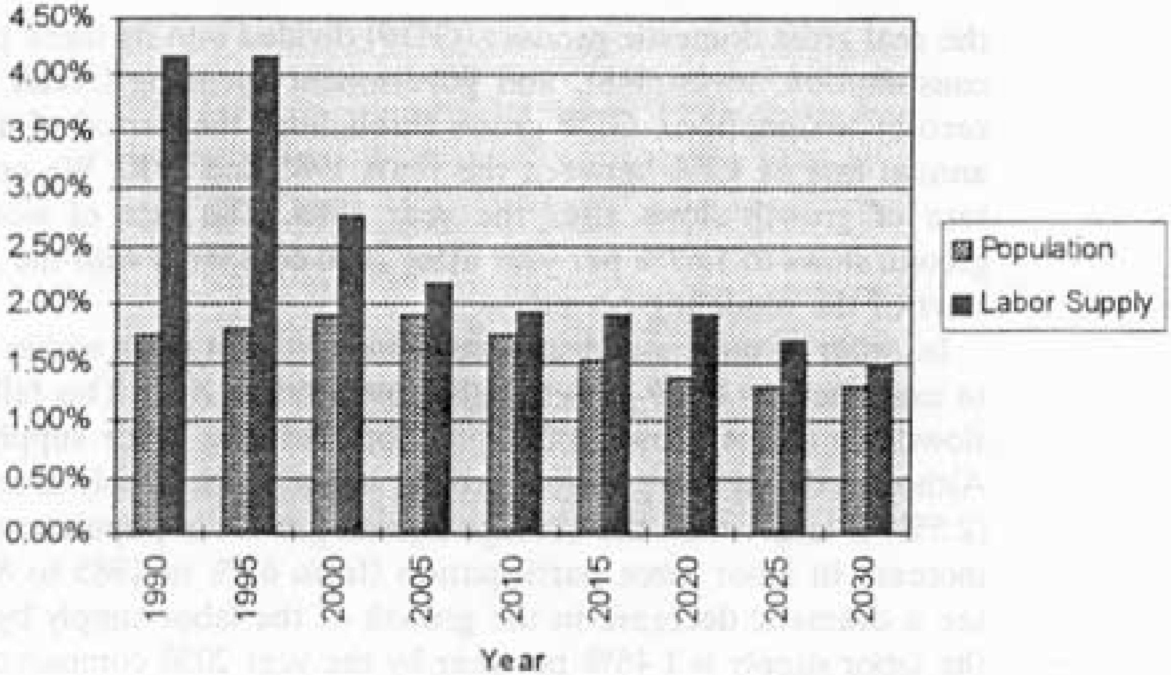

Fig. 3. Growth in population and labor supply.

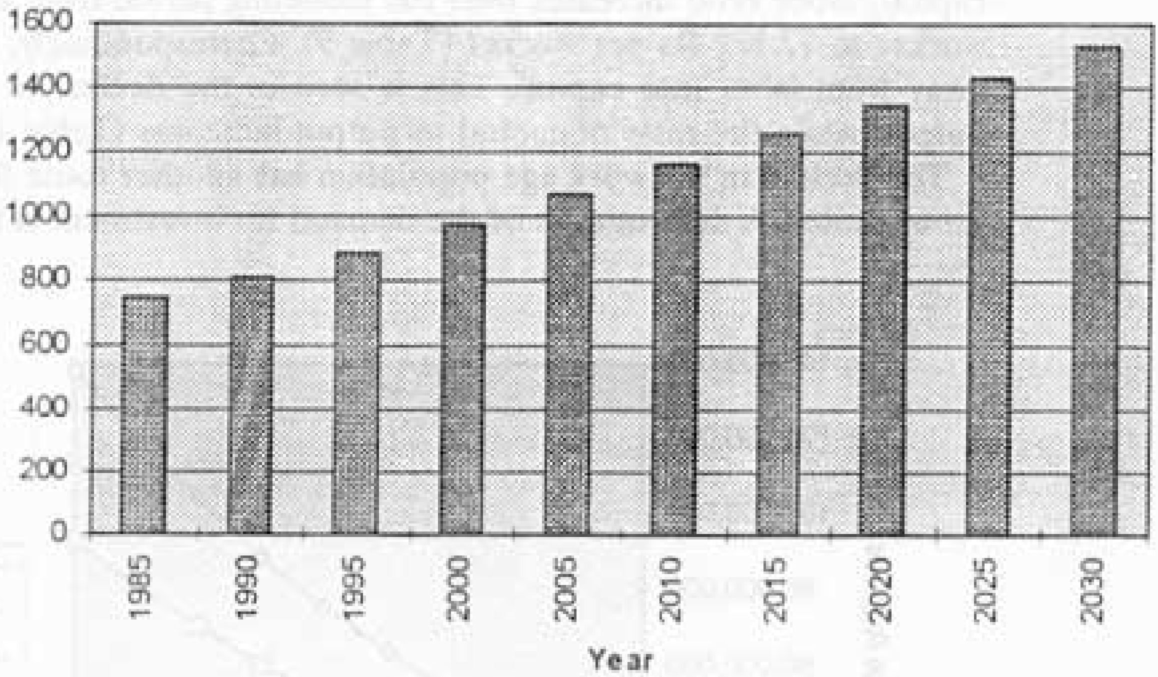

Fig. 4. Population (millions).

of potential growth of the economy; namely, the change in worker productivity and the change in population.

Growth in productivity, measured as output per worker (Table 10), also slows after 2000, as does working age population growth, thus slowing growth in investment. Examination of the components of GDP makes this clear, as growth in

Table 9
Factors affecting employment

Year	Work age population growth (%)	Labor supply growth (%)	Percent at work	Wage annual (100 Rs. constant 1985 prices) [Average annual growth rate]	Capital/labor ratio (constant 1985 Rs./worker [Average annual growth rate]
1985			67.3	59.43	22,821
1990	3.09	4.16	70.9	66.82 [2.37%]	25,098 [1.92%]
1995	3.07	4.15	74.7	76.31 [2.69%]	27,797 [2.06%]
2000	1.67	2.77	78.8	89.93 [3.34%]	33,148 [3.58%]
2005	1.40	2.18	81.9	103.93 [2.94%]	40,549 [4.11%]
2010	1.41	1.93	84.0	116.86 [2.37%]	48,229 [3.53%]
2015	1.57	1.91	85.4	128.19 [1.87%]	55,267 [2.76%]
2020	1.69	1.92	86.4	138.12 [1.50%]	60,959 [1.98%]
2025	1.52	1.69	87.1	147.96 [1.39%]	66,425 [1.73%]
2030	1.31	1.46	87.7	158.91 [1.44%]	72,132 [1.66%]

investment (capital stock) slows after 2000 (Fig. 2 and Table 10). This leads to an increase in the average age of capital, which slows down the rate at which technical change is realized in the economy. (By assumption, neutral technological change occurs at a constant pace for each industry.)

4.2. The reference case energy system

Total primary energy use increases dramatically over the modeling period with an overall increase of approximately 350% between the years 1990 and 2030 (Fig. 5). A period of rapid increase (averaging more than 5% annually) occurs during the period 1990 to 2005, mirroring the rapid growth in the economy. A relative modest growth (approximately 2% average annual rate) in primary energy consumption occurs between 2005 and 2030 as a result of a slowdown in the economy and an increase in energy prices caused by the depletion of the less costly grades of domestic resources. This leads to a 24% decrease in the ratio of energy use to GDP during this period (Fig. 6).

Oil and coal remain the dominant fuels over this period (despite the fact that the price of crude oil is assumed to rise by more than 50% between the years 1990 and 2010), rising to almost 6 and 13 exajoules (from almost 3 and 5 exajoules)

Table 10
Factors affecting the capital stock

Year	Capital stock growth (Average annual %)	Capital/output ratio [Average annual growth %]	Labor/output growth (Average annual %)	Output/worker growth (Average annual %)
1985		2.740		
1990	6.16	2.789 [0.36]	−1.53	1.56
1995	6.30	2.789 [0.00]	−2.02	2.06
2000	6.46	3.011 [1.54]	−1.98	2.02
2005	6.38	3.361 [2.23]	−1.81	1.84
2010	5.52	3.721 [2.06]	−1.42	1.44
2015	4.72	3.964 [1.22]	−1.45	1.47
2020	3.93	4.099 [0.67]	−1.28	1.30
2025	3.45	4.199 [0.49]	−1.23	1.24
2030	3.15	4.288 [0.42]	−1.22	1.24

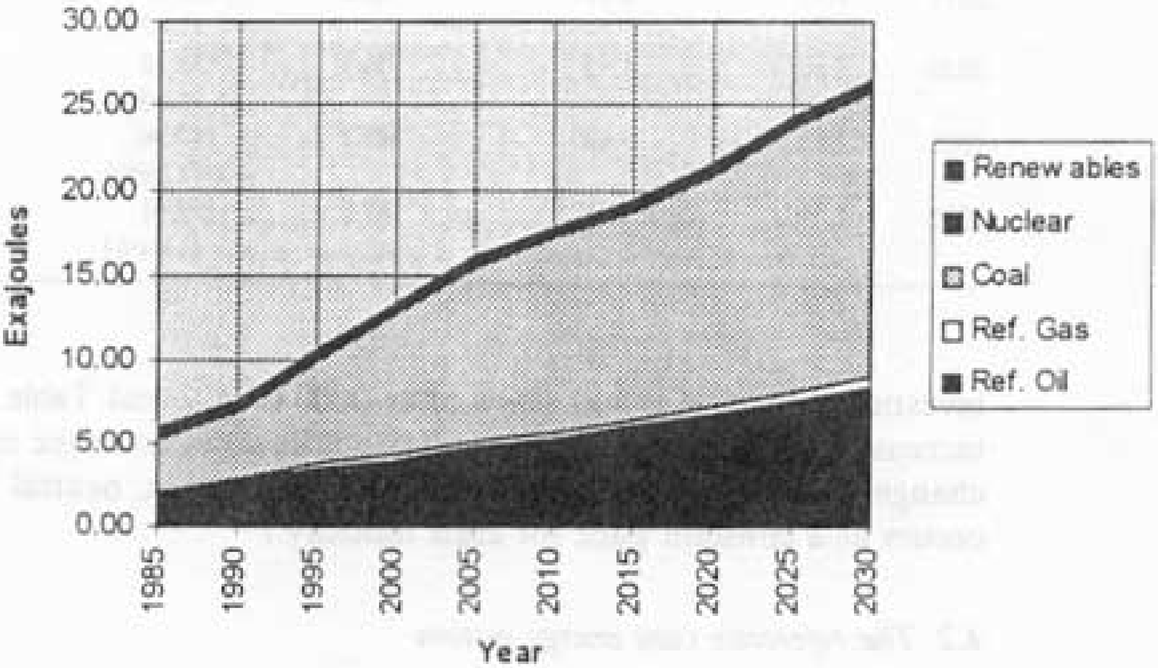

Fig. 5. Primary energy use.

consumed per year, respectively, by the year 2015. The growth in consumption is relatively stable throughout the remainder of the period of analysis. The escalation in oil consumption between 1990 and 2010 leads to a substantial increase in oil imports, beginning in the year 2000.

The only primary energy carrier whose price remains relatively stable is coal. The stability of coal prices keeps electricity prices stable due to coal's dominance in electric power generation.

The relative stability of the price of coal compared with other fuels, in addition to the abundance of domestic coal, leads to an increase of domestic coal produc-

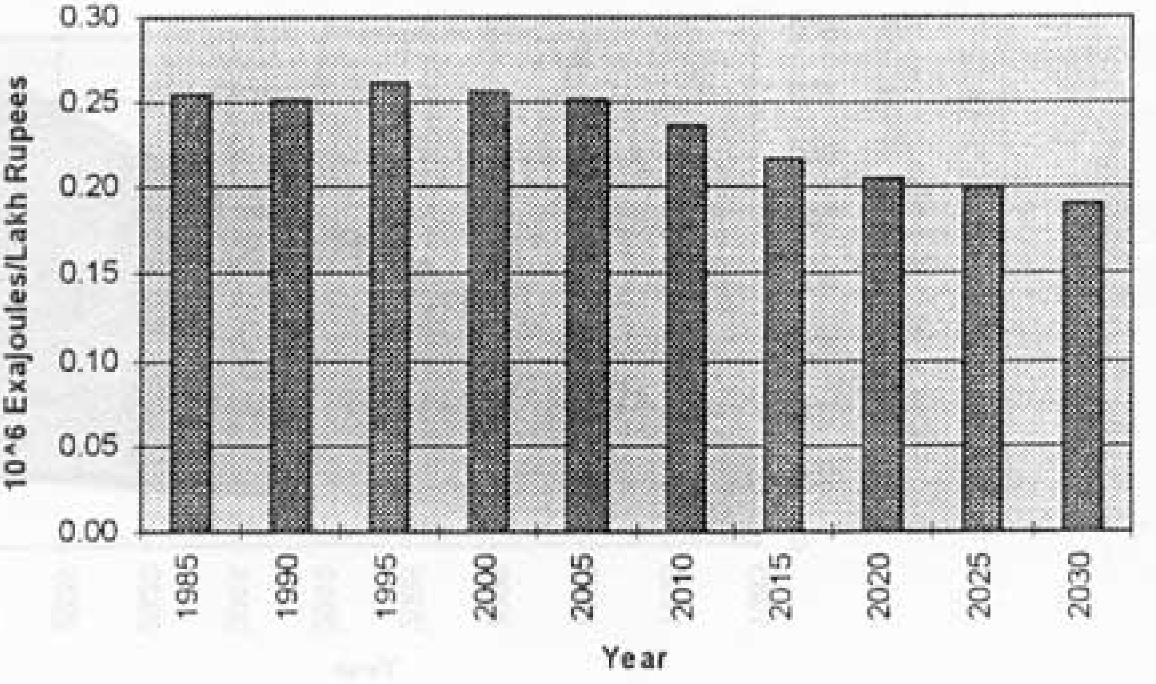

Fig. 6. Primary energy use per GDP.

tion and consumption of more than 400% between 1990 and 2030. Natural gas production increases by almost 300% between 1990 and 2030.

The abundance of cheap coal for use in electricity generation results in a stable pattern of nuclear power generation during the modeling period.

Electric power consumption as a whole expands steadily over the period of analysis, growing at an average annual rate of 3.3% over the modeling period.

4.3. Reference case GHG emissions

In India, carbon is emitted predominantly by fossil fuel combustion, although total emissions include emissions from other human activities, notably cement manufacture and agriculture.[5] The time profile of emissions of carbon is shown in Fig. 7. Reference case emissions are anticipated to rise relatively rapidly between the years 1990 and 2010, at an average rate of 4.7% per year. The larger growth ramp-up in emissions than in total energy use is the consequence of an increased fraction of coal in the energy mix. While the rate of growth ofcarbon emissions declines somewhat over time, the continuing increase in the share of energy use in the form of coal results in a growth in carbon emissions that remains above that of total energy use.

Emissions from other GHGs are displayed in Fig. 8. Since most carbon monoxide (CO) emissions are a result of refined oil combustion activities, we see the growth in these emissions mirroring that of refined oil consumption. Other GHG

[5] We note that the dominant source of non-energy related emissions of carbon are CH_4 from ruminant livestock.

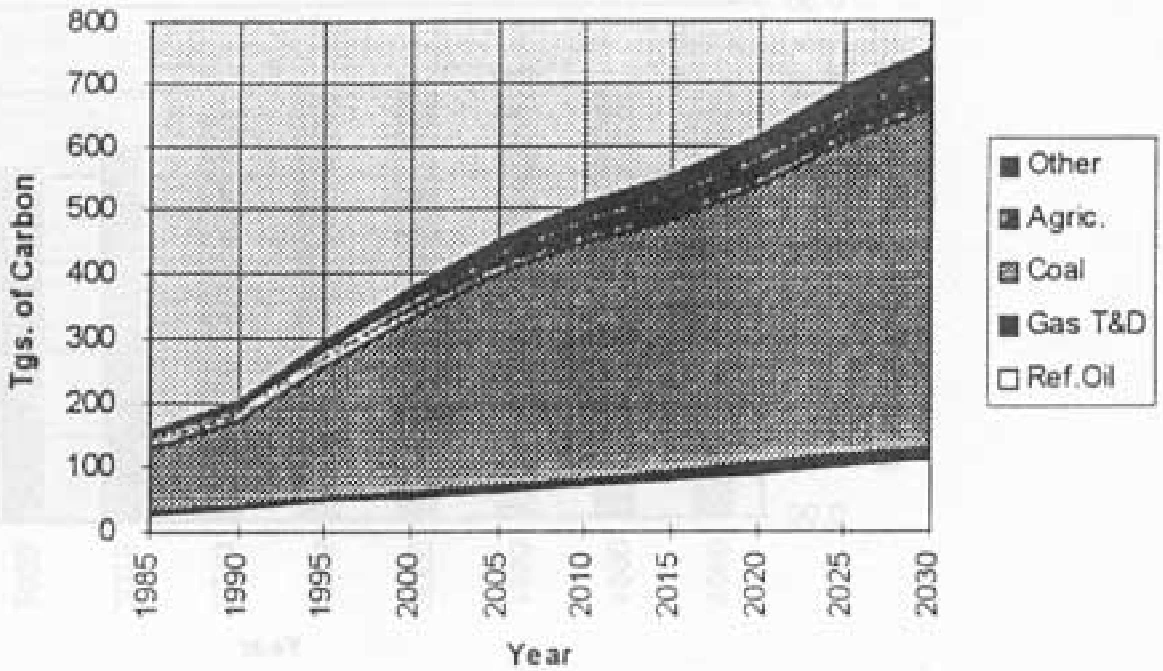

Fig. 7. Carbon emissions.

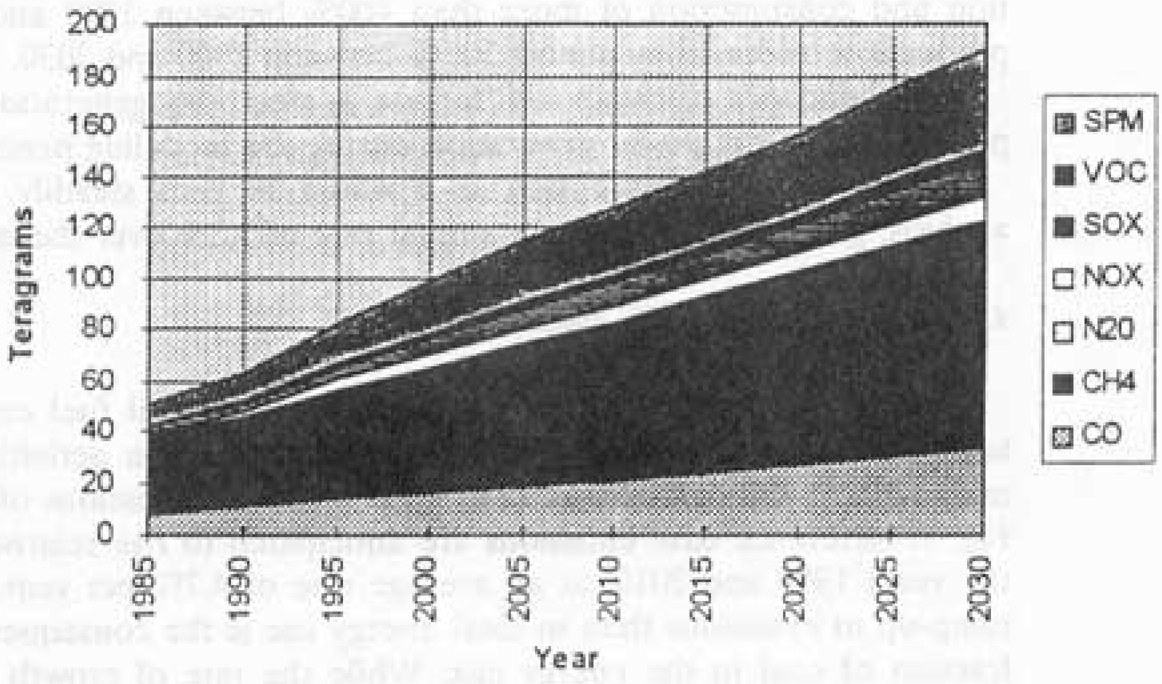

Fig. 8. Other GHG emissions.

emissions also experience a steady increase over the modeling period. SO_x emissions increase dramatically over the modeling period, mirroring coal consumption during this period. These will be a source of local air quality concerns.

In order to truly assess India's contribution to global carbon emissions, we must look at its carbon emissions on a per capita basis. As shown in Fig. 9, India's carbon emissions per capita in 1990 was approximately 0.2 tonnes carbon per

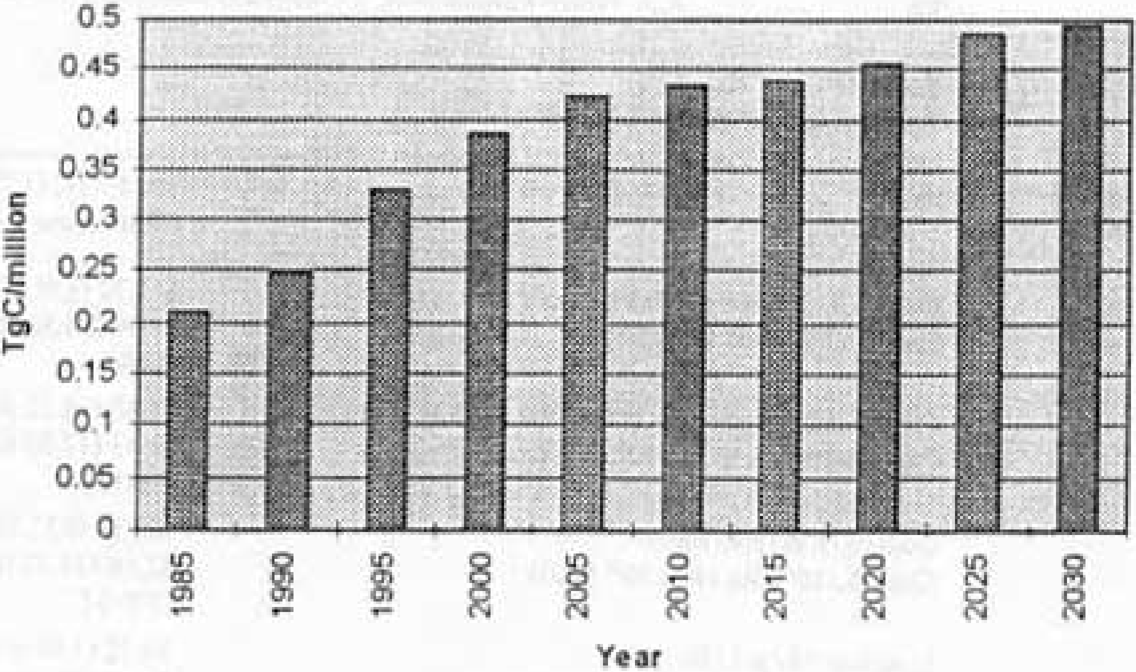

Fig. 9. Per capita carbon emissions.

person per year (tC/person/year) and is expected to grow to almost 0.5 tC/person/year by 2030. Although this growth seems dramatic, the 0.5 figure is still low compared with global per capita emissions which currently stand at approximately 1.0 tC/person/year and are expected to fall to approximately 0.7 tC/person/year by 2030.

5. Carbon taxes to reduce GHG emissions

In this section, we focus our attention on the policy issue of carbon taxes. While we have recognized the importance of the full suite of GHGs, most policy discussions center on fossil fuel carbon emissions.[6]

Carbon taxes are the most direct price instruments to reduce carbon emissions. Such an instrument was modeled in the SGM as a tax on the production of fossil fuels. The tax was additive, based on the proportion of each fuel's carbon content (i.e. $ (or Rs) per ton of carbon (TC)). Carbon taxes raise the price of fossil fuel by the amount of the additive tax, thus affecting carbon emissions. Based on the

[6] The suite of GHGs can be aggregated and dealt with as a single entity only if some metric of comparison can be found. The concept of a global warming potential (GWP) was developed by the Intergovernmental Panel on Climate Change (IPCC) and elsewhere, to provide a metric by which to compare the various gases. But problems in defining these coefficients have emerged, which have been most acute with regard to those gases with the greatest indirect effects on climate change: precisely those gases for which the GWP is most important.

[7] Based on a 1985 exchange rate of 12.24 Rs per US$1.

Table 11
Taxes based on carbon content of fuels

Fuel	100 \$/TC (1224 Rs/TC[a]) carbon tax [% increase from 1985 prices]
Crude oil (\$/barrel (Rs/barrel))	\$11.37 (139.17 Rs)
Crude oil (\$/10^6 Btu (Rs/10^6 Btu))	\$1.99 (24.36 Rs) [98%]
Crude natural gas (\$/1000 ft^3 (Rs/1000 ft^3))	\$1.48 (18.12 Rs)
Crude natural gas (\$/10^6 Btu (Rs/10^6 Btu))	\$1.43 (17.50 Rs) [161%]
Coal (\$/ton (Rs/ton))	\$51.94 (635.75 Rs)
Coal (\$/10^6 Btu (Rs/10^6 Btu))	\$2.56 (31.33 Rs) [276%]
Gasoline (\$/gal (Rs/gal))	\$0.25 (3.06 Rs)
Gasoline (\$/10^6 Btu (Rs/10^6 Btu))	\$1.80 (22.05 Rs) [34%]

[a]Based on a 1985 exchange rate of 12.24 Rs = US\$1.

known carbon content of various fuels, Table 11 shows how a 100 \$/TC (or 1224 Rs/TC[7]) carbon tax is translated into price increases for each of these fuels. The price increase is largest for coal, since coal contains the largest concentration of carbon.

In this analysis we explore three policy options based on carbon taxes to reduce carbon emissions:

1. varying carbon taxes to ensure carbon emissions do not exceed 1990 levels in each period (referred to hereafter as the 1X case);
2. varying carbon taxes to ensure carbon emissions do not exceed two times the 1990 levels in each period (referred to hereafter as the 2X case);
3. varying carbon taxes to ensure carbon emissions do not exceed three times the 1990 levels in each period (referred to hereafter as the 3X case).

The reference case results in carbon emissions which are no more than four times the 1990 levels in any given period. Comparisons of the above carbon tax cases with the reference case are presented below.

5.1. Carbon emissions and energy prices

The SGM was used to determine the tax rates required in each period to offset carbon emissions above the targeted stabilization levels (i.e. 1X, 2X, and 3X). These tax rates are given in Table 12 and shown in Fig. 10. All revenue received from the carbon tax is recycled back to the household sector as additions to personal income.

In the 1X case, tax rates begin at \$40 (490 Rs) per ton in 1995 and rise steadily until 2015 when a much larger growth in carbon taxes is required to stabilize

Table 12
Carbon tax rates

Year	1X case		2X case		3X case	
	Tax rate (1985 $)	Average annual %	Tax rate (1985 $)	Average annual %	Tax rate (1985 $)	Average annual
1990	0		0		0	
1995	40		0		0	
2000	75	13	0		0	
2005	115	9	8		0	
2010	155	6	20	20	0	
2015	225	8	36	12	0	
2020	425	14	65	13	2	
2025	665	9	117	12	15	50
2030	1100	11	162	7	25	11

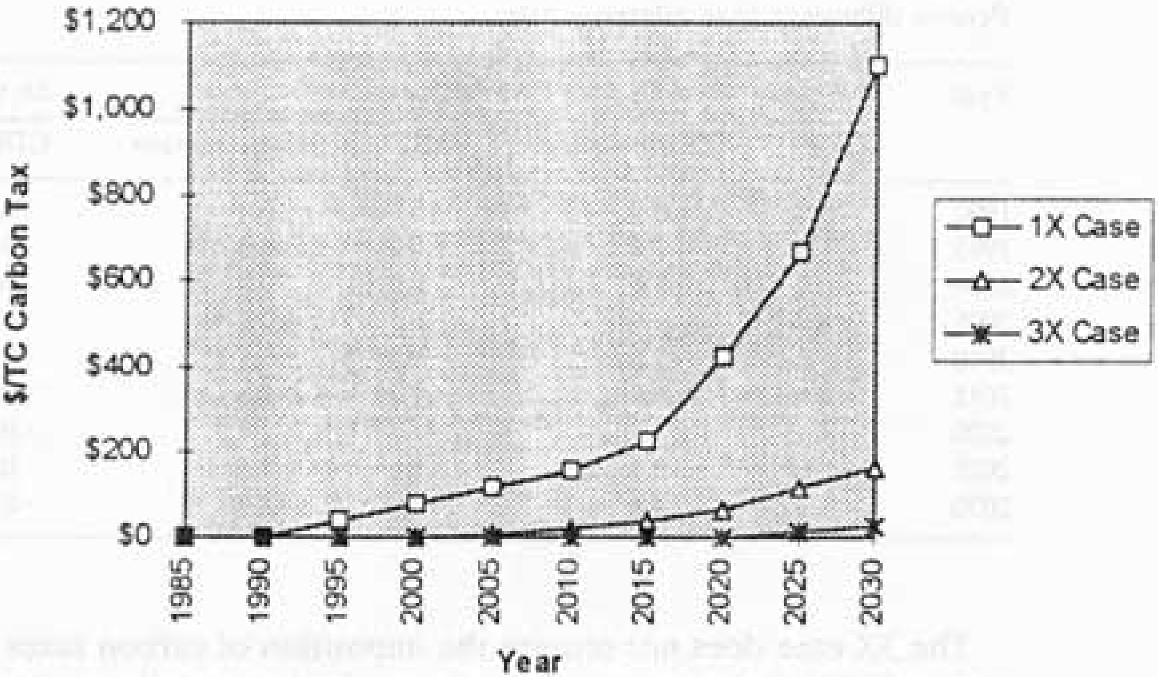

Fig. 10. Carbon tax rates.

carbon emissions at 1990 levels. By the end of the modeling period, a $1100 (13,464 Rs) per ton carbon tax is required to attain 1990 levels. Higher carbon tax growth rates after 2015 reflect sustained high population and real economic growth rates which lead to increased energy consumption; most of which involves oil and coal.

In the 2X case, carbon taxes are not required until 2005 when carbon emissions under the business-as-usual (or reference case) scenario rise above two times the 1990 levels. The tax rates with this policy option begin at $8 (98 Rs) per ton in 2005 and rise quickly over the modeling period, reaching $162 (1985 Rs) per ton by 2030. Again, large increases in the carbon tax rates are required due to high population and economic growth that increase fossil fuel consumption.

Table 13
Energy prices (percent difference from reference case)

Year	1X case			2X case			3X case		
	Crude oil	Natural gas	Coal	Crude oil	Natural gas	Coal	Crude oil	Natural gas	Coal
1990	0	0	0	0	0	0	0	0	0
1995	33	65	227	0	0	0	0	0	0
2000	47	146	523	0	0	0	0	0	0
2005	65	243	846	4	12	54	0	0	0
2010	80	296	1051	10	32	128	0	0	0
2015	105	330	1508	17	62	211	0	0	0
2020	185	786	2234	28	125	373	1	3	9
2025	277	1551	3691	49	277	656	6	34	78
2030	445	2024	6383	66	287	947	10	40	143

Table 14
Percent difference from reference case

Year	1X case		2X case		3X case	
	GDP	Consumption	GDP	Consumption	GDP	Consumption
1990	0.0	0.0	0.0	0.0	0.0	0.0
1995	−1.8	−2.5	0.0	0.0	0.0	0.0
2000	−3.7	−4.6	0.0	0.0	0.0	0.0
2005	−4.9	−6.9	−0.3	−0.2	0.0	0.0
2010	−4.0	−7.8	−0.4	−0.7	0.0	0.0
2015	−4.6	−8.5	−1.1	−1.5	0.0	0.0
2020	−4.4	−9.2	−1.3	−2.4	−0.1	−0.1
2025	−5.0	−10.5	−1.6	−3.3	0.0	−0.2
2030	−6.3	−14.6	−2.9	−4.9	−0.1	−0.4

The 3X case does not require the imposition of carbon taxes until 2020, at which time a $2 (24 Rs) per ton tax rate is required to stabilize carbon emissions at three times the 1990 level. Since taxes are not imposed until 2020, coal makes up 57% of total primary energy consumption, unlike the 1X and 2X cases where coal makes up 12% and 44%, respectively.

The imposition of these carbon taxes is reflected in energy prices. Table 13 presents the percent difference in energy prices between each of the tax cases and the reference case.

5.2. Impacts on GDP and consumption

In this analysis, no specific new energy-efficient technology options were introduced. Instead, any increase in energy efficiency in the production process is modeled as the result of general productivity growth. (Productivity growth assumptions are presented in Table 7.) Therefore, in all three carbon tax cases, most of the required emissions reductions must come from fuel switching or reduced energy use, both of which affect economic growth. Table 14 presents the percent difference between each of the tax cases and the reference case. As is expected, the large carbon tax rates in addition to the cumulative effects of the tax affect real GDP in the 1X case significantly as the percent difference reaches −6.3% by 2030.

In order to understand how the economy adjusts to the imposition of such taxes, it is important to separate cumulative effects from relative ones by looking at the *loss in growth* of GDP and consumption. In the 1X case, GDP growth is lower than the reference case in the beginning years, but the GDP growth rate picks up as the tax is built into investment decisions (by way of expected prices) in the later years. Growth in GDP falls again in 2030 when the economy's only option to reduce carbon emissions further is to reduce overall energy use which slows economic growth.

Losses in consumption growth were greater than losses in GDP growth even though the revenue collected from the carbon tax is recycled to consumers in the way of additions to personal income. This is due to reductions in production levels which lower the demand for labor, causing wages and the number of employees to decrease, thus causing total disposable personal income to fall. In addition, energy prices increase dramatically under the 1X case; most of these increases are passed on to consumers in the way of higher prices for consumer goods, lowering real consumption. The addition to personal income from the carbon tax revenue is not enough to offset this fall in total disposable income and increased prices for consumer goods.

Government expenditure is also a contributor to the larger loss in consumption growth than GDP growth (Fig. 11). This seems counter-intuitive, as less production

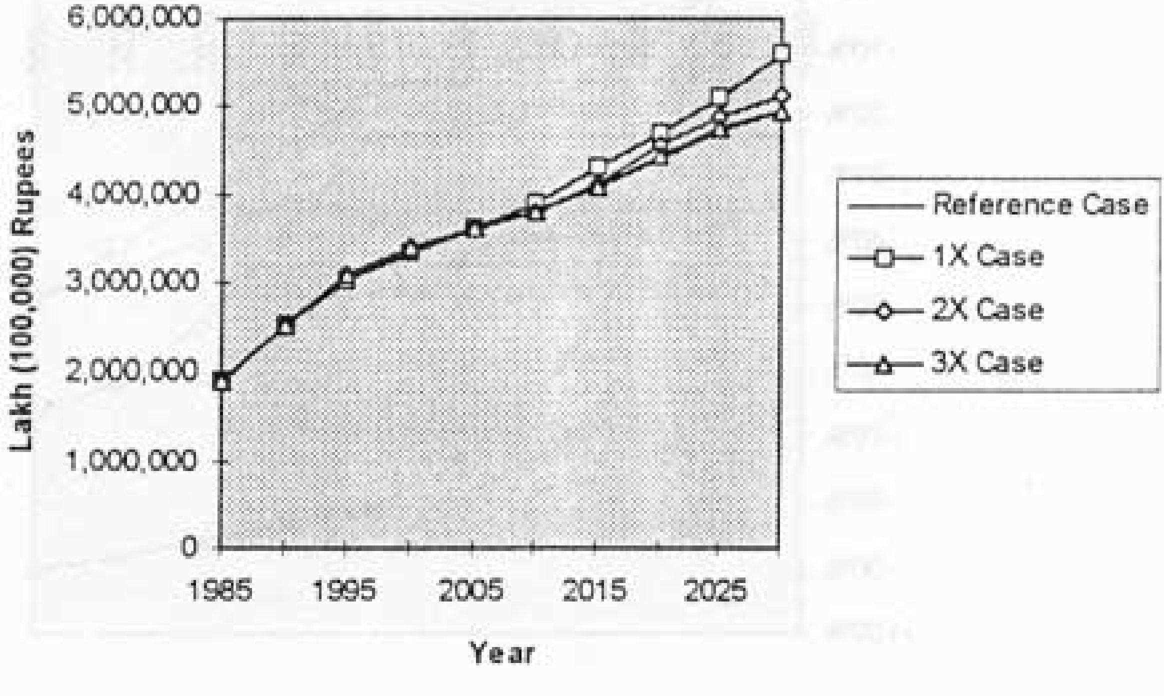

Fig. 11. Real government expenditures.

and less personal income means less tax revenue received by the government sector. However, higher energy prices and prices for goods in the other products sector results in lower *relative* prices for agricultural goods, land, and labor; all of which comprise approximately 70% of government expenditures in 1985. Therefore, although the government is spending less in nominal terms, the government is purchasing more in real terms because of reduced relative prices for agricultural goods, land, and labor.

The 2X case follows a different pattern with losses in GDP growth larger in the later periods. We see the losses increase in the later years because previous investments were unable to adjust to the imposition of carbon taxes as in the 1X case. Since the tax program begins later, start-up costs are delayed. The 3X case follows a similar pattern to the 2X case but shifted out three periods. Similar to the 1X case, real government expenditures are higher in both the 2X and 3X cases (Fig. 11) because of increased energy prices relative to other commodities.

5.3. Impacts on primary energy consumption

Results from the SGM show a dual effect on primary energy consumption resulting from the 1X carbon tax case—a reduction in total primary energy consumption and a shift to lower carbon emitting sources of energy such as nuclear power and renewables. With the imposition of carbon taxes in the 1X case, primary energy consumption in 2030 is 49% less than the reference case, while the consumption of coal is 90% less than the reference case (Fig. 12). This would indicate that the carbon taxes had a greater effect on shifting energy consumption from higher carbon emitting sources of energy to lower ones than reducing overall

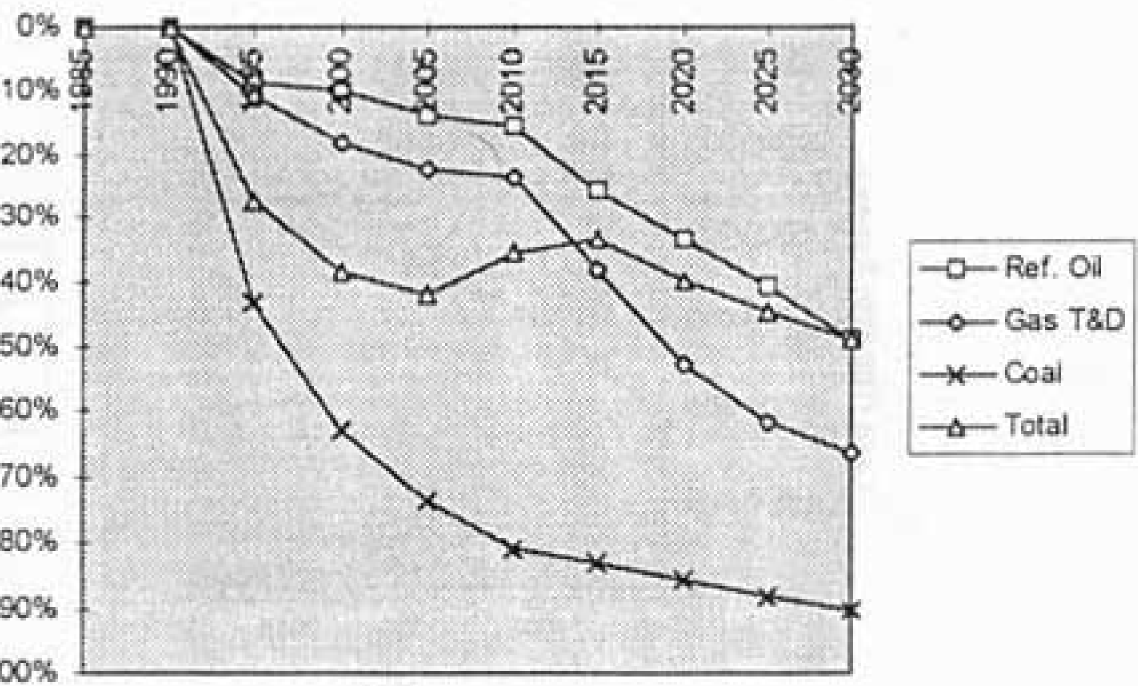

Fig. 12. Primary enery consumption—1X case.

Table 15
Electricity generation

Year	1X case		2X case		3X case		Reference case	
	Electricity generation (EJ)	% Change	Electricity generation (EJ)	% Change	Electricity generation (EJ)	% Change	Electricity generation (EJ)	% Change
1985	0.49		0.49		0.49		0.49	
1990	0.67	6.48	0.67	6.48	0.67	6.48	0.67	6.48
1995	0.74	2.00	0.92	6.46	0.92	6.46	0.92	6.46
2000	0.79	1.13	1.13	4.18	1.13	4.18	1.13	4.18
2005	0.85	1.65	1.28	2.61	1.34	3.46	1.34	3.46
2010	0.97	2.59	1.38	1.50	1.52	2.60	1.52	2.60
2015	1.22	4.74	1.44	0.88	1.65	1.70	1.65	1.70
2020	1.51	4.40	1.46	0.28	1.82	1.88	1.83	2.08
2025	1.72	2.57	1.46	0.10	1.92	1.17	2.00	1.76
2030	1.83	1.29	1.37	−1.28	1.98	0.61	2.14	1.33

energy consumption. This is most evident in the electricity sector where electricity generation grows steadily over the modeling period (Table 15) at an average annual growth rate of 3.0% compared with 3.3% in the reference case. Coal-fired, natural gas, and diesel generation, however, are completely phased out by 2015, replaced by nuclear power and electricity generation from renewables (e.g. hydro).

This shift in mode of generation does not occur in the 2X and 3X cases. Coal still plays a dominant role in electricity generation (Fig. 13). Interestingly, electricity generation in the 1X case exceeds that of the 2X case by the end of the modeling period (Table 15). In the 1X case, the tighter carbon emissions constraint, relative to the 2X case, leads to higher fossil fuel prices. This pushes fossil fuels out of the energy system. Because the electric power sector can dramatically reduce emissions by substituting nuclear power for fossil power at higher costs, electricity becomes an attractive substitute for fossil energy in the 1X case. Because the constraint is less binding in the 2X case, fossil energy costs never rise sufficiently high to drive out coal in favor of nuclear. This in turn means that the relative price of electricity does not improve significantly relative to fossil fuels, and electricity does not capture as great a share of the final energy market as in the 1X case (Table 16).

5.4. Impacts on energy resources

Domestic resources of oil are almost entirely depleted by 2015 in the reference case and all carbon tax cases. Since the SGM allows for unconstrained imports of crude oil at the world oil price, price is the only constraint on consumption.

This is not the case with domestic resources of natural gas, which are physically constrained. Although carbon taxes cause a shift to less carbon-intensive sources of energy, the price of natural gas is too high (due to the depletion of lower cost

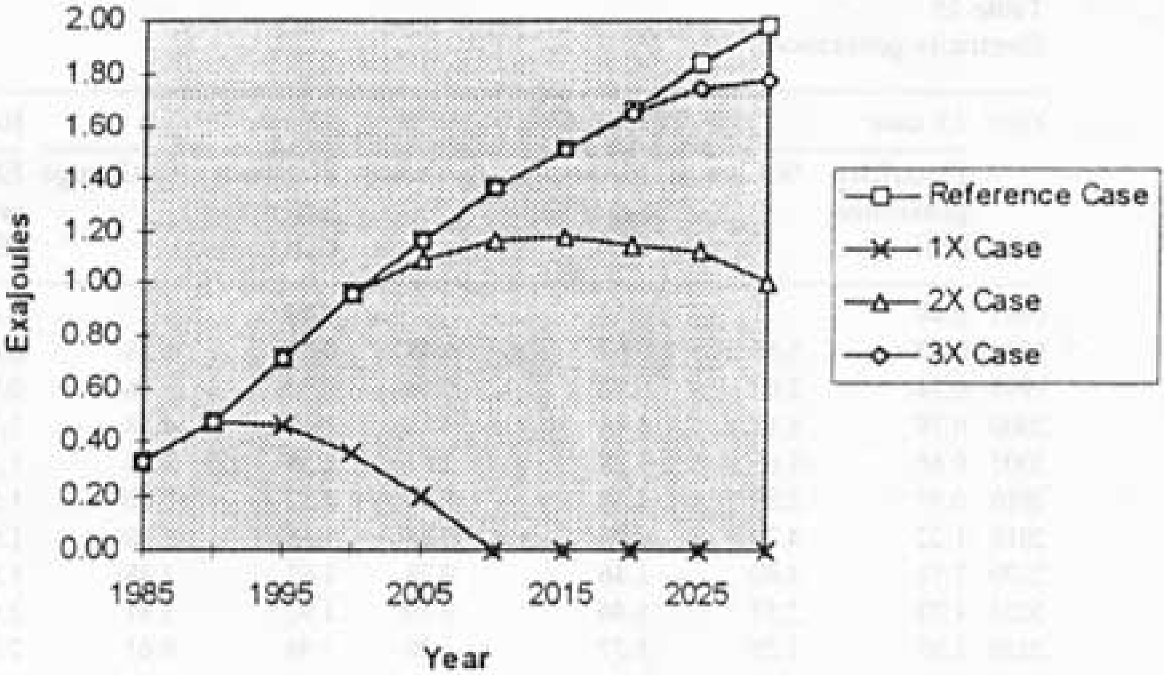

Fig. 13. Coal-fired electricity generation.

Table 16
Electricity generation as a percentage of the total energy market

Year	Reference case	1X case	2X case	3X case
1990	6	6	6	6
1995	6	6	6	6
2000	6	6	6	6
2005	7	7	7	7
2010	8	9	9	8
2015	8	10	9	8
2020	8	11	9	8
2025	7	12	9	8
2030	7	13	8	8

grades of natural gas) to create a shift to consumption of natural gas. Rather, other less carbon-intensive sources of energy are consumed such as nuclear power and renewables. In addition, carbon taxes reduce the overall consumption of energy. Because of this, domestic resources of natural gas are conserved with the imposition of carbon taxes. For instance, in the reference and 3X cases, the cheaper grades of natural gas deplete by the end of the modeling periods; this constitutes a constraint by 2020. In the 2X case, natural gas is not a constraint until 2025 and is not much of a constraint in the 1X case (Fig. 14).

5.5. Energy ratios

The disparity between methods of reductions in the three tax cases is also

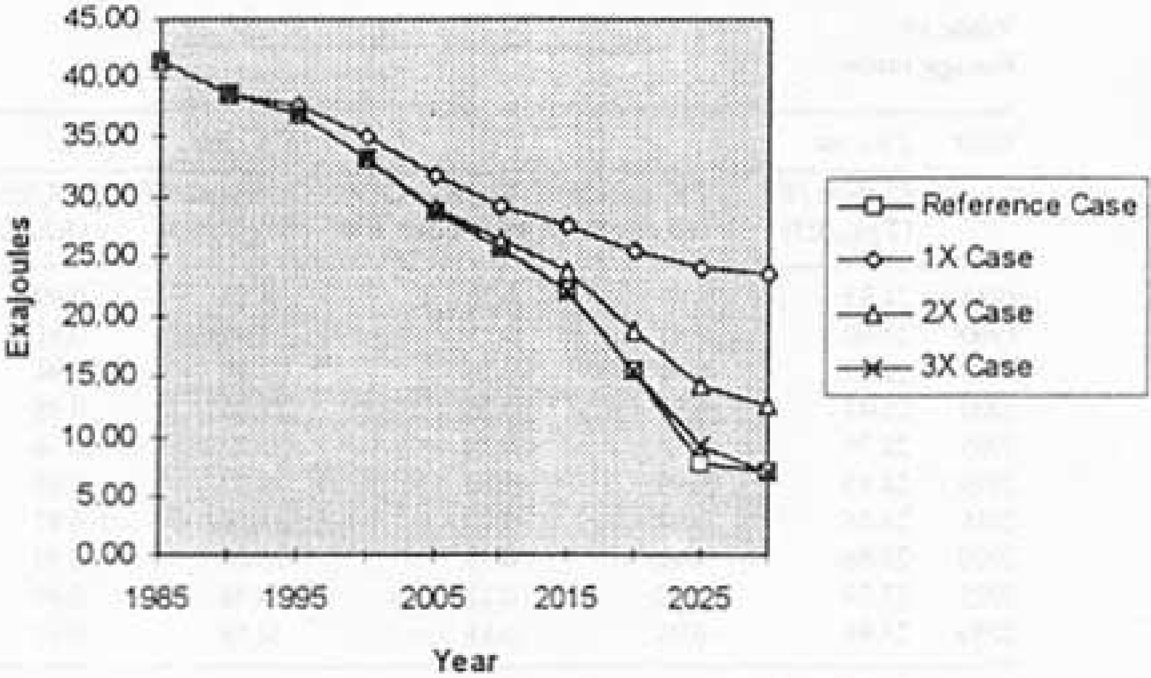

Fig. 14. Natural gas resources.

Table 17
Energy ratios

Year	1X case			Reference case		
	Carbon/FF(TgC/EJ)	FF/energy (EJ/EJ)	Energy/GDP (EJ/Lakh Rs)	Carbon/FF (TgC/EJ)	FF/energy (EJ/EJ)	Energy/GDP (EJ/Lakh Rs)
1985	24.82	0.89	0.26	24.82	0.89	0.26
1990	23.60	0.91	0.25	23.60	0.91	0.25
1995	22.99	0.90	0.19	24.09	0.94	0.26
2000	22.48	0.85	0.16	25.03	0.95	0.26
2005	22.03	0.76	0.15	25.23	0.96	0.25
2010	21.56	0.61	0.16	25.30	0.97	0.24
2015	22.53	0.53	0.15	25.28	0.97	0.22
2020	23.48	0.52	0.13	25.19	0.97	0.21
2025	24.54	0.49	0.12	25.17	0.98	0.20
2030	25.71	0.45	0.10	25.24	0.98	0.19

Note: FF = fossil fuel.

apparent when looking at the various ratios shown in Table 17. In the 1X case, most of the carbon emissions reductions in 1995 are attributed to a reduction in the ratio of energy to GDP which implies increased energy efficiency. This changes, however, by 2030 when most of the reductions in emissions are attributed to a fall in the use of fossil fuel energy.

This is reversed in the 2X and 3X cases where, throughout the modeling period, emissions reductions are attributed to increased energy efficiency or a decline in the ratio of energy to GDP (Table 18).

Table 18
Energy ratios

Year	2X case			3X case		
	Carbon/FF (TgC/EJ)	FF/energy (EJ/EJ)	Energy/GDP (EJ/Lakh Rs)	Carbon/FF (TgC/EJ)	FF/energy (EJ/EJ)	Energy/GDP (EJ/Lakh Rs)
1985	24.82	0.89	0.26	24.82	0.89	0.26
1990	23.60	0.91	0.25	23.60	0.91	0.25
1995	24.09	0.94	0.26	24.09	0.94	0.26
2000	25.03	0.95	0.26	25.03	0.95	0.26
2005	24.76	0.95	0.23	25.23	0.96	0.25
2010	24.49	0.95	0.19	25.30	0.97	0.24
2015	24.05	0.94	0.17	25.28	0.97	0.22
2020	23.86	0.93	0.15	25.10	0.97	0.20
2025	23.79	0.92	0.13	24.78	0.97	0.18
2030	23.94	0.91	0.11	24.58	0.97	0.16

Note: FF = fossil fuel.

6. Participation in possible protocols to reduce GHG emissions

Much international discussion has focused on the use of tradable permits to obtain global carbon stabilization. Such a policy scheme creates a pool of carbon emissions allowances that totals the global emissions target. Each country is given a share of this pool according to a predetermined allocation scheme (e.g. based on a country's share of global population, or historical emissions).[5] Each participating country must cover its total emissions with allowances. If a country chooses to emit more than its allocation, it must obtain allowances from another country's allocation. A country can sell excess allowances if it emits less than its allocation. With buying and selling of allowances, a market in allowances is assumed to form, similar to other financial markets (e.g. stocks, bonds, commodities).

Many believe that such a global policy scheme is the most cost-effective method to reduce carbon emissions globally, as countries with higher marginal costs to reduce emissions would be able to purchase allowances from countries with lower marginal costs. Also, depending upon the allocation scheme, such a policy mechanism would allow for wealth transfers which more closely represent each country's cost of participation in a global policy to reduce carbon emissions.

In this analysis, we have studied the effects of two allocation schemes on the Indian economy. Edmonds et al. (1992) have examined such mechanisms and have computed the market price of permits under a regime of stable global fossil fuel carbon emissions. We have adopted their time path of permit prices for this analysis. From Fig. 15, we see that the permit price trajectory to stabilize global carbon emissions closely tracks that of the 2X carbon tax case discussed previously. However, the global permit price trajectory is almost linear, while the 2X case is

[5] See, for example, Grubb (1992) for a discussion of various alternatives.

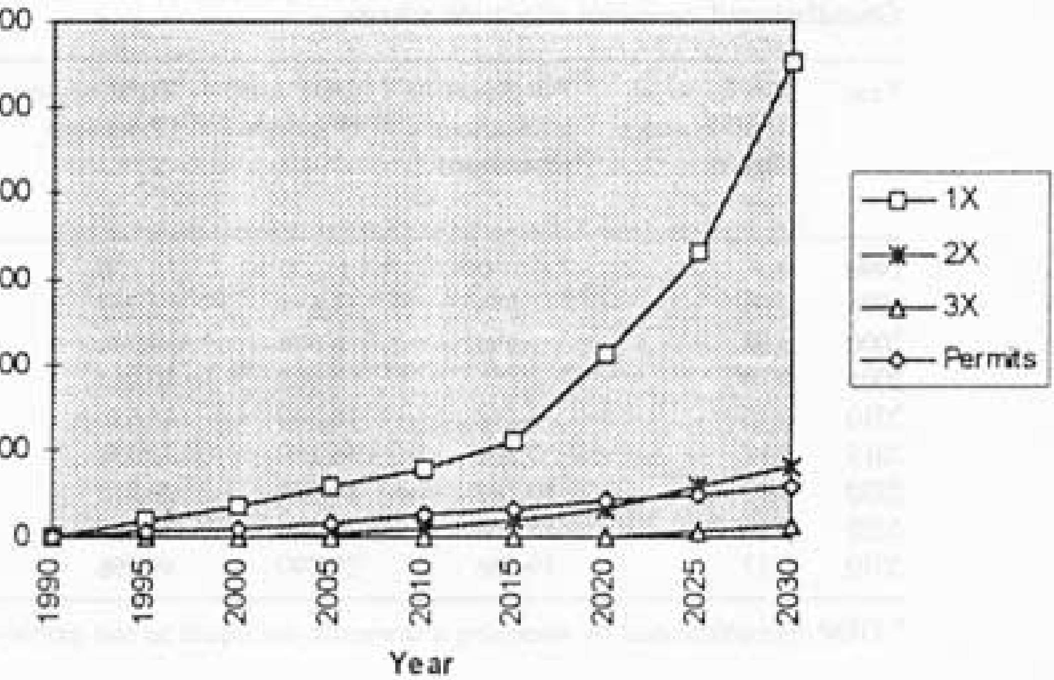

Fig. 15. Tax rates.

approximately exponential, reflecting the upward pressure on carbon emissions imposed by Indian economic growth.

The following two emissions allowance allocation schemes were studied:

1. Grandfathered emissions allocation: allowances are allocated based on each country's 1990 carbon emissions.
2. Equal per capita emissions allocation: allowances are allocated based on each country's share of global population in the current period.

We model the tradable permits system as a central government program which sells permits to emitters at the market price. In effect the government imposes a domestic carbon tax. Revenues are assumed to be recycled to the household sector as in the carbon tax cases. The government retains any net revenue gains and absorbs any net revenue shortfalls.

Allowances are usable only in the year they are allocated. Countries cannot save allowances or borrow against future allocations.

6.1. Tradable permits with grandfathered emissions allocations

Table 19 presents the results of a tradable permits market under the grandfathered emissions allocation scheme. Due to India's rapid future economic growth, India is a net *buyer* of carbon allowances. Combining the net external transfer of wealth from allowance purchases with the GDP loss resulting from imposing the global stabilization tax rate trajectory (which represents the opportunity cost of using its allocation of allowances), we obtain the total loss to India's economy from

Table 19
Grandfathered emissions allocation scheme

Year	Net buyer of of allowances (PgC)	Purchases of allowances ($ million)	GDP loss[a] ($ million)	Total net loss ($ million)	Stabilization tax case GDP GDP loss ($ million)	Trading benefit ($ million)
1990	0	0	0	0	0	0
1995	0.05	576	1,691	2,267	5,969	3,702
2000	0.08	1,693	5,548	7,241	15,847	8,606
2005	0.10	3,378	7,585	10,963	25,745	14,781
2010	0.10	5,218	10,362	15,580	24,508	8,929
2015	0.11	7,200	16,150	23,350	33,464	10,113
2020	0.12	10,182	19,535	29,717	37,907	8,190
2025	0.16	15,853	20,314	36,167	49,850	13,683
2030	0.17	19,806	29,790	49,596	71,767	22,171

[a] GDP loss calculated by imposing a domestic tax equal to the global carbon permit price.

its participation in a global tradable permits market with a grandfathered emissions allocation scheme (Table 19).

The grandfathered emissions allocation scheme is essentially India's stabilization case with the option to purchase emissions allowances from other countries (which may have the ability to reduce emissions at a lower cost) in a global market for allowances. Therefore, comparing the GDP loss from the previously discussed 1X stabilization carbon tax case with this tradable permits case allows us to weigh the benefits to India of a global allowance trading market. As shown in Table 19, the benefits from tradable permits start at $3.7 billion in 1995 and grow to $22.2 billion by 2030.

6.2. *Tradable permits with equal per capita emissions allocations*

Table 20 presents results from a global tradable permits market with an equal per capita emissions allocation scheme. With this allocation scheme, India is a net *seller* of allowances because of its relatively large population and low carbon emissions. India benefits tremendously from the sale of excess allowances; these benefits more than outweigh the GDP loss from the imposition of a global carbon tax (i.e. opportunity cost of an allowance), resulting in a total net gain of $5.6 billion in 1995 and reaching $56.9 billion in 2030.

The sale of allowances can be interpreted as the wealth transfers from high per capita emissions countries (such as the US) to low per capita emissions countries (such as India) under such a global carbon stabilization policy. (The grandfathered emissions allocation scheme, in contrast, transfers wealth out of India.)

The GDP loss computed for the domestic tax based on the global permit price represents the compensation India needs to be indifferent to participation in a global carbon stabilization agreement. This amount implies an allocation of trad-

Table 20
Equal per capita emissions allocation scheme

Year	Net seller of allowances (PgC)	Sale of allowances ($ million)	GDP loss from global tax ($ million)	Total net loss ($ million)	Stabilization tax case GDP loss ($ million)	Trading benefit ($ million)
1990	0	0	0	0	0	0
1995	0.674	7,323	1,691	5,632	5,969	11,601
2000	0.673	15,183	5,548	9,635	15,847	25,482
2005	0.674	22,534	7,585	14,948	25,745	40,693
2010	0.713	35,748	10,362	25,386	24,508	49,895
2015	0.742	48,997	16,150	32,847	33,464	66,311
2020	0.757	62,650	19,535	43,115	37,907	81,022
2025	0.732	73,441	20,314	53,127	49,850	102,977
2030	0.735	86,695	29,790	56,905	71,767	128,673

able permits that lies somewhere between that implied by a grandfathered emissions allocation and an equal per capita emissions program.

In conclusion, India is better off participating in a global tradable permits market to stabilize global carbon emissions using either allocation scheme than if it attempted to stabilize emissions in isolation using a national carbon tax policy. Under an equal per capita emissions allocation scheme, India would not be hurt economically if it participated in a global tradable permits market. India would be adversely affected under a grandfathered emissions allocation scheme, but not as dramatically as the 1X carbon tax case which does not include an allowance market.

7. Conclusions

Our analysis shows that stabilization of fossil fuel carbon emissions by India at 1990 levels, via a domestic carbon tax and without joint implementation measures, would imply major changes in the Indian energy system. First, it requires Indian per capita emissions, already well below the global average emissions rate of 1 tC/person/year, to fall from 0.25 tC/person/year to 0.13 tC/person/year over the next 40 years. This would only be possible if, in addition to major energy conservation measures, energy supply rapidly shifted from a coal-based to a nuclear and solar-based system.

India's participation in a global tradable permits market using either of the allocation options examined is more cost effective than independently imposed carbon taxes for the purpose of stabilizing carbon emissions. Under an equal per capita emissions allocation scheme, India would benefit absolutely from participation in a global tradable permits market, but Indian economic growth would be slowed under a grandfathered emissions allocation scheme.

Without major contributions of advanced technologies from developed economies, India could stabilize carbon emissions at two or three times the 1990 levels. Either option would result in substantial reductions in carbon emissions while avoiding drastic negative affects on the economy.

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Appendix A: Model description

In this appendix we provide a brief overview of the model and its numerical embodiment of the Indian economy. The theoretical structure of SGM version 0.0 is described in detail in Edmonds et al. (1993). The development of estimates for parameters is documented in Fisher-Vanden et al. (1993).

A.1. Origins

The SGM's intellectual roots can be traced to the modeling work of Edmonds, Reilly, and Barns, who developed and exercised the Edmonds–Reilly–Barns model of long-term global energy and GHG emissions (Edmonds and Reilly, 1985, 1986; Edmonds and Barns, 1991). This model (a member of the first generation of models) focused on emissions of energy-related GHGs. The model was simple and transparent, but had long time steps, did not consider non-energy-related GHG emissions and sinks, and completely neglected impacts on human systems from global change. The SGM is structured to provide both increased scope (including both energy- and non-energy-related emissions activities and a framework designed to assess impacts of global change on human activities), and finer resolution of human activities (including a five-year time step, enhanced technology descriptions, and an integrated demographic module).

The analysis reported here uses SGM version 0.0. The SGM representing the Indian economy will be integrated with 16 other regional SGMs currently being developed for a global implementation of the SGM. In this exercise, however, only the SGM for India is used.

A.2. Overview of SGM version 0.0

In summary, the SGM is a member of the CGE class of models. The SGM version 0.0 has nine producing sectors:

1. agriculture;
2. crude oil;
3. natural gas production;
4. coal production;
5. uranium production and refinement;
6. electric power generation;
7. oil refining;
8. natural gas transformation and distribution;
9. other production.

We note that seven of the nine sectors of the economy in SGM version 0.0 are energy sectors. The emphasis on the energy sector in SGM version 0.0 reflects the central role energy plays in the determination of emissions of GHGs to the atmosphere.

In addition to the producing sectors of the SGM, there are four final demand sectors:

1. households;
2. government;
3. investment;
4. net export.

Producing sectors use goods and services produced by other producing sectors, itself, and primary factors of production to produce net output. The three primary factors of production are:

1. land;
2. labor;
3. capital.

There is a market, which is cleared by the price mechanism, for each producing sector of the economy. Similarly, there is a market for each of these three primary factors of production.

The interactions of the main components of the SGM are shown in Fig. 16, where the seven energy sectors are included in the energy box. In general energy, agricultural, and other production sectors supply net quantities of goods and services for each other and for final consumption by households, the government, investment, and net exports. Primary factors of production—land, labor, and capital—are also used by the producing sectors. Labor and land are assumed to be owned by members of the household sector who supply them to the market. Capital is associated with producing sectors. Net profits are returned to the household sector, while taxes are collected from producers and households and provide the revenues for local, regional, and national governments.

Producing sectors are assumed to make decisions regarding production and investment with the objective of maximizing expected wealth. Governments are assumed to produce government services, including education, national defense, and general services, according to prescribed production functions. Households

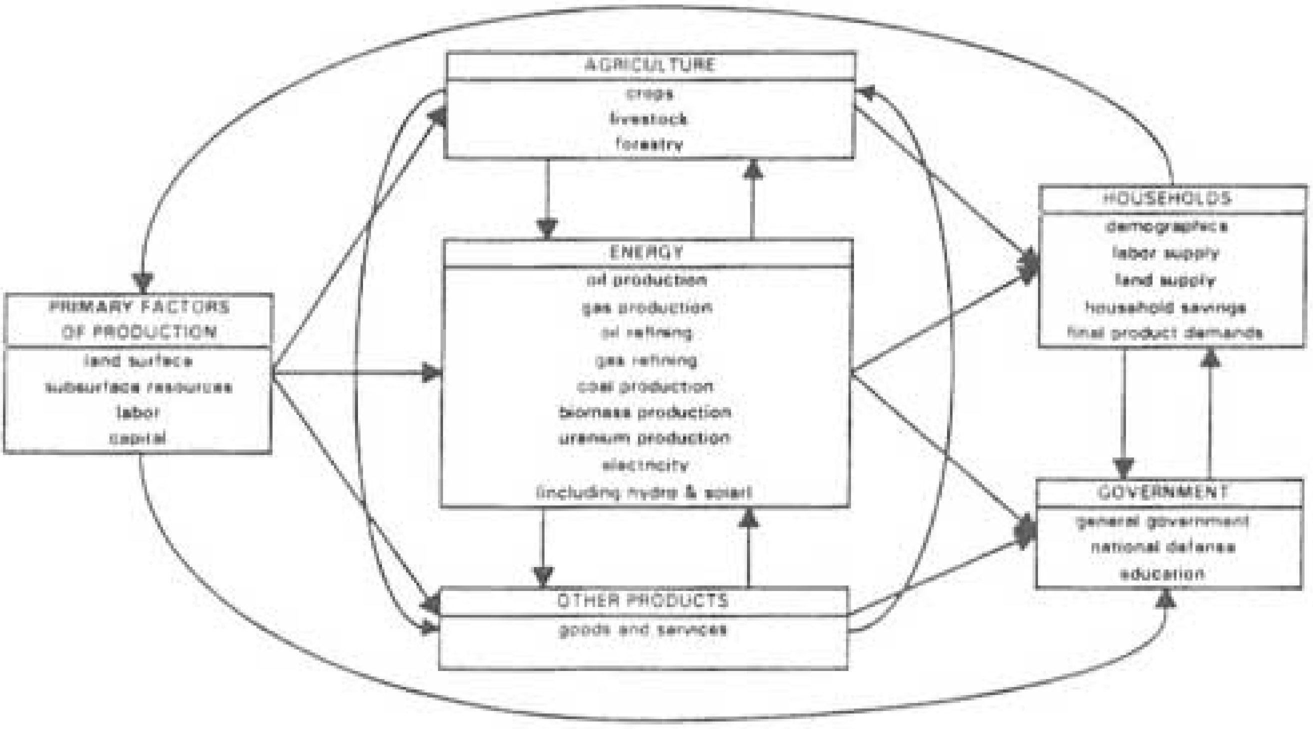

Fig. 16. The flow of goods and services in the SGM.

behave as if they are maximizing utility with regard to the allocation of resources to current consumption; however, the supply of savings and labor is modeled by exogenously specified rules.

All produced goods and services, and primary factors of production pass through markets which are assumed to clear in every period via a price mechanism. Estimates of gaseous emissions are computed in the model via the application of emissions coefficients to inputs and outputs of processes. Variation in these coefficients reflect variation in the emissions characteristics of alternative human activities.

In the remainder of this appendix, we will briefly highlight some of the more salient features of the SGM.

A.3. Subsectors and technologies

Within the nine producing sectors of SGM version 0.0, several sectors have subsectors and technologies defined. Each subsector, defined for a specific sector, is assumed to produce a homogeneous good which becomes part of the total production of the sector. For example, the electric power generating sector has six subsectors defined: oil (diesel), gas, coal, biomass, nuclear, and hydro. Subsectors defined for the SGM version 0.0 are shown in Table 21.

Just as sectors can have subsectors, subsectors can have technologies. Technologies are alternative modes for producing the product of the subsector. For example, there may be two technologies for producing electricity with natural gas (a subsector of electric power generation): conventional combustion, and combined

Table 21
Subsectors in SGM version 0.0

Producing sector	Number of subsectors	Description of subsectors
1. Agriculture	1	Agriculture
2. Crude oil production	1	Crude oil is treated as a depletable resource consisting of one grade.
3. Natural gas production	5	Natural gas is treated as a depletable resource with five grades modeled as subsectors.
4. Coal production	5	Coal is treated as a depletable resource with five grades modeled as subsectors.
5. Uranium production and refinement	1	Uranium is treated as a depletable resource consisting of one grade.
6. Electric power generation	6	Power generation by mode is defined for oil (diesel), gas, coal, biomass, nuclear, and hydro.
7. Oil refining	1	Conventional oil refining.
8. Natural gas transformation	1	Natural gas transformation and distribution is defined for natural gas.
9. Other production	1	Other production

cycle combustion. Although in this exercise an average technology in 1985 is assumed, the framework of the model is sufficiently flexible to allow an arbitrary number of technologies to compete.

A.4. Natural resources

Natural resources are treated explicitly in the SGM, which identifies two forms: depletable and renewable. Depletable resources are consumed in use, for example, fossil fuels. Renewable resources are not consumed in use, for example, land. This distinction is important to the treatment of energy production and transformation, as well as agricultural activities.

Fossil fuels and uranium are treated as depletable natural resources. They are divided into two categories, resources and reserves. Reserves are those energy sources whose location is known, which are producible using present technologies under present and anticipated economic conditions, and which investment for extraction purposes has been made. (Some crude oil, discovered conventional, and some Alaskan oil are examples of crude oil reserves.) Resources include all energy sources, including those which are known by location and those whose existence is inferred, those which are producible under present technologies and economic conditions, and those which may require greater incentives to exploit. Total resources include reserves. (In the SGM, reserves are created as economically recoverable resources are discovered.) In the SGM, energy production from depletable natural resources occurs only from reserves. The rate of production from reserves depends on the amount of productive capacity put in place with discovery, and prices of inputs and outputs.

Biomass and hydroelectric power are renewable resources. Biomass feedstocks are treated as a component of the agricultural production. Total domestic production is therefore constrained both by the total available arable land, and the competition for the use of that land for other purposes. Biomass feedstocks are either transformed to liquids or gases, or consumed as a solid by electric utilities. Electric utilities also consume hydro power. Hydro power capacity is fixed for the purposes of this analysis.

Land is modeled as a separate factor of production. The identification of land reflects its potential importance as a constraint in emissions reduction strategies which utilize biomass or carbon sequestration by trees.

A.5. Expectations, capital formation, and productivity

In the SGM, the demand for capital by producing sectors depends on expected profits. Expectations of profits in turn depends on both the technology which describes the relationship between inputs and outputs, and expected prices over time, for inputs and outputs, including capital. The SGM provides a variety of options for describing the formation of price (and tax/subsidy) expectations, including assumptions that

1. prices will remain at current levels over the expected life of the equipment (assumed in this exercise);
2. prices will change at rates which reflect behavior over a prior period of experience; and
3. price expectations are exogenously specified (which can be used to generate a rational expectations price path).

The last capability can be used to explore behavior when future prices are known. We note also that different combinations of expectation formation for market prices and taxes/subsidies can be constructed. Thus, the formulation of price expectations is not restricted to the assumption of perfect knowledge about future events.

Sectors and subsectors with the highest expected profits experience the greatest realized investments, although within a sector a logit function distributes investment resources across all subsectors which are economically attractive. Investment opportunities which have zero or negative expected contributions to wealth (after allowing for taxes and subsidies) receive no investment funds. The inclusion of subsidies in the expected contribution to wealth calculation is important.

The SGM uses a putty-clay specification of capital. That is, once an investment occurs, capital is permanently associated with that particular application. Thereafter, capital does not move from one sector to another. This is a particularly useful assumption for modeling energy applications where capital investments are highly specialized. It is also not particularly restrictive to the rest of the economy, which is modeled as a single aggregate sector.

Using a vintage approach to modeling capital also means that capital investments become a fixed cost of production. Thus, existing vintages continue to

Table 22
Data sources for SGM version 0.0 calibration to 1985 Indian economy

Data type	Data source	Use
1985 Input–output table	Central Statistical Organization (1989)	Provide statistics for flows between different economic activities in 1985.
1985 Energy flows	Centre for Monitoring Indian Economy (1990)	Provide benchmark flows of energy throughout the economy for 1985.
Investment patterns 1959–1985	Centre for Monitoring Indian Economy (1992b)	Provides pattern of capital accumulation by sector.
Resource and reserve estimates	Centre for Monitoring Indian Economy (1992b)	Provide total resource constraints on fossil fuels and uranium, distinguish between reserves and resources, provide a basis for allocation of reserves and resources to economic grades.
Demographic profile	United Nations (1990)	Estimate fertility, survival rates, and net immigration in the demographic module.
Land	Centre for Monitoring Indian Economy (1992b)	Estimate payments to land by sector of the economy.
Emissions	WRI (1992)	Provide estimates of emissions fluxes by human activity.

operate as long as they can cover their operating expenses, even if the rate of profit differs from that anticipated at the time the original investment was made. We note here that other factors of production are not fixed; they can be varied to either expand or contract output from an existing facility. Other factors of production also move freely among alternative applications.

Because a production function is associated with each capital investment by application, factor productivity can be manifest as both embodied and disembodied changes in input requirements. That is, combustion efficiencies may be embodied in the physical plant and vary depending upon the date of installation. On the other hand, agricultural productivities may be weakly associated with capital stocks, and more closely associated with changing management practices and seedstocks. The SGM can represent both types of productivity change.

A.6. Demographics

Estimates of population and its structure are developed within the SGM by a demographic module. The SGM is therefore capable of creating an array of internally consistent estimates of population and critical details such as the associated size of the work age population disaggregated by gender. The SGM demographic module builds population estimates from assumptions about age-specific fertility rates, survival rates, and net immigration rates.

A.7. Emissions

The SGM was explicitly designed to provide estimates of gaseous emissions from all human activities, including those associated with energy, agriculture, and industrial processes. Not only does the model yield estimates for carbon emissions, but it also tracks emissions of CO, CH_4, volatile organic compounds (VOCs), N_2O, NO_x, and SO_2. These emissions are associated with specific human activities, and where appropriate, with specific technologies.

A.8. Data sources and calibration

Parameters for the Indian module of the SGM are derived so as to be consistent with the behavior of the Indian economy in 1985, investment behavior over the prior 26 years, and physical flows of energy resources in 1985, as well as the distribution of resources and reserves in that year, the demographic structure of the Indian population, and emissions rates by human activity in 1985.

A variety of statistical information was used to develop calibration parameter estimates for the SGM. Table 22 contains a summary of these data, their sources, and an indication of their use.

The methods used to transform data into model parameters are documented in detail in Fisher-Vanden et al. (1993).

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