Energy Security, Climate Change and Sustainable Development
Edited by Jyotirmay Mathur, H.-J. Wagner and N.K. Bansal

Economic Impact of Carbon Emission Restrictions: The Case of India

Jyoti Parikh[1] and Chandra Kiran B. Krishnamurthy[2]
[1]Integrated Research and Action for Development (IRADe), C-50
Asian Games Village Complex, Khelgaon, New Delhi - 110 049, India
[2]School of International and Public Affairs, Columbia University, New York 10027, USA

Abstract: This article – an extension of Murthy et al. (1997) – examines the consequences of various carbon emission mitigation measures on economic development and, in particular, the implications for the poor by empirically implementing an economy-wide model for India over a 35-year time period. A multi-sectoral, inter-temporal model in the activity analysis framework is used for this purpose. The results indicate that carbon dioxide (CO_2) emission reduction imposes costs in terms of lower Gross Domestic Product (GDP) and higher poverty. In fact, the effects of environmental constraints are found to be virtually equivalent to a major oil shock, lending credence to the belief that constraining carbon emissions of developing countries without providing adequate compensation imposes large costs on these economies and denies them access to legitimate avenues of development. In addition, the effect of increased population growth rates on the carbon emission profile is found to be not as large as surmised. Finally, the parameter sensitivity of non-linear predictive models, of the type used here, is brought out, pointing out to the fact that generic models, of the type used extensively in literature, may not quite provide the results that reflect the conditions obtained in the developing economies.

Introduction

The contribution of the developing countries to the climate change problem has been historically small and their per capita emission of carbon dioxide (CO_2) is significantly lower than those in the developed world (Parikh et al., 1991). But, some of them are expected to significantly increase their emissions in the next couple of decades (WRI, 1996). China and India account for 21 and 16% of the current world population, respectively, and will need special attention in the future for the success of any global CO_2 emission reduction strategy. The developed countries might also find CO_2 abatement in the developing countries to be less costly compared to their own domestic costs of mitigation. For the developing countries, the developed nations may be seen as a source of financial and technological resources to help control CO_2 emissions without detracting from their developmental objectives. The developed countries – Annexure I countries in the Kyoto Protocol Parlance – have been assigned the task of mitigating their emissions to below that obtained in 1990 (in the Kyoto Protocol), the actual level varying by countries/regions, and that too by 2012. However, the progress has been mixed with some countries being already well on the way to achieving their targets while others lagging behind. In fact, the emissions of certain countries, such as Australia and the United States of America (USA), display a rising trend. Simultaneously, pressure is mounting on the developing countries, especially the larger ones like India, China and Brazil, to accept certain binding commitments to reduce their rising carbon emissions. But, many countries point to the projected increases in population and economic well-being as indicative of proportional rises in carbon emissions. China is already the world's second largest carbon emitter, after USA. The developing countries have resisted all efforts to apportion to them some of the responsibilities of the developed countries pointing out, rightly so, that the cause of the problem is excessive pollution by the now-developed countries over a long period of time and that, furthermore, the developing countries have priority aims – poverty alleviation and increased access to commercial energy sources – that, by definition, would entail an increase of energy consumption and, hence, carbon emissions. These aims, in fact, are universal and their fulfilment can brook no delay, a fact recognised by the United Nations Framework Convention on Climate Change (UNFCCC) and embodied as the "common but differentiated responsibilities" assigned to the developed and developing countries.

Much of the perceived rise in emissions of the developing countries is attributed to their rising populations, increasing urbanisation and economic well-being. The projections are made to point out that these countries might become among the largest emitters of carbon after another 25 years. Hence, it is argued that before they become as large a problem as the currently developed countries, the developing countries must take measures to ensure that their emissions do not rise by as much as projected. But, it is not realised or considered significant that these measures might constrain the economies of developing nations, causing large welfare losses.

The following questions are addressed here:

- Do carbon emissions rise drastically with population increase, for various projections of population increases?
- Do carbon emission restrictions have any impact on welfare, with GDP and consumption (per capita) as the metric by which welfare is captured?
- How sensitive are non-linear predictive models to parameters?

The framework of the multi-period activity analysis model, its specific features, several sets of model results, the issue of parameter sensitivity and policy implications of results are also discussed The equations used to formulate the model are given in the Appendix.

A Review of the Modelling Efforts with Reference to India

Models that assess economic impact of climate change in the literature can be classified as bottom-up, top-down and integrated. The bottom-up models bring technological knowledge and specificity. However, often techno-economic evaluations are incomplete and overtly optimistic in that policy and institutional obstacles are not fully accounted for. Top-down models bring macro-consistency. Among them are econometric models which use reduced form equations and the implied policies behind them remain unclear. Another approach of top-down modelling is the computable general equilibrium (CGE) approach where a sequence of single period equilibria are worked out. In econometric and CGE models, often a high substitution elasticity is assumed, which makes it easy and relatively costless to adjust to CO_2 constraints. The problem is, thus, assumed away. An activity analysis approach permits macro-consistency, truly dynamic behaviour, new and specific technological options and, thus, limited substitution. It can constitute a truly intregrated top-down-bottom-up approach.

A few modeling studies have explored India's options. Blitzer et al. (1992a, b), in a multi-sectoral, inter-temporal activity analysis framework, are primarily concerned with examining the impacts of restrictions on emissions of CO_2 and other greenhouse gases on India's and Egypt's economic growth. They also examine cost-effectiveness of different measures for improving energy efficiency in reducing CO_2 emissions. Their analysis of the trade-off between economic and environmental performances focuses on aggregate welfare measures like the GDP or total consumption of the society as a whole. Shukla (1996) uses two models: the bottom-up MARKAL (Berger et al., 1987), which is an energy system model suitable for techno-economic analysis given exogenously specified sectoral growth rates, and the top-down Second Generation Model (SGM) with endogenous macro variables such as growth rate. The Indian component of SGM has been used to explore CO_2 policy options for India (Shukla, 1996; Fisher-Vanden et al., 1997). Gupta and Hall (1996) have tried to use a simple econometric macro-model as a top-down model to integrate the technological options identified by techno-economic assessment of various technical options for carbon abatement.

The Model Structure

The model, an extension of Murthy et al. (1997), is a multi-sectoral, inter-temporal dynamic optimisation activity analysis. It permits exploration of alternative technologies and CO_2 strategies from a long-term dynamic perspective. Alternative activities representing different technologies permit substitution and incorporate non-linearities in this model. It maximises a social welfare function given as the present discounted value of utility streams corresponding to per capita consumption of an average consumer, given the available resources and the various technological possibilities for using them. The time horizon is taken to be 35 years in this model.

The whole economy is represented as consisting of eight commodities/goods, some of which can be produced in more than one way. In particular, electricity can be produced by coal, oil, gas – combined cycle gas turbine (CCGT) – and other sources like hydro and nuclear. The focus is on specific options on the power generation and the transportation sectors as large amount of India's CO_2 emissions occur in these sectors and policy options here need to be clearly understood. Industrial output can be produced by two alternative activities that use coal-boiler and oil-boiler. Technical progress and energy efficiency gains over time are prescribed exogenously. These remain the same across all scenarios. Income distribution is endogenous and depends on the total consumption, exogenously projected total population and specified Lorenz ratio. Thus, population belonging to each consumption expenditure class is determined in the model. The composition of aggregate consumption, therefore, changes non-linearly as the economy grows and people move from one income class to another. In each class, 15 alternative consumption bundles are provided to represent, approximately, the indifference curve of the class, which permits substitution across commodities as relative prices change. The bottom class corresponds to those below the poverty line so that we also get an indication of the number of poor in each period.

Various constraints, such as those on domestic oil and gas production and capital constraints are imposed to keep the model and its results realistic. On the trade side, a balance of payment constraint is imposed. There is a wedge between export and import prices to reflect international trade and transport margins. Restrictions are imposed on export and import growth rates by sectors to keep the model and its results, realistic. Import of agricultural commodities is restricted to reflect a self-sufficiency requirement. Table 1 gives the values of the bounds. A

Table 1

Parameter sensitivity	BAU	% Change over BAU	
		Oil shock-FT lower	ICOR falling
GDP (Rs. billion)			
Year 15	26969.00	– 7.13	15.20
Year 25	46980.00	– 11.15	34.28
Year 30	6599.00	– 12.57	46.31
Per capita consumption (Rs.)			
Year 15	17301.00	– 9.75	15.29
Year 25	23851.00	– 16.61	36.61
Year 30	30205.12	– 19.67	50.28
Number of poor (millions)			
Year 15	62.30	32.76	– 94.83
Year 25	26.96	80.95	– 98.75
Year 30	13.57	122.22	– 99.55
Cumulative emission (million tonnes)			
Year 15	12488.00	– 6.57	9.97
Year 25	26419.00	– 10.38	23.68
Year 30	37007.73	12.19	– 34.00
Selected activity levels (Rs. billion)			
Electricity (Year 15)	1532.00	– 100.00	21.08
Coal (Year 15)	1546.00	– 3.10	6.08
Oil (Year 15)	847.00	0.00	0.00
Electricity (Year 25)	2510.00	– 100.00	48.76
Coal (Year 25)	2120.00	– 5.33	17.45
Oil (Year 25)	1033.00	– 2.90	0.00
Oil imports (Rs. billion)			
Year 15	218.00	– 77.52	77.52
Year 25	619.00	– 83.00	103.07

FT: foreign trade; ICOR: incremental capital-output ratio.

savings constraint is imposed to restrict marginal savings rate to 30%. Finally, though the model is run for a period of 35 years, the post-terminal future has to be taken care of. It is done by postulating a stationary state in the future with the composition of output, consumption, investment etc., fixed and growing at a prescribed rate.

The model is solved using the GAMS programming tool developed by Brooke et al. (1988). For endogenous income distribution consistency, we iterate over optimal solutions changing distribution parameters between iterations till they converge. More details on the model may be found in Murthy et al. (1997).

Emissions Inventory

The emissions from the production sectors are computed by considering the scalar product of the activity vector and the emission coefficient vector that indicates the amount of emissions per unit level of activity. The emission coefficient for an activity is derived by considering the fuel specific emission coefficient and the fuel input coefficient. Apart from the production activities, emissions are also caused by the private and public consumption of fuels like kerosene, liquefied petroleum gas (LPG) and motor gasoline, which are accounted for by considering the emission coefficients attached to each consumption activity. The cumulative emission of CO_2 at the end of any period is computed by adding the emission flows during the current period to the cumulative emissions carried over from the previous period.

Carbon Reduction Options

In the model, CO_2 emissions can be reduced in a number of ways. The first method involves reducing the levels of different activities, as it directly reduces income and consumption and, hence, results in a loss in the social welfare. The second method is to change the composition of production in the economy in favour of less CO_2-intensive activities. This can be done either by changing the structure of trade so that the more CO_2-intensive products are imported or the structure of consumption and other final demand may be changed by reducing the budget share of CO_2-intensive goods in total final demand. This leads to an indirect loss of current welfare as the investor and consumer choices get distorted.

In addition, technological options that reduce emissions without any significant loss of output are also available for reducing the CO_2 intensity of activity levels. Essentially, the two types of such options are as follows:

(a) Reducing the amount of CO_2 emitting energy inputs required by different activities. Additional investment may be required to install equipment that can operate these processes at higher energy efficiency.
(b) Switching to less carbon intensive fuels.

The Scenarios and Data

Since the objective is to evaluate the impact of carbon emission restrictions on the Indian economy, specifically on the welfare losses that might be incurred, the scenarios also correspond to restrictions on carbon emissions. The types of restrictions considered herein are cumulative. Another objective is to investigate the relationship between population growth variations (increases) and increases in carbon emissions, which is an important issue. The model is run with various population growth scenarios and the results are compared with the BAU and carbon emission restriction scenarios, given as follows:

Business as Usual (BAU)

There are no restrictions on the economy. Both income and consumption are determined endogenously.

Carbon Emission Restriction of 10% (C10)

The carbon emissions of the economy are constrained to 10% less than that of the BAU scenario, with income and consumption determined endogenously.

Carbon Emission Restriction of 20% (C20)

The carbon emissions of the economy are constrained to 20% less than that of the BAU scenario, with income and consumption determined endogenously.

Population Growth Scenarios (PG1, PG2 and PG3)

These scenarios investigate the effect of population growth rate falling at 0.0327, 0.0297 and 0.0024% times the time period, respectively, from 1.8%.

Oil Shock Scenario

The economy is assumed to suffer from an oil shock in the base year of 300%, i.e. the price of oil is taken to rise three-fold in the base year and to remain the same throughout, in real terms. This scenario is considered significant in the model for two reasons: Firstly, it serves as a metric to compare the results for the carbon emission constraint and population growth scenarios and, secondly, it allows one to investigate the effect of a significant shift, albeit price-induced as opposed to policy induced, away from oil based energy sources. Although, it must be noted, nothing in the model prevents the economy from shifting to a more intensive usage of coal – a more polluting fuel.

Data

The model has been empirically implemented by using recent data for India to estimate the various parameters. The initial values of different variables included in the model structure have been discussed earlier. Input-output coefficients and capital-output ratios for various activities form the core of the model. This data is available from published sources for most sectors (Parikh et al., 1995). Future projections of government consumption levels as well as the upper and lower bounds for exports and imports (where relevant) are specified in terms of growth rates.

The base year for the model is 1996-97 and all monetary values are in terms of the value of Rupee in 1996-97.

Results of the Model Runs

Table 2 shows the values of some important macroeconomic variables and alternative activity levels for selected years for BAU scenario and various scenarios involving

Table 2

Scenarios for carbon emission reductions	BAU	% Change over BAU		
		C10	C20	Oil shock
GDP (Rs. billion)				
Year 15 (2011)	26969.00	0.00	0.11	– 1.71
Year 25 (2021)	46980.00	0.00	0.64	– 2.30
Year 30 (2026)	6599.00	0.88	1.32	2.58
Per capita consumption (Rs.)				
Year 15 (2011)	17301.00	0.00	0.01	– 5.51
Year 25 (2021)	23851.00	0.11	– 0.82	– 9.14
Year 30 (2026)	30205.12	0.98	1.57	11.06
Number of poor (millions)				
Year 15 (2011)	62.30	0.00	0.00	17.24
Year 25 (2021)	26.96	0.00	4.76	38.10
Year 30 (2026)	13.57	0.00	0.00	– 55.56
Cumulative emissions (million tonnes)				
Year 15 (2011)	12488.00	0.01	– 1.67	– 2.48
Year 25 (2021)	26419.00	0.20	– 6.65	– 2.47
Year 30 (2026)	37007.73	4.65	13.50	2.31
Selected activity levels (Rs. billion)				
Year 15 (2011)				
Electricity	1532.00	0.46	– 1.37	– 1.89
Coal	1546.00	0.00	– 0.65	– 0.58
Oil	847.00	0.00	0.00	0.00
Year 25 (2021)				
Electricity	2510.00	0.40	– 2.19	– 1.24
Coal	2120.00	– 1.23	– 9.43	– 0.28
Oil	1033.00	0.00	0.00	0.00
Oil Imports (Rs. billion)				
Year 15 (2011)	218.00	0.00	– 2.75	– 14.68
Year 25 (2021)	619.00	0.48	1.29	– 11.63

BAU: Business as usual.
C10, C20: Cumulative carbon emission reductions of 10 and 20%, respectively.
Oil shock: 300% oil price shock over the 1996 price (US$ 10 per barrel).

cumulative and annual emission reduction. Under it, the economy grows at an average annual rate of 5.03% over 35 years. The carbon emissions grow from 1035 million ton of carbon (mtc) in 1996 to 2984 mtc in 2030.

Enforcing a 10% cut on cumulative CO_2 emissions has, virtually, no impact in the medium-term (see column C10, Table 2, Year 15), while the GDP and consumption levels fall only marginally. In the long run (year 34), however, the effects of emission restriction are more visible. In the 34th year under the C20 scenario, e.g. GDP falls by 2.87% compared to the BAU scenario.

As the emission restriction level is tightened from 10 to 20%, the effects on long-term GDP and welfare become increasingly adverse. The flexibility of the economic system gets reduced, as emission restriction becomes tighter. Also, note that the loss in GDP and consumption is non-linear, i.e. loss rises at an increasingly faster rate than emission restriction. Furthermore, the losses are more severe towards the end of the target period (34th year) than near the beginning of the restriction period. The model tries to postpone the economic losses due to two reasons: (i) It discounts the future consumption flows, and (ii) it enjoys the facility of attaining emissions reduction target over a 35-year period rather than in just one or two years.

In addition, the results clearly illustrate that when a CO_2 emission constraint would be active, India would shift away from coal-based activity to oil- and gas-based activities. Over the long run, the shift away from coal is clearly pronounced. There is, however, no changeover to a new technology in the short run when cumulative restriction of less than 20% is effected.

These scenarios suggest that reduction targets increase poverty and reduce GDP. Moreover, the GDP loss is also not negligible in the long run, as many seem to suggest.

Another simulation carried out illustrates the effect of an oil price shock on the economy and traces the path of the economy as it responds to the shocks. Table 2 proves that an oil shock of the magnitude presented here is extremely detrimental to the economic development. Also, the effects of such shocks tend to be permanent and shift the economy onto a lower growth path, rather than a mere temporary shock causing deviation from the long run growth path. In fact, the effect of the shock is higher during the terminal stages since the model tends to postpone consumption (and GDP) losses to the end. This simulation is extremely relevant since it illustrates that an oil shock has a very similar impact on the economic aspects, albeit of a much higher magnitude, as compared to a carbon emission constraint. Also, such shocks are unlikely to be in India’s interests because in the aftermath of an oil shock, carbon emissions tend to rise due to the substitution of oil by coal, mainly due to the cost advantage enjoyed by it vis-à-vis gas. Indeed, the losses can be taken to be the lower bound since the model has sufficient scope for substitution of oil with coal and gas within one time period – something that actual economies do not possess. In addition, both oil shocks and carbon emission mitigation are the focus of much attention, but the former is a major, and immediate, issue for India. Oil prices have virtually quadrupled (current prices) over the past decade or so, from US$ 10 (average) in 1996-97 to US$ 55 in 2004-05, for various reaons (irrespective of which type of crude is considered, Brent, Dubai or the Indian Basket, the differences are still huge in terms of prices compared to a decade ago) and the impact on India is especially large since she imports around 70% of her total petroleum requirements and oil imports are the largest segment of imports for India.

A major reason for the pressure on developing countries to curb emissions is their high carbon intensity (of GDP) and a perceived rise in the same over a period of time, as these economies develop and populations rise. We investigate whether fears of a rising trend of carbon intensity are indeed likely to be proved true and find that the carbon intensity is, in fact, falling in the latter periods. This may be accounted for by the changing structure of the economy, with services playing a dominant role – services is the largest sector of the economy by the terminal period in all scenarios (Table 3) – with the share of services in GDP rising from 33.4 to 58.2% and having a much smaller emission associated with it while emission intensive transportation and industrial sectors are a much smaller proportion of the economy (Table 4).

Per capita emissions do rise in all the scenarios but once again, they are well below the current world average (3.89 ton) throughout the timeframe of the model and rise only upto half the world's current average, i.e. 1.90 (a factor of 2.4) (Table 5), while, at the same time, GDP and per capita consumption rise by a factor of 5.4 and 4.7, respectively (w.r.t. the base year) (Table 6).

Table 3. Selected model parameters

1	Maximum domestic incremental savings rate	0.30
2	Annual growth rate of government consumption	0.05
3	Annual social discount rate	0.10
4	Post-terminal annual growth rate	0.05
5	Population in base year in 10^6	821.90
6	Annual growth rate of population (%)	1.80
7	Lorenz Ratio of private consumption expenditure distribution *LR*	0.38
8	Upper cut-off level of expenditure for bottom class (Rs.)	4500
9	Upper cut-off level of expenditure for middle class (Rs.)	8000

Table 4. Structural changes in the Indian economy

Time period	Proportion of services in the GDP	Value added coefficient for services	Emission coefficient (g of CO_2 per Rupee of output)
Base	0.33		
Terminal	0.58	0.79	1.11

Table 5. Per capita emissions and carbon intensity

Time period	Per capita emissions (ton of CO_2)	Carbon intensity of GDP (ton of CO_2 per Rupee of output)	World average of per capita emissions (ton of CO_2) (2003)
Base	0.78	0.04	
Terminal	1.90	0.03	3.89

Table 6. Growth in GDP and per capita consumption (base)

Time period	GDP (Rs. hundreds of billions)	PCC (Rs.)	Magnitude of rise over base	
			$GDP_{terminal}/GDP_{base}$	$PCC_{terminal}/PCC_{base}$
Base	17.89	8,799.07		
Terminal	96.93	41,651.17	5.4	4.7

PCC: Per capita consumption.

Parameter Sensitivity of the Model

The simulations in Table 1 illustrate the pitfalls of relying on the quantitative predictions of models to draw conclusions on policies that have economy-wide ramifications. To illustrate, it is argued that oil shocks have a positive effect on economies by promoting efficient use of energy sources, especially over the longer run. But most of this will assume that a country will have sufficient foreign exchange to finance at least a very necessary part of its imports, in the short- and medium-term – an issue of some importance for most developing countries including India but not to the developed ones. As soon as the availability of foreign exchange is reduced, the losses due to an oil shock are magnified, with the long-term effects being more pronounced than those of the medium-term – evidenced by the fall in GDP up to 11.15% at the 25th period and 14.88% at the end of the 34th period. In addition, the results of the model illustrate the capital-output ratio – another major factor driving most models – and assumptions regarding this parameter may, in fact, drive model results. For instance, if the capital-output ratio (COR) is assumed to fall due to technical progress, the GDP over a long period rises significantly – by a stunning 55% over a long period with medium-term effects and a corresponding rise in carbon emissions.

The point to be noted here is the sensitivity of the quantitative results to parameter changes and assumption regarding the various linkages in these models. While the direction of changes may be quite useful for policy formulation and discussion, to conclude that the numerical values are to be interpreted as accurate indicators of actual possibilities is to ignore inherent uncertainties with regard to the 'correct' parameter values and the necessity to re-calibrate, if not restructure, models that have been constructed for extremely different economies. However, the qualitative results of the model are unaltered (Figs. 1 and 2), wherein the trends of carbon intensity and per capita emissions of the economy are similar to the base case. This result also corroborates that for various general equilibrium models, the quantitative results differ widely while the qualitative results all agree on the point that the carbon intensity of India is on a decreasing path. In the present model, though, the carbon intensity decreases after a point, not before,

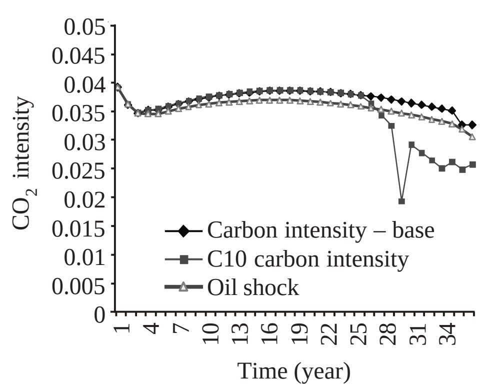

Fig. 1. Carbon intensity (kg of CO_2 per Rupee of output).

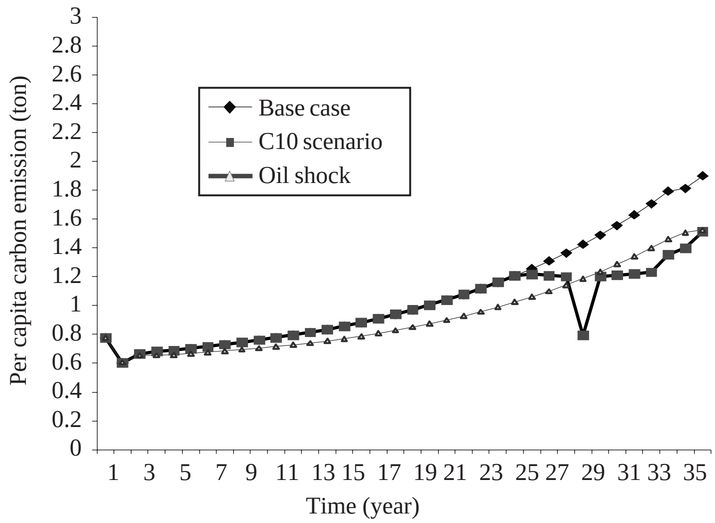

Fig. 2. Per capita emission of CO_2.

probably due to the fact that the rise in GDP tends to overwhelm the structural change effects in the economy.

Conclusions

Large developing countries, such as India, are under pressure to agree to some commitments regarding carbon emission mitigation. An argument most often used is that they are likely to overtake the developed countries in terms of emissions of carbon. It is also felt that the developing countries may, with suitable assistance, 'leapfrog' the 'dirty' development stage by making use of the latest technologies. But unless there is a binding compensation framework, India stands to lose quite significantly, in terms of losses in GDP and, equally important, in greater poverty, if she agrees to any binding commitments to reduce emissions.

Contrary to many predictions, the emission intensity of the Indian economy is seen to reduce after a point of time while the per capita emissions – a point of focus for the alleged rise engendered by the rise in population – show a rising trend. But this is much below, almost by half, even the current world average. Therefore, the emissions of India, while definitely rising, are not expected to rise so much that they cause any drastic changes in the distribution of world emissions, much less than to exacerbate the problem of climate change. The model also brings out the uncertainty involved in the quantitative predictions of non-linear predictive models of the type used here and the pitfalls of policy being driven by these predictions. This indicates that the utility of modelling exercises lies not in the predicted magnitudes of the solution variables, but in the qualitative results that they provide. Thus, the models serve as an aid to, rather than the basis of, policy.

Given this scenario, there is no reason for India to agree to any binding emission constraints and the focus must be firmly on achieving domestic economic and social goals viz. poverty eradication, a problem that, as the model points out, does persist to the end of the time period considered.

References

1. Berger, C., Haurie, A. and Loulou, R., *Modeling Long Range Energy/Technology Choices: The MARKAL Approach*, Report, GERAD, Montreal, 1987.
2. Blitzer, C.R., Eckaus, R., Lahiri, S. and Meerhaus, A., "Growth and Welfare Losses from Carbon Emissions Restrictions: A General Equilibrium Analysis for Egypt", *The Energy Journal*, Vol. 14, No. 1, 1992a.
3. Blitzer, C.R., Eckaus, R., Lahiri, S. and Meerhaus, A., "How Restricting Carbon Dioxide and Methane Emissions Would Affect the Indian Economy?", Background Paper for World Development Report 1992, *Policy Research Working Paper Series No. 978*, The World Bank, 1992b.
4. Brooke, A., Kendrick, D. and Meerhaus, A., *GAMS: A User's Guide*, The Scientific Press, Redwood City, 1988.
5. Fisher-Vanden, K., Shukla, P.R., Edmonds, J.A., Kim, S.H. and Pitcher, H.M., "Carbon Taxes and India", *Energy Economics*, 19, 1997, pp. 289-325.
6. Gupta, S. and Hall, S.G., "Carbon Abatement Costs: An Integrated Approach for India", *Environment and Development Economics*, 1, 1996, pp. 41-63.
7. Murthy, N.S., Panda, M. and Parikh, K., "CO_2 Emissions Reduction Strategies and Economic Development of India", *Working Paper*, Indira Gandhi Institute of Development Research, Mumbai, 1997.
8. Parikh, J., Parikh, K., Painuly, J.P., Shukla, V., Saha, B. and Gokarn, S., *Consumption Patterns: The Driving Force of Global Environmental Stress*, Report Submitted to the United Nations Conference on Environment and Development by the Indira Gandhi Institute of Development Research, Mumbai, 1991.
9. Parikh, K., Panda, M. and Murthy, N.S., "Modelling Framework for Sustainable Development: Integrating Environmental Considerations in Development Strategies", *Discussion Paper No. 127*, Indira Gandhi Institute of Development Research, Mumbai, 1995.
10. Shukla, P.R., "The Modeling of Policy Options of Greenhouse Gas Mitigation in India", *Ambio*, 25(4), 1996, pp. 241-248.
11. World Resources Institute, *World Resources 1996-97*, Oxford University Press, New York, 1996.

Appendix: Model Equations

The model's objective is to maximise a social welfare function W given as the present discounted value of utility streams U_t corresponding to the per capita consumption PC_t of an average consumer over the time horizon 1,2,....,T. The social discount rate chosen is ρ.

$$\text{Maximise} \qquad W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} \qquad \text{where } U_t = \log(PC_t) \qquad (1)$$

The maximisation is subject to several constraints. In the description below, we have omitted what is obvious, that constraints have to be specified for each commodity or each activity and for each period. The first constraint refers to material balance. The total supply of each commodity i, domestic production Y, plus imports M, must be no less than the total demand which is the sum of intermediate demand, private consumption H, public consumption G, investment N, and exports E. All these are real variables evaluated at base year's prices:

$$Y_{i,t} + M_{i,t} \geq \sum_{j=1}^{m} a_{i,j}\, X_{j,t} + H_{i,t} + g_i G_t + N_{i,t} + E_{i,t} \qquad (2)$$

where a is the input-output matrix with i commodities and m activities, X is a vector of activity levels and g is the vector of public consumption budget shares. G_t is specified exogenously, while determination of $H_{i,t}$ in relation to PC_t is discussed later. The input-output matrix need not be square as we distinguish between the set of commodities and the set of activities that produce them. In general, more than one activity is capable of producing a given commodity. A make matrix u links each production activity to the commodities it produces. Additionally, this allows the possibility of joint production – an activity may produce more than one output. There is one column vector corresponding to each activity in the matrix, which represents, numerically, the commodity-wise composition of its gross output:

$$Y_{i,t} = \sum_{j=1}^{m} u_{i,j}\, X_{j,t} \qquad (3)$$

The income generated by each production activity is proportional to its respective level X and is equal to the value of the output less the cost of the inputs. Aggregation over all activities j gives the gross domestic product (GDP) at market prices:

$$\text{GDP}_t = \sum_{j=1}^{m} \sum_{i=1}^{n} (u_{i,j} - a_{i,j}) X_{j,i} \qquad (4)$$

The constraints in Eqs. (5) to (9) describe the capacity and investment relations in the economy. All activities must operate within the available domestic capacity:

$$b_j X_{j,t} \leq K_{j,t} \qquad (5)$$

where $K_{j,t}$ is the capital stock available for activity j in period t and b_j is the incremental capital output ratio (ICOR) for activity j. The production capacities available in different sectors at the beginning of the first period are specified as a part of the initial conditions:

$$\{K_1\} = \{\bar{K}_1\} \qquad (6)$$

We have computed $\{\bar{K}_1\}$ using Eq. (5) as an equality for $t = 1$, assuming that there was full capacity utilisation in that year. Capital stock for the later periods is accumulated through investment Z which matures into new capacity after a lag of one period:

$$K_{j,t} \le (1-d_j)K_{j,t-1} + Z_{j,t-1} \tag{7}$$

where d_j is the rate of depreciation of capital stock in sector j.

The aggregate level of investment is constrained by the total savings generated in the economy. The model chooses consumption and savings levels for each period by optimising the inter-temporal preferences. To counter the possibility of high savings rates resulting in unrealistically low consumption levels we impose an upper limit on the aggregate investment by specifying a marginal savings rate s:

$$\sum_{j=1}^{m} Z_{j,t} \le S^0 + s(\text{GDP}_t - \text{GDP}_0) + F_t \tag{8}$$

where S^0 is the savings at time period 0, GDP_0 is the base year GDP and F_t is the exogenously specified level of foreign capital inflows in period t.

The investment by sector of destination Z such as agriculture or electricity must be balanced against the investment goods available by sector of origin N such as machinery or construction. Therefore, we have

$$\sum_{j=1}^{m} k_{i,j}\ Z_{j,t} \le N_{i,t} \tag{9}$$

where $k_{i,j}$ is the capital coefficient indicating the amount of i^{th} type of capital per unit investment in sector j.

Turning now to trade, we impose the constraint that the total value of imports cannot exceed the foreign exchange available either through export earnings or through inflows of foreign capital F_t:

$$\sum_{i=1}^{m} M_{i,t} \le \sum_{i=1}^{n} E_{i,t} + F_t \tag{10}$$

The export markets are not unlimited for India and an upper bound on the growth rate of exports is more realistic:

$$E_{i,t} \le E_{i,t-1}(1 + g_i^{EU}) \tag{11}$$

where g^{EU} is upper bound on growth of exports. Similarly, import upper bounds are also used for a few sectors on grounds of food security and limited trade possibilities in sectors like electricity and transport:

$$M_{i,t-1}(1 + g_i^{MU}) \ge M_{i,t} \tag{12}$$

where g^{MU} is the upper bound on imports.

While we might restrict our choices to T periods in practice, the economy would continue to evolve beyond this limited horizon. This calls for a minimum level of post-terminal capital stock $\{\bar{K}_{T+1}\}$ to provide for the future:

$$\{K_{T+1}\} \ge \{\bar{K}_{T+1}\} \tag{13}$$

However, what is $\{\bar{K}_{T+1}\}$? We assume that output, capital stock and consumption grow at a constant rate ϕ in the post-terminal period T+1,…,∞, i.e., the economy attains a stationary state:

$$\{Y_t\} = (1 + f)\ \{Y_{t-1}\} \quad \text{for } t > T \tag{14}$$

$$\sum_{j=1}^{m} \frac{u_{i,j}\bar{K}_{j,T+1}}{b_j} = (1+\phi)Y_{i,T} \qquad \text{or} \qquad \sum_{j=1}^{m} \frac{u_{i,j}(J_{j,T} - d_j K_{j,T})}{b_j} \geq \phi Y_{i,T} \tag{15}$$

The above simplification might compromise the optimality of the terminal year solution determined by us. However, a compromise is unavoidable in this case.

The objective function is now modified to include the utility from post-terminal consumption, which is assumed to grow at the post-terminal rate of ϕ. The revised objective function can be expressed as

$$\text{Maximise} \qquad W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} + \alpha U_T \quad \text{where} \quad \alpha = \frac{1+\phi}{(1+\rho)^{T-1}(\rho-\phi)} \tag{16}$$

which gives a higher weight (typically, $\alpha > 1$) to the utility derived from consumption in the terminal period, because the post-terminal consumption is directly proportional to it. This is in contrast to the objective function defined earlier in Eq. (1), in which the weight attached to utility is the least in the terminal period. In case the objective function was not modified in the above fashion, the model would choose a smaller consumption level for the terminal period as this leads to a smaller requirement of capital investment for post-terminal growth.

The basic framework discussed here suffices to describe the likely growth pattern of an economy. Only one thing remains to be specified – How is $H_{i,t}$, the consumption expenditure by sectors, determined in relation to PC_t? This is discussed as follows:

Consumption Expenditure Distribution and Poverty

Developing countries typically articulate two concerns other than aggregate economic growth: (i) reduction of mass poverty, and (ii) provision of minimum basic needs to their people. We incorporate aspects related to absolute poverty in our model by focussing on the distribution of consumption expenditure amongst the population. Parikh et al., 1995 describe how provision of basic needs can also be represented in this modeling framework. We segment the total population into three different classes by arranging the population in ascending order of per capita consumption expenditure. A fixed pair of lower and upper boundaries (e^{p-1}, e^p) defines the class p. The lowest income households are included under the class $p = 1$, their per capita consumption being less than e^1, which is made equal to the poverty line so that households belonging to this class are identified as poor.

The distribution of population across the three classes is given by a function $f(PC_t; LR, e^p)$, which represents the proportion of total population having per capita consumption expenditure less than e^p. Typically, in the literature, a two-parameter standard lognormal probability density function, *SLN* underlies the distribution function *f*. The two parameters are the Lorenz Ratio *LR* and the per capita expenditure *PC*. We calculate the proportion $pop_{p,t}$ of people in the p^{th} class using the value of PC_t chosen optimally by the model, the class expenditure boundaries (e^{p-1} and e^p) for the p^{th} class, and the value of *LR*, each specified exogenously. The magnitude of population in the p^{th} class is given as

$$pop_{p,t} = pop_t \, . \, pop_{p,t} \text{ where } pop_{p,t} = f(PC_t; LR, e^p) - f(PC_t; LR, e^{p-1}) \tag{17}$$

$$f(PC_t; LR, e^p) = SLN\left(\frac{1}{LR}\, ln\left(\frac{e^p}{PC_t}\right) + \frac{LR}{2}\right) \quad \text{where} \quad SLN(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{s^2}{2}} ds \tag{18}$$

Note that $e^0 = 0$ and $e^3 = \infty$ which yields $f(PC_t; LR, 0) = 0$ and $f(PC_t; LR, \infty) = 1$.

The average consumption expenditure $PCC_{p,t}$ of class p can be computed as

$$PCC_{p,t} = \frac{PC_t \cdot SLN\left(\frac{1}{LR} ln\left(\frac{e^p}{PC_t}\right) - \frac{LR}{2}\right)}{f(PC_1; LR, e^p)} \quad (19)$$

A representative consumer of the p^{th} class is allowed to choose a linear combination of R different types of commodity bundles. His consumption expenditure budget $PCC_{p,t}$ is allocated across the R bundles in each time period t so that the following identity holds:

$$PCC_{p,t} = \sum_{r=1}^{R} PCB_{r,p,t} \quad (20)$$

Each commodity bundle is composed of different commodities in fixed proportions. For example, μ_i is the expenditure share of commodity i in the r^{th} bundle available to a consumer of class p and this value remains fixed in the model. Nevertheless, the consumer achieves a degree of substitution between different commodities by choosing the combination of different bundles and the amounts he spends on each of them. The consumption vector C of each class is the aggregate over the set of R consumption bundles:

$$C_{p,i,t} = POP_{p,i} \cdot \sum_{r=1}^{R} \mu_{i,r,p}\, PCB_{r,p,t} \quad (21)$$

The economy-wide consumption vector H is then represented by the sum of consumption vectors corresponding to the individual classes:

$$H_{i,t} = \sum_{p=1}^{P} C_{p,i,t} \quad (22)$$

Since the distribution parameter LR is fixed in our model, poverty alleviation requires growth in consumption, which is chosen optimally in the model subject to the constraints.

Another point to note in this connection is that we have used the GAMS program to solve the model. GAMS, however, does not permit equations with standard lognormal functions, *SLN*(.). It, however, permits a loop where the *SLN* function could be computed before obtaining the optimisation solution and iterations could be carried out within the loop such that the value of the *SLN* function converges. We have taken advantage of this facility.

Emissions Inventory

The emissions from the production sectors are computed by considering the scalar product of two vectors: (i) the activity levels X, and (ii) an emission coefficient vector e^X. Emissions are also caused by the private and public consumption of fuels like kerosene, LPG and motor gasoline. We account for these by considering two other emission coefficient vectors, e^C and e^G. The total emissions in period t is, therefore, given as:

$$EM_t = e^X X_t + e^c H_t + e^G G_t \quad (23)$$

The cumulative stock of CO_2 emissions CEM_t at the end of any period t is computed by adding the emission flows EM_t during the current period to the stock CEM_{t-1} carried over from the previous period:

$$CEM_t = EM_t + CEM_{t-1} \quad (24)$$