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Abstract

This paper examines the consequences of alternative CO_2 *emission reduction strategies 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 horizon. A multi-sectoral, inter-temporal model in the activity analysis framework is used for this purpose. The model with specific technological alternatives, endogenous income distribution, truly dynamic behaviour and covering the whole economy is an integrated top-down bottom-up model. The results show that* CO_2 *emission reduction imposes costs in terms of lower GDP and higher poverty. Cumulative emission reduction targets are, however, preferable to annual reduction targets and that a dynamically optimum strategy can help reduce the burden of emission reductions. The scenarios involving compensation for the loss in welfare are not very encouraging as they require large capital inflows. Contrasted with these, scenarios involving tradable emission quota give India an incentive to be carbon efficient. It becomes a net seller for the first 25 years and because of reduction in carbon intensity it would demand less in later years when it becomes a net buyer. The results suggest that for India, and other developing countries, the window of opportunity to sell carbon quotas is the next two decades or so.*

CO_2 Emissions Reduction Strategies and Economic Development of India[*]

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1. Introduction

The contribution of the developing countries to the climate change problem has been historically small and their per capita emission of CO_2 is significantly lower than those in the developed world (Parikh et al., 1991). Yet, some of these developing countries 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. The developed countries may be seen by the developing countries as a source of financial and technological resources to help them control CO_2 emissions without detracting from their developmental objectives. This paper examines the impact of CO_2 emissions constraints on economic development and, in particular, the implications for the poor by empirically implementing an economy wide model for 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 modeling is the computable general equilibrium (CGE) approach where a sequence of single period equilibria is 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

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analysis approach permits macro-consistency, dynamic behaviour, new and specific technological options and thus limited substitution. It can constitute a truely integrated top down-bottom up approach.

Energy sectors have been the focus of attention of several studies concerned with CO_2 emissions. Manne and Richels (1992) is an example of this type of models built at a global level. Nordhaus (1994) synthesizes a climate feedback sub-model and a world economic sub-model to determine the optimal path of economic growth and carbon dioxide emissions over a long period of time. These global models tend to aggregate the economic activity in the world into a single sector. McKibben and Wilcoxen (1995) describe a global model in which money and financial constraints are incorporated. Cline (1992) and Fankhauser (1995) review various models of interactions between carbon dioxide emissions and the economy. Among global models the second generation model (SGM) of Edmonds et al (1992) is a general equilibrium multi-regional model used to calculate a sequence of equilibria. At the national level, computable general equilibrium models, which incorporate behaviour of individual agents in response to endogenous prices, have been used for development policy analysis (Adelman & Robinson, 1978, Dervis et al., 1982, Narayana et al., 1991). These are either static models (Bergman, 1990) or dynamic ones (Jorgenson and Wilcoxen, 1990), useful for analyzing the effects of adopting alternative market-based policy instruments. The dynamic models typically lack sufficient inter-temporal choices; they obtain a sequence of single-period solutions with exogenously controlled state variables over time (Glomsrod, 1992). Shukla (1995) provides a critical assessment of greenhouse gas models and abatement costs for developing nations.

A few modeling studies have explored India's options. Blitzer et al. (1992a,b) use a multi-sectoral inter-temporal activity analysis framework and examine the impacts of restrictions on emissions of CO_2 and other greenhouse gases on economic growth of Egypt and India. They also examine the 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 the total consumption of the society as a whole. Shukla (1996) uses two models, the bottom-up MARKAL (Bergel et al, 1987) which is an energy system model suitable for techno-economic analysis given exogenously specified sectoral growth rates and the top-down 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 and Fisher-Vander et al, 1997). Gupta and Hall (1996, 1997) have tried to use a simple econometric macro-model as a top-down model to integrate technological options identified by techno-economic assessment of various technical options for carbon abatement.

In this paper, we have used the traditional activity analysis framework to model the linkages between the national economy and environment. Our programming model is multi-sectoral and inter-temporal and maximizes an objective function, which is the discounted sum of utilities from consumption. The dynamic framework permits examination of optimal inter-temporal choices. There are some specific features we wish to highlight in our model of the Indian economy, which distinguish our approach from other models of India. Compared to Blitzer et al. (1992b), our model has endogenous income distribution. We also trace welfare effects for the low-income groups. This is done by examining the incidence of absolute poverty in the population. Secondly, there are large differences in consumption patterns among different income classes in a developing country, which are represented in our model. In this context, we also specify several alternative consumption bundles for each income class from which the respective representative consumers can choose. Thus, we permit consumer purchases to be sensitive to the relative shadow prices of commodities in our programming model. Endogenous income distribution is important because it will have considerable impact on the structure of consumption demand in the economy, as population in a lower income class today will move to a higher income class in the future as income growth takes place. Finally, we impose terminal conditions on stock variables in our model. With the inclusion of natural resources among the stock variables, the terminal conditions can be interpreted as sustainability constraints since it takes care of the assets left for the future generation. Compared to SGM's India model, which calculates a sequence of equilibria over time, ours is a dynamic model where inter-temporal substitution possibilities are permitted in the optimization process. Compared to Gupta and Hall's econometric model also, ours is dynamically optimal and we confine ourselves to specific technical options, which have few unexplored barriers.

The main question we address is: what would be the consequence for growth and poverty in India of different carbon emission reduction strategies? Specifically, we examine the likely loss in national income growth and increase in the incidence of poverty due to annual or cumulative restrictions on CO_2 emissions. Next, we have attempted to estimate the incremental costs of abating CO_2 emissions and quantify the additional inflows of foreign finances, which will compensate the welfare losses incurred for abatement. Finally, we report on our results from simulating a system of global trade in CO_2 emissions quotas to look at the attractiveness of such schemes for India.

The organization of the paper is as follows. The framework of the multi-period activity analysis model is briefly described in section 2. Several sets of model results are dealt with in Section 3: the economy-wide impacts of imposing CO_2 emission constraints, the magnitude of income transfers from abroad as a measure of compensation for the developing countries that undertake emissions reduction and some experiments with internationally tradable CO_2 emission quotas. We conclude in section 4 and point out policy implications of our results. The equations are given in the Appendix. The database used to implement the model is also laid out in the Appendix in Tables A1-A3.

2. Model Structure

The model is an activity analysis, multi-sectoral inter-temporal dynamic optimization one. This permits exploration of alternative technologies and CO_2 strategies from a long term dynamic perspective. With alternative activities representing different technologies, one can permit substitution of various kinds and incorporate non-linearities in such models. The model maximizes a social welfare function given as the present discounted value of utility streams corresponding to the per capita consumption of an average consumer, given the resources available to it and the various technological possibilities for using them. In principle, the time horizon of the model must extend to infinity. Empirical models, however, work with a finite time horizon of length, say, *T* time periods only (taken to be 35 years in our case) as it is computationally very difficult to work with an infinite number of time periods. Instead, they account for the post-horizon periods in other ways such as by making simplifying assumptions for the post terminal period, as we do below..

We represent the whole economy with seven 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 others (hydro and nuclear). We focus on specific options on the power side as large part of India's CO_2 emissions occur in this sector 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 changes nonlinearly as the economy grows and people move from one income class to another. Fifteen alternative consumption bundles are provided for each class to represent approximately the indifference curve of the class. This 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.

Ideally income distribution should be linked to production structure and techniques. Unfortunately, adequate data on income generated by activities and how they are distributed to different income classes are not available. However, empirically income distribution as reflected in consumption expenditure has remained very stable with slow and miniscule changes in the Lorenz ratio. National Sample Survey (NSS) data show that it varied with minor fluctuations between 0.3417 in 1956-57 and 0.3202 in 1992 [see, Panda (1999)]. Thus an assumption of a constant Lorenz ratio over a long period of time is justified for India.

The constraints in the model include the following:

(i) Commodity balance to ensure that demand does not exceed availability;

(ii) Production requires fixed capital which once allocated to an activity can not be shifted. Capacity constraints ensure that production does not exceed capacity created by investment in each activity;

(iii) Capital accumulation constraints that restrict capital stock in each activity to increase by net investment in each activity;

(iv) Domestic production of oil is restricted to reflect the small oil reserves in India.

On the trade side, we impose a balance of payment constraint. There is also a wedge between export price and import price to reflect international trade and transport margins. Some restrictions are imposed on exports and import growth rates by sectors to keep the model realistic. Thus, import of agriculture is restricted to reflect a self-sufficiency requirement for a large country, which is considered necessary for food security. We also restrict import of services as not all services can be imported. In the absence of non-linear export demand functions, export bounds are introduced to account for fall in export price and profitability consequent to large exports by India. The values of the bounds are given in the Appendix Table A2.

A savings constraint is imposed to restrict marginal savings rate to 30 percent. Programming models often give high investments and implied savings rate. Such rates are not realistic as governments in democratic developing poor countries are not able to force savings rate beyond a limit. Finally, though the model is run for a period of 35 years, the post-terminal future has to be taken care of. This is done by assuming that a stationary state would prevail in the future with the composition of output, consumption, investment etc. fixed and growing at a prescribed rate. This translates into a larger weight for the terminal year consumption in the objective function.

The model is solved using GAMS programming tool developed by Brooke et al. (1988). Income distribution is endogenous in the model. It depends on the total income generated, which in turn depends on the income distribution. We assume an initial income distribution, compute the optimal solution and the resulting income and distribution and iterate till they converge.

Emissions Inventory

CO_2 is emitted when fossil fuels such as coal and oil are burnt in production and household activities. For a given fuel, the amount of emission is directly proportional to its quantity burnt. The CO_2 emission coefficient of a fuel depends upon its carbon content. We account for these emissions in two different ways: flows and stocks. 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, LPG and motor gasoline. We account for these by considering 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. CO_2 emissions are known to accumulate and reside for long duration in the atmosphere leading to increase in CO_2 concentrations.

Carbon Reduction Options

In the model CO_2 emissions can be reduced in a number of ways. First, it can be reduced by reducing the levels of different activities. This has the direct effect of reducing income and consumption and hence 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 are also available for reducing the CO_2 intensity of activity levels. These have the virtue of reducing emissions without any significant loss of output. There are essentially two types of such options: (a) Reduce 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) Switch to less carbon intensive fuels. For example, instead of a coal based power plant, we may install a CCGT power plant, or instead of running industrial boilers on coal, we may use oil. The CO_2 emission coefficient varies across the fuels, being highest for coal (26 tC/GJ), followed by oil (21 tC/GJ) and the lowest for natural gas (14.7 tC/GJ). Thus, oil or natural gas can substitute coal and lower CO_2 emissions.

Alternative fuels or production technologies can be introduced by expanding the set of activities. None of the equations (given in Appendix) need change when new activities are introduced.

3. Analysis of CO_2 Emissions Reduction in India

We use the model described in the earlier section to evaluate the impact on economic growth and other related variables of several alternative CO_2 reduction targets over a period of 35 years from 1990 to 2025. The reference scenario is a ‘business-as-usual’ (BAU) scenario in which the pattern of growth of various variables is determined by the model in the absence of any emission constraints. We then develop scenarios in which there are restrictions on the amount of CO_2 that can be emitted. These restrictions are applied in two different forms: (a) reduction of 10%, 20% and 30% in cumulative CO_2 emissions (CEM_T) over 35 years (these three scenarios are labeled C10, C20 and C30 respectively); (b) annual reduction of 10%, 20% and 30% in CO_2 emissions (EM_t) in each year of the 35-year time horizon (these three scenarios are labeled A10, A20 and A30 respectively). Thus, we have six different scenarios of emission restrictions for comparison with the BAU scenario. Next, we carry out a few compensation runs where loss in welfare due to emission restrictions is compensated through foreign income transfers. Lastly, we introduce a carbon quota regime with tradable permits and examine implications on India of such permits under alternative permit prices on the world market.

3.1 Data

We have empirically implemented the model by using recent data for India to estimate the various parameters and initial values of different variables included in the model structure discussed in the previous section. Input-output coefficients and capital-output ratios for various activities form the core of the model. These data are available from published sources for most sectors.[1] In some cases, like the capital-output ratios for the generation of electricity using alternative technologies, we have based our estimates on statistics published by the Centre for Monitoring Indian Economy (1995) on the ongoing and proposed power projects in India. Future projections of government consumption levels and of the upper and lower bounds for exports and imports (where relevant) are specified in terms of growth rates. The database for operating the model is listed in Appendix Tables A1-A3.

3.2 Impact of Carbon Dioxide Emission Restrictions

Table 1 shows the values of some important macroeconomic variables and alternative activity levels for selected years for BAU scenario as well as various scenarios involving cumulative and annual emission reduction. Some characteristics of the BAU scenario may be noted. Under it, the economy grows at an average annual rate of 6.3% over 35 years. The carbon emissions grow from 157 mtc in 1990 to 1421 mtc in 2025. Of these emissions, 61 mtc are from electricity generation and 53 mtc from industrial production in 1990 and 659 mtc and 397 mtc respectively in 2025. The annual emissions are plotted in Figure 1. The cumulative emissions over the 35-year period amount to 20353 mtc.

Enforcing a 10% (or even a 20%) cut on cumulative CO_2 emissions has virtually no impact in the short run (3rd or 5th year) or medium run (10th year); see column C10 or C20 of Table 1. The GDP and consumption levels fall only marginally. In the long run (30th year), however, the effects of emission restriction are more visible. In the 30th year under the C20 scenario, for example, GDP and consumption per capita fall by 1.36% and 1.85% respectively compared to the BAU scenario. As a result, number of people below the poverty line increases by 5.94%.

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[1] Details are available in Parikh et al. (1995)

As the emission restriction level is tightened from 10% to 20% and further to 30%, the effects on long run GDP and welfare become increasingly adverse. Thus, GDP falls by 0.53%, 1.36% and 4.06% and the number of poor increases by 2.1%, 5.9% and 17.5%, in the 30th year for 10%, 20% and 30% cumulative carbon emission restrictions respectively. The flexibility of the economic system gets reduced, as emission restriction becomes tighter. Also, note that the loss in GDP and consumption is nonlinear i.e., loss rises at an increasingly faster rate than emission restriction. For the case of a 30% restriction, even the short run effects (up to 5 years) are noticeable: GDP and per capita consumption loss is about 0.2% and incidence of poverty is higher by 0.3% compared to the BAU scenario. Furthermore, the losses are more severe towards the end of the target period (30th year) than near the beginning of the restriction period. The model tries to postpone the economic losses due to two reasons: it discounts the future consumption flows and it also enjoys the facility of attaining emissions reduction target over a 35-year period rather than in just one or two years.

Next, we consider the impacts of imposing annual reduction targets for CO_2 emissions. A 10% annual reduction target over each of the 35-year period (scenario A10) achieves the same reduction over the period as the 10% cumulative reduction scenario (C10). But the economic losses are larger under annual reduction scenario than cumulative reduction of the same order. For example, in the 20% restriction case, annual constraints lead to a GDP fall of 3.66% in 30th year as compared to 1.36% for cumulative constraint and for 30% reduction, GDP is lower by a whopping 10.7%. Annual constraints are more restrictive than cumulative constraints because they deprive the economic system of its freedom to choose an adjustment path over time, though the terminal period carbon stock level is the same under both types of constraints. It can be seen in Figure 1 that under the C30 scenario, emission reductions are postponed towards the later part of the time horizon.

The short-run effects are also large for the case of annual constraints. GDP losses in 3rd year vary from 0.47% in the case of 10% annual emission restriction to 11.86% for 30% restriction. The increase in number of poor is a large 20.67 percent increase even in the short run, and in the 30th year the number of poor increase by nearly 50 percent for a 30% annual reduction, which indicates a significant short run burden on the lower income segment of the population.

The model results for alternative activity levels for 5th and 30th years are also presented in Table 1. These results clearly illustrate that, when a CO_2 emission constraint would be active, India would shift away from coal based electricity to oil and gas based electricity and from coal-boiler based manufacturing to oil-boiler based manufacturing. There is, however, no change over to a new technology in the short run when cumulative restriction of 20% or less is affected.

These scenarios suggest the following :

(a) Cumulative emission reduction targets are preferable to annual reduction targets and that a dynamically optimum strategy can help reduce the burden of emission reductions. Methodologically it suggests that an inter-temporal optimizing framework as we have used, is needed for exploring CO_2 reduction strategies. One may note that sequential general equilibrium models, which have many desirable features should be driven by dynamically optimal scenarios generated by the type of model presented here.

(b) Even cumulative reduction targets increase poverty by a larger percentage than it reduces GDP. The GDP loss is also not negligible in the long run.

(c) Annual emission reductions, which is implicit in the pressures put on developing countries by denying them finance and credit for coal based power plants, for example, imposes unnecessary costs in terms of reduced GDP and higher poverty, both in the short and the long run through distortions in choice of techniques in electricity generation as well as in energy use in industry.

3.3 Compensation for Reduction of CO_2 Emissions

A developing country like India, which has so far contributed very little to the climate change problem, cannot afford a loss in GDP and an increase in poverty due to carbon emission restriction. India could justifiably seek financial assistance or other forms of compensation from the rest of the global community for reducing its domestic CO_2 emissions for the sake of meeting global emissions reduction targets.[2] What would be the quantum of such compensation? Our model provides a

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[2] Technological assistance could be another form of compensation.

framework to compute the level of financial compensation that will offset the loss of social welfare associated with a given target of reducing domestic CO_2 emissions.

We model the financial compensation in the form of additional foreign capital inflows coming from a global fund[3]. The exact procedure we follow is to let foreign transfers in each year become an endogenous variable while it was exogenously fixed earlier. The objective function is also modified: we minimize the discounted sum of foreign inflows subject to maintaining the consumption path and welfare level as in the BAU scenario. This ensures that the additional inflows of foreign capital are not larger than the minimum required.

These scenarios assume that whatever additional foreign capital inflowsocccur, they will be used appropriately. In reality, such compensation is unlikely to be optimally used and welfare loss is bound to result. Nonetheless, the scenarios provide an idea of the broad magnitude of the compensation needed.

The results of a numerical exercise to compute the compensation levels for two scenarios C30 and A30 are reported in Table 2. The capital flows are not needed in each year of the 35-year time horizon considered here. They would be needed only in some years when additional investments are undertaken in carbon saving technology. The required capital flows needed to compensate for welfare loss for the cumulative reduction case (C30Comp) amounts to Rs.1453 billion ($ 87 billion at the exchange rate of Rs.16.65 to a US$ prevalent in 1989-90) during the whole period. However, the very first year an inflow of US$ 41 billion is called for. Such large flows seem highly unlikely. Even if this were available, India's capacity to absorb this fruitfully is very doubtful. If, however, the inflows in a given year were restricted so as to spread them out over time, the total inflows would have to be larger. This is obvious as the economy would be additionally constrained. The scenario estimate of $ 87 billion has to be recognized as a lower bound. The magnitude of such flows rises three-fold to $ 278 billion for the case of annual emission reduction (A30Comp). The foreign capital flows are used to invest for shifting away from coal based production to oil and gas based production processes. In

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[3] The Global Environmental Facility (GEF) is a leading example of such a fund though its finances are very limited at present.

particular, large scale oil-boiler is adopted for the manufacturing sector when capital flows accompany the emission restriction targets (compare activity levels in Table 2 with those in Table 1 under the same column headings). Moreover, the capital flows required under annual reduction scenario is very large in the initial year (about 70% of GDP or $ 165 billion) and points to the infeasible nature of annual reduction strategy in practice. Lastly, it may be pointed out that terminal consumption level in these scenarios remains the same as in BAU scenario and so no costs are shifted to the post-terminal period even as CO_2 constraints are being met within the 35-year period.

These scenarios show the compensation has to be large running into US$ 87 to US$ 278 billion if India were to be induced to reduce its CO_2 emissions. Such compensations seem unlikely at present and thus, other mechanisms should be explored to induce India (and other developing countries) to reduce their CO_2 emissions. Tradable emission quota is an obvious instrument. We now examine it.

3.4 Tradable CO_2 Emission Quotas

A variety of market-based instruments to implement CO_2 abatement objective like a carbon tax or a tradable emission quota are discussed in the literature. The quantitative implications of adopting such policies for the economic performance of the Indian economy is worth examining. In a global scheme of tradable emission quotas, each country is allotted a fixed annual emission quota. A country’s right of emission could, however, be augmented through purchase of quota right of another country which has generated a surplus by keeping its emission less than the quota. No country is permitted to emit in excess of the total quota held by it net of sales and purchases. This ensures that the global emissions never exceed the total quotas allotted to all the countries. In a system of tradable emission quotas, the efficiency and equity issues may be treated independent of each other. The opportunity to trade in quotas leads to efficient use of means of abatement, while the initial allocation rule could take into account equity and need of various countries. Bertram (1992) and Parikh and Parikh (1998) have argued among others the case for tradable permits as a global policy option for limiting greenhouse gas emissions.

We now describe a set of simulations performed with our model, which brings out the impact of emission quota trade on economic development in India. The revenue from the sale of surplus emission quota affects the economy in two ways:

(a) it relaxes the foreign exchange constraint and permits larger volume of imports, and

(b) the increased foreign savings in the form of additional foreign exchange availability helps to expand domestic investment.

We stipulate a few simple rules of trade in emission quotas. If emissions in a country fall short of quota allotted for any particular year, then it has permission to sell the surplus quota in the same year at ruling world market prices. Similarly, its emissions may exceed the quota allotted for any particular year provided it bridges the deficit by purchasing them in the same year at going world market prices. We have not considered the scope for banking the quota unused in one year for use in another year. Nor do we permit lending and borrowings of foreign exchange from one year to the other. Yet, this is a potentially better situation than an annual restriction on CO_2 emissions (section 3.2) as some inter-temporal adjustment is possible by trading in quotas. Permission to bank or borrow quotas or dollars from one year to another will be more beneficial just like cumulative restriction on emission compared to annual restriction.

It is beyond the scope of this paper to specify how the world market price (P^{CQ}) of carbon quota is determined. One method could have been to use the price emerging from a global modelling system, which links policy models of different countries. Examples of such models are the Basic Linked System (BLS) of agricultural policy models by Fischer et. al (1988) and the SGM model by Edmonds et. al (1992). However, the prices generated in a scenario of such a global model will depend on the policy reactions of many countries. Moreover, the equilibrium quantity trajectory for India underlying the price trajectory in the global modelling system would not be consistent with the quantity trajectory generated using our model. Hence, we take a simple approach of specifying a constant real price of carbon quota for all the 35-year time period in a scenario, but we simulate over a set of alternative prices in different scenarios to map out the supply function of India’s net exports of carbon quotas.

The economy reacts to variations in this price by buying or selling emission quotas in different simulation runs. How should emission quotas be allocated? Parikh and Parikh (1998) have argued for equal per capita allocations, which are kept fixed to the population of the country on the day a global agreement is signed. This is to give an incentive to developed countries to sign the agreement quickly and not to give developing countries a perverse incentive to increase their population. They have also suggested that this should be on a cumulative basis covering emissions over some past and some future years. Here, however, we make a simpler assumption. The emission quota is fixed at 1 tonne of carbon (tc) per capita[4] based on 1990 population. This amounts to 821.9 million tc per year and remains at that level for the entire period[5]. Table 3 shows the results for a world market price ranging between Rs. 100 to Rs.1000 at 1989-90 prices[6], i.e., US$ 6 to 60 per tonne. It might be noted that in the compensation scenarios, the implicit cost per tonne of carbon reduction was $ 15 in C30Comp and $ 42 in A30Comp. Also, in these scenarios, India is assumed to be a small country in the world quota trade and so its sale or purchase does not affect the world market price.

Under the above quota system, it is usually the case that a developing country like India would have surplus emission quotas in the initial years because the size of its economy is small on a per capita basis during the initial years. As Table 3 shows the cumulative sale by India of surplus quota in the world market would be between about 10400 to 11400 mtc over the 35-year period, i.e. an average of about 297-325 mtc per year under different price scenarios. Over time, however, the economy grows and the surplus gets reduced. Indeed, India starts purchasing the quota of other countries sometime between the 24th and 27th year. The cumulative purchase of quota by India over the 24th to 35th year turns out to be about 3200 to 4500 mtc, or an average of 91 to 129 mtc per year.

Tradable carbon quota is an asset held by the economy and an increase in its sale revenue permits domestic consumption and/or investment level to expand. Earnings from the sale of surplus quota may thus be viewed as similar to the financial compensation schemes discussed above. In the experiments

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[4] This is roughly equal to per capita world emission in 1990.

[5] It should be pointed out that, starting from 1 tC/capita in 1990, the emission quota decreases at a rate equal to the rate of growth of population (1.8% per year) and drops to only 0.53 tC/capita by the year 2025, the terminal year in the model.

[6] The exchange rate of the Indian rupee was US$ 1= Rs. 16.65 in 1989-90.

carried out here, the economy grows over and above the base run (BAU) since the quota fetches additional revenue from rest of the world in the initial 24-27 years. The net present value (NPV) of per capita consumption stream, a measure of aggregate welfare, increases with quota price. With additional growth in the economy, cumulative carbon emissions rises over the BAU run by 400 to 3300 mtc (an increase of 2 to 16%) depending on price of the quota (Table 3).

Does India sell more as quota price rises? India's offer curve for the price range considered here is drawn in Figure 2. It is not upward slopping at all ranges. The supply curve is backward bending in several ranges. The supply or surplus depends on the size of the domestic economy and the carbon intensity of the production processes. In order to understand the turning points in the curve, we document the activity levels in Table 4 in the electricity and the manufacturing sectors which have alternative production techniques in the model. Table 4 reveals that India finds it optimal to invest in new carbon saving production techniques with rise in world price of carbon quota. The production techniques of the BAU run continues till quota price reaches Rs. 150 (US$ 9) when it becomes economical to invest in combined cycle gas turbine (CCGT) to produce electricity. The processes adopted at price of Rs. 150 again continues there after till world quota prices reaches Rs. 400 when there is a shift to hydro and nuclear options as indicated by the expansion of the 'other electricity' activity. The next jump in technology occurs at a price of Rs.700 with adoption of oil-boilers for industrial production.

It is interesting to note in Figure 2 that the supply curve for carbon quota turns upwards precisely as a shift occurs to a new technology at prices Rs. 150, 400 and 700. Clearly, it is optimal for India to invest in new technology and thereby generate surplus quota to increase the sale of the quota in the world market at these prices. However, when the production techniques remain unchanged, the economy does not find it optimal to expand sale of quota in the international market even at higher quota prices in some ranges. The supply curve thus bends backwards in the price range Rs. 150-350, 450-650 and beyond Rs.700. It is optimal for India to reduce its offer of quota to rest of the world in these ranges and use the quota for expanding domestic production instead.

We document in Table 5 some key variables for the 30th year to examine long run effects. The quota runs show significant welfare gains for India. GDP in 30th year increases by 6.7% over BAU for a quota price of Rs 100 ($ 6) per tc. It turns out to be significantly larger for higher quota prices and rises by about 60% for a quota price of Rs 1000 ($60). The number of poor declines substantially by 20% or more compared to the BAU scenario. The total CO_2 emission in the 30th year goes up by 10 to 20% over the BAU scenario because of the larger size of the economy. But, carbon intensity of the production process falls drastically by 6 to 25% for quota price of Rs. 200 ($12) and above, reflecting adoption of new technology. Thus, while a carbon quota system helps to raise GDP in a developing country like India, it also helps in reduction of carbon intensity in the production process. In the Indian case, as we have discussed above, this occurs through substitution of coal by oil and gas.

We have carried out the numerical experiments of the model with relatively few alternative techniques. With increased revenue from sale of tradable quota, technical change could be further induced. One could then expect a more comprehensive new menu of options for CO_2 mitigation to develop. Such an emerging scenario is likely to reduce even total emission from the BAU level even as GDP rises.

4. Conclusions

Based on our analysis and the rationale we have presented, India should not have any obligation to reduce its carbon emissions for quite some time. Emission reduction imposes costs in terms of lower GDP and higher poverty. If India is to reduce emissions, it should be compensated for the loss. The compensation scenarios are not very encouraging as they require large capital inflows to ensure that welfare levels are maintained.

Can one interpret the compensation scenarios as scenarios of Kyoto protocol? In the compensation scenarios, India needs US$ 87 billion to US$ 280 billion of capital inflows to reduce its carbon emissions by 30 percent cumulatively for 35 years or every year for 35 years respectively and it still maintain its welfare level. Under the Kyoto protocol inflows may come from private firms setting up carbon reduction projects in India. Should India welcome this? Of course, the answer would depend upon what price India gets for emission reduction. The 30 per cent reduction scenarios reduce emission by 6.1 billion tones of carbon over 35 years. In the annual reduction scenario to maintain welfare at the same level, a compensation of $278 billion is required. This means that the welfare cost of reducing emissions by 1 tc is about $45 for India. In the cumulative reduction scenario, the implicit welfare cost comes to $14 per tc. For simplicity, we have not discounted compensation and emission reductions. Thus, if any CDM project that gives India as its share less than $14 per TC, then India should not accept it. At $14 India just breaks even. It ought to get something more to make it worth its while. The fact that CDM projects bring investment may be looked at its own right as any other foreign direct investment project. Accept it if it makes sense by itself. One may also note that at $14 per tc, India does not gain anything from it. The emission credits would be claimed by foreign investors, and if anything, India loses the low hanging fruits of carbon emission reduction, which may be more valuable when the time comes for it to curtail its emissions.

Contrasted with these, the tradable quota scenarios give India an incentive to be carbon efficient. It becomes a net seller for the first 25 years and because of reduction in carbon intensity it would demand less in later years when it becomes a net buyer. In any case, a tradable quota regime would lead to much more induced technical change than what is provided in our scenarios. One can even expect a net reduction in India's emissions in spite of higher growth.

In the quota scenarios, India remains a net seller only for around 25 years. This suggests that for India, and other developing countries, the windows of opportunity to sell carbon quotas is the next two decades or so. If these are missed, it would be difficult to persuade them to join in a global effort to reduce carbon emissions. A global agreement without their willing participation would be that much more difficult.

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Table 1: Scenarios for Carbon Emission Reduction by India

	BAU	C10	C20	C30	A10	A20	A30
		Percentage Change from BAU					
Gross Domestic Product (Rs. Billion)							
Year 3	4850	-0.02	-0.02	-0.19	-0.47	-3.79	-11.86
Year 5	5301	-0.02	-0.02	-0.17	-0.47	-2.83	-10.45
Year 10	6801	-0.03	-0.03	-0.62	-0.59	-2.93	-9.07
Tear 20	12307	-0.02	-0.30	-1.45	-0.59	-3.30	-10.17
Year 30	24595	-0.53	-1.36	-4.06	-0.69	-3.66	-10.70
Per Capita Consumption (Rs.)							
Year 3	3758	0.00	0.00	-0.21	-0.48	-4.18	-12.43
Year 5	3902	0.00	0.00	-0.21	-0.44	-3.13	-11.05
Year 10	4431	-0.02	-0.02	-0.74	-0.59	-3.14	-9.86
Tear 20	6520	-0.02	-0.41	-2.42	-0.71	-3.74	-11.86
Year 30	10888	-0.63	-1.85	-4.95	-0.81	-4.14	-12.03
Number of Poor (Million)							
Year 3	298.80	0.03	0.03	0.34	0.77	6.58	20.67
Year 5	292.35	0.03	0.03	0.33	0.72	5.04	18.90
Year 10	258.83	0.04	0.04	1.34	1.04	5.70	19.02
Tear 20	139.58	0.08	0.99	5.95	1.65	9.42	33.22
Year 30	39.43	2.10	5.94	17.48	2.45	14.34	49.65
Cumulative Emissions (mtc)	20353	-10.00	-20.00	-30.00	-10.00	-20.00	-30.00
	Absolute Levels in Rs. Billion						
Selected Activity Levels in Year 5							
Electricity-coal	216	216	216	173	162	142	129
Elecctricity-others	41	41	41	41	52	64	58
Electricity-oil	16	16	16	16	16	10	0
Electricity-CCGT	0	0	0	37	37	42	47
Industry-coal	3962	3961	3961	3895	3734	2330	2074
Industry-oil	0	0	0	0	164	1454	1350
Selected Activity Levels in Year 30							
Electricity-coal	1190	664	635	616	901	704	575
Elecctricity-others	10	269	289	280	36	197	251
Electricity-oil	4	4	4	0	4	4	4
Electricity-CCGT	0	229	227	224	230	221	202
Industry-coal	17526	17421	4879	1172	17362	16320	14317
Industry-oil	0	0	12689	16193	41	403	801

BAU: Business as usual

A10,A20,A30: Annual reduction of CO2 emission by 10%, 20%, 30% over BAU

C10,C20,C30: Cumulative reduction of CO2 emission by 10%, 20%, 30% over BAU

Table 2: Compensation Through Additional Foreign Capital Flows

	C30Comp	A30Comp
Additional Foreign Capital Flows (Rs. Billion*)		
Year 1	685 ($41)	2753 ($165)
Year 3	0	319 ($ 19)
Year 5	0	279 ($ 17)
Year 10	0	0
Tear 20	0	0
Year 30	0	0
Year35	768 ($46)	0
Cumulative over 35 years	1453 ($87)	4634 ($278)
Additional Foreign Capital Flows as % of GDP		
Year 1	15.4	69.7
Year 3	0.0	6.9
Year 5	0.0	5.4
Year 10	0.0	0.0
Tear 20	0.0	0.0
Year 30	0.0	0.0
Year35	2.2	0.0
Cumulative over 35-years	0.29	0.94
Selected Activity Levels in Year 5 (Rs. Billion)		
Electricity-coal	150	139
Elecctricity-others	68	63
Electricity-oil	0	0
Electricity-CCGT	55	51
Industry-coal boiler	2330	0
Industry-oil boiler	18214	3690
Selected Activity Levels in Year 30 (Rs. Billion)		
Electricity-coal	643	642
Elecctricity-others	292	287
Electricity-oil	0	4
Electricity-CCGT	234	228
Industry-coal boiler	629	629
Industry-oil boiler	17541	17729

Note: Compensation is through minimum additional foreign capital inflows that would maintain the consumption path of BAU scenario.

* Figures in parentheses are in Billions of US$.

Table 3: Tradable Carbon Quota for India: 1990-2025

Emission Quota Price Rs/tC	Cumulative sale of carbon quota over 35 years (mtC)	Cumulative purchase of carbon quota over 35 years (mtC)	Cumulative net sale of carbon quota over 35 years (mtC)	Year by which there is purchase of quota	Cumulative emission rise over Base Run (mtC)	Increase in NPV of per capita cons stream (%)
100	11207	3203	8004	26	1231	4.5
150	11711	2870	8841	26	394	6.8
200	11435	3231	8204	26	1031	9.0
300	10913	3930	6983	25	2251	13.2
350	10690	4312	6378	24	2857	15.3
400	10529	2992	7537	27	1698	17.3
450	11127	3298	7829	25	1406	19.4
500	11127	3611	7516	26	1719	21.5
550	10931	3911	7021	24	2214	23.5
600	10758	4201	6557	25	2678	25.4
650	10570	4481	6089	24	3146	27.3
700	10489	3925	6564	25	2671	29.2
800	10429	3907	6522	25	2713	32.9
900	10473	4139	6334	25	2901	36.6
1000	10457	4546	5912	24	3323	40.3

Notes: (i)Carbon quota of 822 mtc per year (1 tc/capita in 1990).
(ii) Rs. 100 was equivalent to US$ 6 in 1989-90, the base price for the model.
(iii) NPV is net present value at a discount rate of 10%.

Table 4: Activity Levels for Different Carbon Quota Prices in Year 30

(Rs. Billion)

Quota Price	Electricity				Industry	
(Rs./tc)	coal	others	oil	CCGT	coal boiler	oil boiler
BAU	1190	10	4	0	17526	0
100	1282	10	4	0	19065	0
150	1043	10	4	259	19899	0
200	1078	10	4	268	20656	0
300	1142	10	4	284	22042	0
350	1175	10	4	312	24186	0
400	828	377	4	297	23320	0
450	853	387	4	306	24082	0
500	875	399	4	314	24801	0
550	896	407	4	322	25464	0
600	917	417	4	329	26104	0
650	935	425	4	336	26637	0
700	956	435	4	344	11420	16385
800	995	452	4	358	4269	250468
900	1036	471	4	373	1736	28968
1000	1073	488	4	386	680	31225

Table 5: Selected Variables for Year 30 Under Different Scenarios

Scenario	GDP (Rs Billion)	Number of Poor (Million)	Carbon Emission (Mtc)	Carbon Emission / GDP (tc/Rs million)	PercentageChange over BAU GDP	Number of Poor	Carbon /GDP ratio
BAU	24595	0	1025	0.042			
QP100	26249	0	1106	0.042	6.7	-21.7	1.1
QP200	27916	0	1090	0.039	13.5	-38.1	-6.3
QP300	29404	0	1156	0.039	19.6	-49.7	-5.7
QP400	30807	0	1066	0.035	25.3	-58.0	-17.0
QP500	32397	0	1128	0.035	31.7	-66.1	-16.5
QP600	33795	0	1184	0.035	37.4	-71.7	-15.9
QP700	35126	0	1141	0.032	42.8	-75.5	-22.1
QP800	36440	0	1145	0.031	48.2	-79.0	-24.6
QP900	37789	0	1175	0.031	53.6	-82.2	-25.4
QP1000	39173	0	1213	0.031	59.3	-85.0	-25.7

Note: QP100 indicates carbon quota run with price Rs.100 and so on.

Figure 1: Annual Emission in Million tC

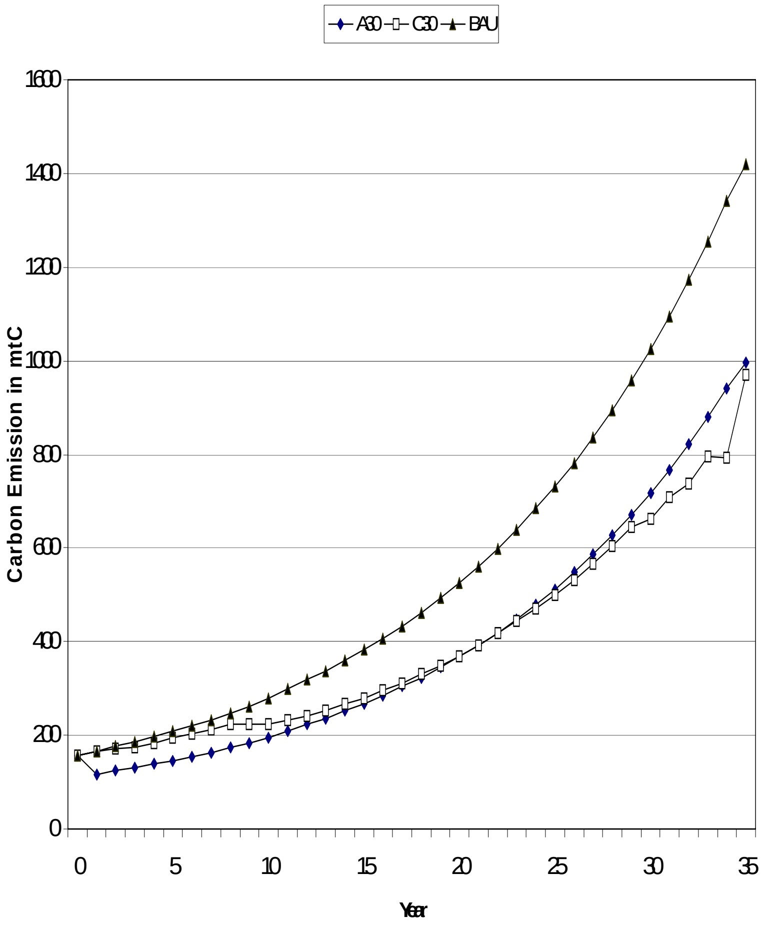
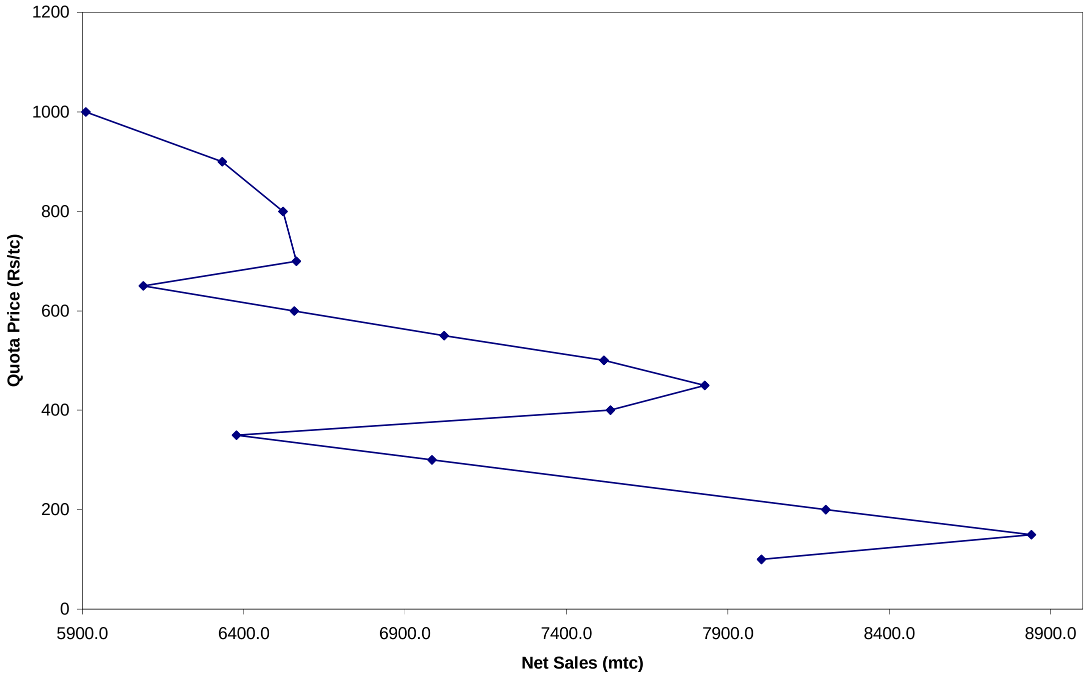


Figure 2: Cumulative Net sales of Carbon Quota



Appendix 1: Model Equations

The model's objective is to maximize 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.

Maximize $$W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} \quad \text{where} \quad U_t = \log(PC_t) \quad \text{and} \quad t = 1,2,...,T \qquad \textbf{(1)}$$

The logarithmic form of the utility function reflects the basic law of 'diminishing marginal utility of consumption' and provides a higher weight to the consumption of a poorer person. We consider n commodities and m activities. For empirical implementation of the model, n = 7, m = 11 and T = 35.

The above maximization is subject to several constraints. 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 the base year's prices.

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

where i = 1,2,…,n and t = 1,2,…,T **(2)**

where $[a_{ij}]$ 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 the per capita consumption (PC_t) is discussed below 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 $[u_{ij}]$, as is commonly called by economists in the input-output literature, links each production activity to the commodities they produce. When premultiplied to the vector of activity levels it gives the vector of commodity outputs. 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 this matrix and it represents numerically the commodity-wise composition of its gross output.

$$\mathrm{Y}_{i\ t} = \sum_{j=1}^{m} u_{i\ j} X_{j\ t} \qquad \text{where i = 1,2,…,n and t = 1,2,…,T} \qquad \textbf{(3)}$$

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.

$$GDP_t = \sum_{j=1}^{m}\sum_{i=1}^{n}(u_{i\ j} - a_{i\ j})X_{j\ t} \qquad \text{where t = 1,2,…,T} \qquad \textbf{(4)}$$

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

$$b_j X_{j\ t} \le K_{j\ t} \qquad \text{where j = 1,2,…,m and t = 1,2,…,T} \qquad \textbf{(5)}$$

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,

$$\{K_{\mathrm{i}1}\} = \{\overline{K}_{\mathrm{j}1}\} \quad \text{where } j = 1,2,...,m \qquad \textbf{(6)}$$

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

$$K_{j\ t} \le (1 - d_j)K_{j\ t-1} + Z_{j\ t-1} \qquad \text{where j = 1,2,…,m and t = 1,2,…,T} \qquad \textbf{(7)}$$

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 optimizing 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).

$$\sum_{j=1}^{m} Z_{j\,t} \leq S^{0} + s(GDP_t - GDP_0) + F_t \qquad \text{where} \quad t = 1,2,..,T \qquad \textbf{(8)}$$

where F_t is the exogenously specified level of foreign capital inflows in period t.

The investment (Z) by sector of destination 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

$$\sum_{j=1}^{m} k_{i\,j} Z_{j\,t} \leq N_{i\,t} \qquad \text{where i = 1,2,…,n and t = 1,2,…,T} \qquad \textbf{(9)}$$

where k_{ij} is capital coefficient indicating amount of i-th type of capital per unit investment in sector j.

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

$$\sum_{i=1}^{n} M_{i\,t} \leq \sum_{i=1}^{n} E_{i\,t} + F_t \qquad \text{where } t = 1,2,...,T \qquad \textbf{(10)}$$

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

$$E_{it} \leq E_{it-1}(1 + g_i^{EU}) \quad \text{where i = 1,2,…,n and t = 1,2,…,T} \qquad \textbf{(11)}$$

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

$$M_{it-1}(1+g_i^{MU}) \geq M_{it} \qquad \text{where i = 1,2,…,n and t = 1,2,…,T} \qquad \mathbf{(12)}$$

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

$$\{K_{T+1}\} \geq \{\bar{K}_{T+1}\} \qquad \mathbf{(13)}$$

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, but not static state.

$$\{Y_t\} = (1+\phi)\{Y_{t-1}\} \quad \text{for} \quad t > T \qquad \mathbf{(14)}$$

$$\sum_{j=1}^{m} \frac{u_{i\,j}\bar{K}_{j\,T+1}}{b_j} = (1+\phi)Y_{i\,T} \quad \text{or} \quad \sum_{j=1}^{m} \frac{u_{i\,j}(Z_{j\,T} - d_j K_{j\,T})}{b_j} \geq \phi Y_{i\,T} \qquad \text{where i = 1,2,…,n and t = 1,2,…,T} \quad \mathbf{(15)}$$

The above simplification might compromise the optimality of the 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

$$\text{Maximize} \qquad W = \sum_{t=1}^{T} \frac{U_T}{(1+\rho)^{t-1}} + \alpha U_T + \beta \qquad \text{where} \quad \alpha = \frac{1}{(1+\rho)^{T-1}\ \rho} \quad \text{and}$$

$$\beta = \frac{1+\rho}{\rho} \alpha \log(1+\phi') \qquad \textbf{(16)}$$

Where ϕ' is per capita consumption growth. The derivation is shown in appendix 2. This 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 equation 1, in which the weight attached to utility is the least in the terminal period. Were the objective function 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 above completes the description of 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? We turn to this now.

Consumption Expenditure Distribution and Poverty

Developing countries typically articulate two concerns other than aggregate economic growth: reduction of mass poverty and 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.[7] 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 (l^{p-1}, l^p) defines the class *p*. The lowest income households are included under the class $p = 1$, their per capita consumption being less than l^1 which is made equal to the poverty line so that households belonging to this class are identified as poor.

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[7] Parikh et al. (1995) describe how provision of basic needs can also be represented in this modeling framework.

The distribution of population across the three classes is given by a function $f(PC_t; LR, l^p)$ which represents the proportion of total population having per capita consumption expenditure less than l^p. Typically, in the literature[8], 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 and the class expenditure boundaries (l^{p-1} and l^p) for the *p*-th class and the value of the Lorenz Ratio (*LR*), each specified exogenously. The magnitude of population in the *p*-th class is given as

$$POP_{p,t} = POP_t \cdot pop_{p,t} \qquad \text{where} \qquad pop_{p,t} = f(PC_t; LR, l^p) - f(PC_t; LR, l^{p-1}) \tag{17}$$

$$f(PC_t; LR, l^p) = SLN\left(\frac{1}{LR}\ln\left(\frac{l^p}{PC_t}\right) + \frac{LR}{2}\right)$$ where SLN(z) is area under standard normal curve up to point z; i.e.,

$$SLN(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{s^2}{2}} ds \tag{18}$$

Note that $l^0 = 0$ and $l^3 = \infty$ 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:

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

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

$$PCC_{p\,t} = \sum_{r=1}^{R} PCB_{r\,p\,t} \qquad \text{where } t = 1,2,\ldots,T \tag{20}$$

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[8] See, for example, Planning Commission (1981 and 1995).

Each commodity bundle is composed of different commodities in fixed proportions. For example, $\mu_{i,r,p}$ 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 she spends on each of them. The consumption vector (*C*) of each class as the aggregate over the set of *R* consumption bundles.

$$C_{pit} = POP_{pi} \cdot \sum_{r=1}^{R} \mu_{irp} \; PCB_{rpt} \qquad \text{where i = 1,2,…,n and t = 1,2,…,T} \qquad \textbf{(21)}$$

The economy-wide consumption vector {*H*} is then represented by the sum of consumption vectors corresponding to the individual classes.

$$H_{it} = \sum_{p=1}^{P} C_{pit} \qquad \text{where i = 1,2,…,n and t = 1,2,…,T} \qquad \textbf{(22)}$$

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(.) above. It, however, permits a loop where the SLN function could be computed before obtaining the optimization 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 the two vectors: the activity levels {*X*} and an emission coefficient vector {e^X}. Apart from the production activities, 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:

$$EM_t = e^X X_t + e^C H_t + e^G G_t \qquad \text{where } t = 1,2,...,T \qquad \textbf{(23)}$$

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.

$$CEM_t = EM_t + CEM_{t-1} \qquad \text{where } t = 1,2,...,T \tag{24}$$

Carbon Quota

Finally, we describe the modifications made in model above in order to accommodate the carbon quota simulations. Equation (8) is modified to:

$$\sum_{j=1}^{m} Z_{j\,t} \leq S^0 + s(GDP_t - GDP_0) + F_t + P^{CQ}(\overline{EM_t} - EM_t) \qquad \text{where } t = 1,2,...,T \tag{25}$$

and Equation (10) is modified to

$$\sum_{i=1}^{n} M_{i\,t} \leq \sum_{i=1}^{n} E_{i,t} + F_t + P^{CQ}(\overline{EM_t} - EM_t) \qquad \text{where } t = 1,2,...,T \tag{26}$$

where P^{CQ} is the price of emission quota (Rs./tC) and $\overline{EM}_t$ is the annual allotment of CO_2 emission quota. This completes the description of the model equations.

Appendix 2

Derivation of equation (16) in appendix 1

Basically, we modify the original objective function W in Eqn. (1) by extending the summation of utilities U beyond the time horizon of T periods to ∞. Utility derived in time period *t* is expressed as a logarithmic function of per capita consumption PC_t in the same time period.

$U_t = \log(PC_t)$.

Beyond the terminal period *T* per capita consumption PC is assumed to grow at the post-terminal growth rate of ϕ' (= ϕ - n), where n is the post-terminal growth rate of population.

$PC_{T+\tau} = PC_T(1+\phi')^{\tau}$

$U_{T+\tau} = \log(PC_{T+\tau}) = \log(PC_T) + \tau \log(1+\phi') = U_T + \tau \log(1+\phi')$

$$W = \sum_{t=1}^{\infty} \frac{U_t}{(1+\rho)^{t-1}} = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} + \sum_{t=T+1}^{\infty} \frac{U_t}{(1+\rho)^{t-1}} = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} + \sum_{\tau=1}^{\infty} \frac{U_{T+\tau}}{(1+\rho)^{T+\tau-1}}$$

$$W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} + \sum_{\tau=1}^{\infty} \frac{U_T + \tau \log(1+\phi')}{(1+\rho)^T (1+\rho)^{\tau-1}}$$

$$W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} + \frac{U_T}{(1+\rho)^T} \sum_{\tau=1}^{\infty} \frac{1}{(1+\rho)^{\tau-1}} + \frac{\log(1+\phi')}{(1+\rho)^T} \sum_{\tau=1}^{\infty} \frac{\tau}{(1+\rho)^{\tau-1}}$$

The second term of the above expression for W can be simplified to αU_T where using the formula for the infinite geometric series ($\rho > 0$)

$$\alpha = \frac{1}{(1+\rho)^T} \sum_{\tau=1}^{\infty} \frac{1}{(1+\rho)^{\tau-1}} = \frac{1}{(1+\rho)^T} \frac{1}{(1-\frac{1}{1+\rho})} = \frac{1}{\rho(1+\rho)^{T-1}}$$

Denote the summation part of the third term of the above expression for W by S. Observe that S can be expanded in the form of the following infinite series

$$S = \{1 + \frac{2}{(1+\rho)} + \frac{3}{(1+\rho)^2} + \frac{4}{(1+\rho)^3} + \cdots\}$$

$$S = \{1 + \frac{1}{(1+\rho)} + \frac{1}{(1+\rho)^2} + \frac{1}{(1+\rho)^3} + \cdots\} + \{\frac{1}{(1+\rho)} + \frac{2}{(1+\rho)^2} + \frac{3}{(1+\rho)^3} + \cdots\}$$

$$S = \frac{1}{(1 - \frac{1}{1+\rho})} + \frac{1}{(1+\rho)}\{1 + \frac{2}{(1+\rho)} + \frac{3}{(1+\rho)^2} + \cdots\} = \frac{1+\rho}{\rho} + \frac{S}{1+\rho}$$

Collecting the terms involving S on the LHS we get

$$S\{1 - \frac{1}{1+\rho}\} = \frac{1+\rho}{\rho}$$

Solving for S from the above equation we get

$$S = \left(\frac{1+\rho}{\rho}\right)^2$$

Therefore the third term in the expression for W evaluates to β where

$$\beta = \frac{\log(1+\phi')}{(1+\rho)^T} S = \frac{\log(1+\phi')}{(1+\rho)^T}\left(\frac{1+\rho}{\rho}\right)^2 = \frac{\log(1+\phi')}{\rho^2 (1+\rho)^{T-2}} = \frac{1+\rho}{\rho}\alpha \log(1+\phi')$$

Thus, the expression for W is

$$W = \sum_{t=1}^{T} \frac{U_t}{(1+\rho)^{t-1}} + \alpha U_T + \beta$$

It may be observed that α depends only on ρ and *T* and given their typical values is usually greater than 1.

Table A1
Model parameters related to activities

Activities	Agri	Coal	Oil	Electricity produced from				Industry		Trans	Service
				Coal	Other	Oil	CCGT	Coal	Oil		
Commodities											
Base Year Input-Output Coefficients : [a]											
Agricult.	0.199		0.000		0.003			0.092	0.092	0.002	0.019
Coal	0.000	0.011	0.000	0.184				0.011	0.004	0.006	0.001
Oil	0.010	0.027	0.469			0.157	0.132	0.016	0.040	0.097	0.008
Electricity	0.007	0.096	0.005	0.248	0.248	0.248	0.186	0.031	0.031	0.015	0.007
Industrial	0.075	0.196	0.042	0.076	0.076	0.076	0.076	0.342	0.342	0.171	0.063
Transport	0.012	0.044	0.012	0.045	0.045	0.045	0.045	0.035	0.024	0.068	0.034
Service	0.038	0.074	0.064	0.045	0.045	0.045	0.045	0.119	0.119	0.079	0.058
Make matrix: [u]											
Agricult.	1	0	0	0	0	0	0	0	0	0	0
Coal	0	1	0	0	0	0	0	0	0	0	0
Oil	0	0	1	0	0	0	0	0	0	0	0
Electricity	0	0	0	1	1	1	1	0	0	0	0
Industrial	0	0	0	0	0	0	0	1	1	0	0
Transport	0	0	0	0	0	0	0	0	0	1	0
Service	0	0	0	0	0	0	0	0	0	0	1
Capital composition matrix: [k]											
Capital goods											
Agricult.	0.15	0	0	0	0	0	0	0	0	0	0
Industrial	0.8	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958
Transport	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Service	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
Base Year Output (10^{12} rupees)											
	1.810	0.064	0.219	0.140	0.054	0.022	0.000	3.028	0.000	0.418	1.832
Incremental capital output ratio: diagonal elements of [b]											
	2.046	1.483	1.500	5.348	6.750	6.750	6.270	0.828	0.845	3.286	1.110
Initial capital stock (10^{12} rupees)											
	3.704	0.095	0.329	0.749	0.365	0.149	0.000	2.508	0.000	1.374	2.034
Emision coefficient: [e] in grams/rupee											
CO2	0.55	39.36	13.98	399.52	0.00	221.40	85.00	17.46	12.04	47.92	1.11

1) I-O table [a] is aggregated from a 60x60 absorption matrix obtained from Planning Commission (1991).
2) Capital Coeff. matrix is obtained by taking the composition of investment demand from 1989-90 I-O matrix and assuming that the investment goods from agriculture sector are entirely used by agriculture sector itself.
3) Base Year capital stock is the product of ICOR and base year output.
4) CO2 emission coefficient are from Parikh, Panda and Murthy (1994).

Table A2

Model parameters related to commodities

Commodities	Agriculture	Coal	Oil	Electricity	Industry	Transport	Service
Budget shares of different goods in private consumption expenditure of households							
Bottom class: {c1}	0.5594	0.0011	0.0075	0.002	0.23	0.03	0.17
Middle class: {c2}	0.4213	0.0009	0.0135	0.0052	0.2803	0.0457	0.2331
Top class: {c3}	0.2915	0	0.0196	0.01	0.3139	0.075	0.29
Budget shares of different goods in government consumption expenditure							
{g}	0.0027	0.0001	0.0195	0.0253	0.1716	0.0257	0.755
Upper bounds on annual growth rate of Imports							
g^{MU}	0.05			0.02		0.05	
Upper bounds on annual growth rate of Exports							
G^{EU}	0.05				0.12		0.12
Base year values (10^{12} rupees)							
Private consumption: C_0	1.077	0.002	0.042	0.017	0.781	0.172	0.741
Govt. consumption: G_0	0.001	0	0.01	0.013	0.088	0.013	0.386
Export demand: E_0	0.029	0	0.005	0	0.204	0.031	0.099
Import demand: M_0	0.016	0.006	0.056	0	0.345	0.039	0.027

1) Budget shares in private consumption classes are from Parikh, Panda and Murthy (1994). Variations in budget shares are permitted around these base values as discussed in the text.

2) Government budget shares are from 1989-90 I-O matrix.

3)Imports and exports bounds appear only for some sectors indicated above.

4) Base year values are from 1989-90 I-O matrix.

TableA3
Other model parameters

1	Total investment in base year in 10^{12} rupees	0.991
2	Maximum domestic incremental savings rate	0.300
3	Annual growth rate of government consumption	0.050
4	Annual foreign borrowings in the dynamics-as-usual scenario (in 10^{12} rupees): Ft	0.120
5	Annual social discount rate:	0.100
6	Post-terminal annual growth rate	0.055
7	Population in base year in 10^6	821.9
8	Annual growth rate of population (%)	1.8
9	Lorenz ratio of private consumption expenditure distribution: LR	0.38
10	Upper cut-off level of expenditure for bottom class: (rupees)	2250
11	Upper cut-off level of expenditure for middle class: (rupees)	4000