Cost-effectiveness Assessment of Greenhouse Gas Mitigation Options:
A Proposed Methodology
Low Carbon Growth Strategies for India

The World Bank has been requested by the government of India to undertake a study, "Strategies for Low Carbon Growth." The study considers different options for low-carbon growth trajectories to fiscal 2031–32, the end of the 15th Plan. The main objectives of this study are to help the government to:

(1) Articulate a cost-effective strategy for further lowering the carbon intensity of the economy in ways that enhance national growth objectives by identifying synergies, barriers, and potential trade-offs, and estimate the financial needs to address the barriers and trade-offs
(2) Identify opportunities to facilitate leveraging of financial resources, including external finance, such as carbon finance, to support a low-carbon growth strategy, as well as explore the possible need for new financing instruments
(3) Raise national awareness and facilitate informed consensus on India's efforts to address global climate change.

For the first objective, a bottom-up model is being developed to project future demand for activities that emit greenhouse gases (GHGs), estimate costs associated with these activities, and calculate GHG emissions under different scenarios. The model considers the following sectors in the economy: electricity generation, transport, residential energy use, non-residential buildings, industry, and limited aspects of agriculture. It builds demand from bottom up and matches supply with demand. Demand is a function, among others, of gross domestic product (GDP), population, household size, household income (household expenditures used as a proxy), household location (urban or rural), and prices. Scenarios considered include carrying out the same economic activities (measured in passenger- and tonne-kilometers provided, tonnes of cement manufactured, and so on) but at varying levels of energy efficiency, resulting in different energy intensities and aggregate GHG emissions. Bottom-up modeling examines, amongst others, the incremental costs of lowering GHG emissions.

This note outlines the basic approach and assumptions common to all sectors, including the methodology for computing marginal abatement costs and switching prices of carbon. A summary of study methodology is given in a summary table at the end of this note. How each sector is modeled is provided in sector-specific methodology papers, which describe scenarios, data sources, and calculation and forecasting methodologies in more detail.

Marginal Abatement Cost and Switching Price of Carbon

Marginal abatement costs are calculated in this study as the present (discounted) values of costs for avoiding a one-tonne increase in the stock of carbon dioxide equivalent (CO_2e) in the atmosphere as of some specified future date. This study takes the view that, given the relatively short time horizon in the study, viz., the next 23 years, the stock of greenhouse gases (GHGs) placed in the atmosphere by the end of the study period, rather than annual flows, determine the long-term damage for the purpose of computing marginal abatement costs. Based on this assumption, GHG emissions are not discounted. By switching from analysis of flows to end-of-period stocks for GHGs, *when* GHG emissions occur does not affect the calculations of differences in GHG emissions between two scenarios. The structure of flows and timing, however, still matters with respect to costs and is reflected in the positive discount rate for costs. The principal reason for selecting this approach is that discounting CO_2e emissions assumes that something is known about the damage cost function, and further that damage is linearly proportional to the amount emitted. The science of climate change is not yet at the stage where there is a broad consensus on the quantitative relationship between CO_2e emitted in one country over the next two to three decades on the one hand, and damage ultimately caused globally and in that country on the other. Nor is it clear that the damage will be linearly related to the amount emitted.[1]

Marginal abatement costs are based on pair-wise comparison of alternatives achieving the same primary (generally non-climate-change related) objective. For example, the pair of activities may be two different vehicles transporting the same number of passengers or amount of goods over the same distance (that is, the same passenger kilometers or tonne kilometers over the life of each vehicle). For power generation, this may be two different generation modes providing the same kilowatt-hours (kWh) with similar temporal generation profiles. The comparison requires matching durations and time profiles of outputs (vehicle kilometers traveled, kWh, and so on). If the two alternatives have different life years, the shorter of the two will need to be replaced to match the alternative with a longer life. The start of outputs begins in year 0, and investments that have been made in preceding years are considered to be in year –1, –2, etc. Discounting is based on a mid-year assumption (0.5, 1.5, 2.5 years and so on).

Based on these assumptions, the marginal abatement cost calculated from a pair of activities A and B is approximated by

$$\frac{PV_A - PV_B}{CO_2e_B - CO_2e_A}$$

where PV_A is the present value of the costs incurred for the activity with lower emissions and higher costs over the life of the equipment or the program and CO_2e_A is the undiscounted cumulative CO_2e emitted. In principle, the numerator should subtract all non-CO_2e benefits. For example, a car equipped with a more fuel-efficient engine may also have exhaust treatment devices that dramatically reduce local pollutant emissions. However, in many, if not most, cases, it may be difficult to attribute incremental costs to various technical improvements (higher fuel economy, lower emissions, greater power, greater safety, less noise, and so on in the foregoing example). Given the additional data requirements to assign incremental costs to different benefits, non-CO_2e benefits are accounted for only when it is relatively easy to do so. Not subtracting all non-CO_2e benefits could over-estimate the marginal abatement cost.

The assumption that the stock at the end of the study period is more important than annual flows is considerably weakened when one of the two options in the pair-wise comparison has a very

[1] It is possible, for example, that there is a threshold stock level of CO_2e above which there is a chain of "autocatalytic" events causing accelerating damage. Such non-linear relationships have been known in other fields. For example, in the area of the effects of air pollution on health, it is generally accepted that the impact on premature mortality and morbidity of fine particulate pollution is not linear but begins to level off at high ambient concentrations, and that the dose-response relationships obtained at low ambient concentrations cannot be linearly extrapolated. Given the level of uncertainty and the relatively short time horizon selected for the study, it seems reasonable to consider the stock rather than flows of CO_2e.

long life. One such example is hydroelectric power, for which a life of 80 years is assumed in this study. However, for the sake of simplicity and consistency, the same methodology is followed, however long the life of a particular plant.

The study also computes the switching price of carbon for each pair of alternatives. This is the price of carbon that makes the choice between the two alternatives financially neutral. In computing the switching price of carbon, both the implicit value of CO_2e emissions and costs are discounted at the same rate. As with marginal abatement cost calculations, not accounting for all non-CO_2e benefits could over-estimate switching prices of carbon.

Scenario Building

Several scenarios will be examined in the bottom-up model to compute CO_2e emissions annually to the terminal year, and the investment, operating, and maintenance costs incurred. Where reasonable estimates can be made, associated transaction costs (for adopting more energy-efficient measures, for example) will be included. In addition, switching carbon prices relative to the reference scenario will be computed. Where linkages exist between the outcomes of different interventions, these will be clearly stated and their combined outcome will be adjusted to avoid double counting.

The selection of the scenarios depends on the objection function used. This is described in some detail below.

Objective function

One option for the objective function is to minimize overall costs.[2] However, when the objective function takes the form of cost minimization, the so-called knife-edge problem occurs. Without further restrictions, a simple cost-minimizing model will select a single technology for all new investments. Similarly, if retrofitting or replacement investment is cost-effective, all plants and equipment will be replaced or retrofitted. Furthermore, at a certain cost the solution will jump to a complete adoption of a different technology as being the lowest-cost option. This is also known as the “winner takes all” or “penny switching” phenomenon.

In actual markets it is clear that this phenomenon does not hold. Across a sector, different agents do not all make the same decisions, there are a variety of technologies in use at any one time, and new investment also encompasses a variety of technologies. Retrofitting or replacement also does not happen to every piece of equipment at the same time. For certain large agents, such as industrial companies or utilities, there may be a decision to invest in several different technologies to deliver the same product at the same time.

There are many reasons why the entire market does not switch to one technology choice for a given activity. One is that actors in markets often seek to minimize risks, not only costs. This is illustrated by portfolio-risk analysis of electricity supply options where mean-variance portfolio

[2] Cost minimization would generally be for achieving the primary objectives of different economic activities (provide passenger and freight transport, produce so many tonnes of cement, and so on), subject to constraints such as regulations and standards.

theory is used to deal with uncertainty and weigh relative cost and risk contributions of different investment options (see for example Jansen *et al*. 2006). Depending on one's aversion to risk and estimates of future price volatility as well as price levels, different decisions are reached. Another example is diversification at the expense of higher initial costs—such as Singapore diversifying away from piped natural gas to liquefied natural gas at a high cost to the economy. Investments to increase energy efficiency are known to face various barriers, including the principal-agent problem (first suggested by Jaffe and Stavins in 1994), inability to finance implementation, competing priorities even when funds are available, uncertainties about efficiency gains that will actually be achieved, high implementation costs in some cases, and lack of information.

In this study, exogenous constraints and vintaging are the primary means for addressing the knife-edge problem.

Exogenous Constraints At the moment at which a new technology becomes available, limits can be set on the amount of adoption of specified technologies per period in order to ensure that all new investment is not of the same type. This technique can also be applied to retrofitting, which might occur at any time according to relative costs and efficiencies of existing and new plants. These constraints are distinct from those that are used to model the uptake of new goods. Regarding the latter, the total uptake of new consumer durables can be constrained by a curve to represent the gradual acceptance of a new good by economic agents. This path is part of the exogenous forecast of the demand for consumer durables. Exogenous constraints here are additional factors that impede adoption, such as supply limitations or much higher expectations for returns by investors for energy efficiency enhancement projects.

Constraints on technology adoption can also be used to represent agents' desire for diversification as a way of increasing energy security (as in the Singapore example above). This is particularly relevant for large multi-plant enterprises and utilities, where there is substantial scope for diversification. Modeling choice for diversification would ideally require data at an enterprise level, but as a first approximation it could be applied to the sector as a whole. Constraints on the uptake of future new technologies will be most important where the sector is expected to grow rapidly.

Vintaging Vintaging of capital stock has two distinct dimensions. First, plant or equipment of a given technology can be differentiated solely by age. With a fixed plant life, replacement for the plant occurs at fixed dates, but with a stock of plants of different ages, replacements occur over time and more recent ones may be able to take advantage of newer technology which has only just become available, thereby producing a mix of technologies in place for each time period. To introduce this level of detail would require technology and age information on individual plants in the sector under consideration. The technique could be applied just to those sectors where such data are available. The treatment of replacement investment clearly requires data on plants by age and life expectancy in order to know when replacement is due. The issue of retrofitting can be treated without reference to the age of the plant in that all existing plants of a given technology could be candidates for retrofitting. However, without the introduction of an age factor, the knife-edge problem would exist in an extreme form, in that all or no plants of the specific type would be viable for the retrofit.

Second, different operating costs or retrofitting costs and the age at which a plant is replaced or retrofitted as an economic decision variable can be attached to plants of different vintages. If the oldest plants have the highest costs of operation, everything else being equal, a cost-minimizing model would tend to replace them before other existing plants of a given technology. This refinement would be most important where the bulk of the investment is in replacement and retrofitting.

Other approaches to tackling the knife-edge problem include the market sharing approach of the Canadian Integrated Modeling System (Rivers and Jaccard 2006), partial market penetration modeling (Boonekamp 2007), endogenous technical progress modeling (Loulou and Noble 2004), and utility-based models that account for heterogeneity in consumer tastes and product qualities (Anderson *et al*. 1989).

This study uses vintaging and exogenous constraints. Road vehicles and power plants are both vintaged. Exogenous constraints are taken from government five-year plans in the power sector. In the residential sector, affordability is taken into account by dividing households into centiles by total household expenditure in urban and rural areas separately (where underlying data are taken from the National Sample Surveys). The study team plans to vintage key industrial plants.

Subject to the foregoing constraints, the objective function will minimize cumulative discounted costs during the study period.

Costing

All costs are expressed in constant rupees, *viz*., in real terms. Economic analysis in the strict sense, in which all direct and indirect taxes and subsidies are excluded, is considered beyond the scope of this study because of the difficulties in tracing all taxes. To a limited degree and to the extent feasible, subsidies and differential taxes will be accounted for. Two examples are future prices of internationally traded fuels—they will be assigned forecast prices with transportation costs added even if fuels are subsidized on the domestic market—and differentiated taxes on "clean" versus ordinary vehicles.

The Discount Rate

Controversies surrounding the discount rate are arguably at the heart of climate change models and policy. This study takes the Ramsey equation,

$$r = \delta + \eta g \qquad \text{(Equation 1)}$$

where r is the interest rate (used to discount consumption), δ is the rate of pure time preference (used to discount utility), η is the elasticity of marginal utility, or, equivalently, the coefficient of relative risk aversion, and g is the per capita growth rate of consumption. *The Economics of Climate Change: The Stern Review* (2007) selects δ = 0.1 percent and $\eta = 1$. The latter prompted Dusgupta (2007) to suggest that "to suppose that *eta* is 1 is to suppose that starvation isn't all that painful!"

This study takes g as the growth rate of GDP per capita in India to March 2032 and varies it by year. The study sets $\eta = 2$ and δ = 0.1 percent. As shown below, the contribution of δ to r is negligibly small when $\eta = 2$ and g is relatively large, as is the case when the time horizon extends only to 2032. Stern considers $\eta = 2$ in a sensitivity analysis. These values give $r = 16$ percent for fiscal 2006–07 and $r = 14$ percent for fiscal 2007–08 (data from MOSPI 2008 and Census of India 2001). This is likely to fall to 12 percent in fiscal 2008–09, and in the longer run to about 10 percent.

The study will also examine discount rates outside of normal sensitivity analysis (which would involve varying the three parameters in equation 1). In particular, a flat discount rate of 10 percent will also be used in the bottom-up model.

Treatment of Terminal Year and Residual Value

This study takes 31 March 2032 as the end of the study period. There will be many items of equipment and plants that will have come on stream towards the end of the study period and that will have many years remaining. In these cases, a residual value of the equipment or the plant equivalent to the fraction of the initial cost (where the fraction is that of the years remaining) is assigned. This approach of assigning the fractional value remaining introduces additional approximations and does not yield the same switching carbon prices as the case in which every item of equipment is used until the end of its useful life.

In pair-wise comparison, the two options being compared may have different life years. In such cases, the item with a shorter life is replaced multiple times until the end of life of the longer-life item is reached. Unless the life years of the longer-life item is an integer multiple of the life years of the shorter-life item, the shorter-life item will have some years remaining in the last replacement. In that case, a residual value is assigned in the same way. Although doing so again widens the margin of error, given that residual value assignment occurs in the last replacement period, this approximation is considered acceptable in this study.

The study will, however, estimate the rate of decline in residual use values using “non-linear” assumptions where asset-specific information to support those assumptions is available.

For existing plants and equipment, residual values will not be assigned except where premature scrappage occurs. The specifics of where these cases arise and how they are handled will be explained in the methodology document for each sector.

Associated Implementation Costs

There are many interventions that are not implemented to the extent that would be suggested based on equipment purchase and operating costs alone, because there are other transaction costs associated with implementation, which can be significant. To the extent possible, this study will incorporate these additional transaction costs.

Rebound Effect

Increasing energy efficiency effectively reduces the cost of using energy and can increase demand. Two examples are an increase in garden lighting after the introduction of compact fluorescent light bulbs and greater kilometers traveled when car owners switch from gasoline to diesel-fueled vehicles. These effects can be large. A study of rebound effects in the Republic of Korea found the effect for refrigerators to be 72–84 percent (Jin 2007), that is, the actual energy savings achieved were only 16 to 28 percent of the reduction in energy consumption theoretically possible. A variant is the time rebound effect, which results when time savings lead to increased consumption. One example is faster transport leading to travelers increasing trip distances while keeping their total travel time constant (Goodwin 1978).

The current state of the literature on the rebound effect is summarized in UKERC (2007). Different mechanisms affect the aggregate energy savings and reductions in GHG emissions.

- Direct effects refer to increasing consumption of energy as a result of an effective reduction in the price of that energy service.
- Indirect effects occur when lower effective prices free up financial resources that are spent on other goods, services, and factors of production which in turn consume energy.
- Economy-wide effects arise from price and quantity adjustments in the economy following a fall in effective energy prices.

The foregoing effects are listed in order of increasing boundary. As with lifecycle analysis, discussed in the next section, defining the appropriate system boundary must consider the trade-off between comprehensiveness and the amount of resources required to undertake the analysis. The wider the system boundary, the more comprehensive but also the more resource-intensive is the study.

Most studies on the rebound effect have been conducted in high-income countries; very few studies are available using data from developing countries. The Stern Review (2007) overlooks the rebound effect altogether. Available studies suggest that direct rebound effects are likely to be higher in developing countries than in high-income countries, because the former are farther from the saturation point in the consumption of energy. Generally, a “win-win” situation whereby energy efficiency improvement reduces both the overall costs of operating an appliance and energy use (and hence GHG emissions) is more likely to have higher rebound effects because the lower expenditures on the appliance make more disposable income available to spend on other goods and services. In the extreme, if the freed-up income is spent on air travel, one may even have a “backfire”: a net increase in energy use and GHG emissions as a result of energy efficiency improvement (UKERC 2007).

Roy (2000) gives an example of direct and indirect rebound effects in rural India. A government program distributing free solar-charged battery lamps in a village found that daily hours of lighting increased from two to four, and kerosene that was previously used for lighting was instead used for cooking or sold. There is no question that the program improved the welfare of the participants, but did not result in net energy savings or GHG emission reductions.

This study will consider only direct rebound effects in a limited way. They will be modeled primarily using price elasticities. Sector-specific background papers will discuss the methodology in more detail.

Lifecycle Emissions

To assess lifecycle emissions of a given activity, all emissions, including “upstream” emissions, should be included and not just emissions after installation of the equipment. For example, solar panels have no GHG emissions during use, but could have considerable emissions during manufacture of the panels. In comparing alternatives, these upstream emissions should be included, or else “lifecycle” emissions could be seriously distorted. In including upstream emissions it is important to set up different accounting systems for keeping track of GHG emissions to avoid double-counting. To compare hydroelectric power plants with diesel generation sets, for example, it is important to include GHG emissions during production of cement and other materials used to build the hydro power plants. These emissions, however, should not be included in computing total CO_2e emissions across the entire economy, if cement manufacture also appears under industry. Separate calculations should be carried out depending on the objective of the calculations and steps taken to ensure that there is no double counting in each comparison of alternatives.

There is very little work done on upstream emissions. A detailed model called GHGenius is available for lifecycle assessment of transportation fuels, but India-specific data are not in the model (GHGenius 2004). This part of the bottom-up model will need to be built over the coming years in alignment with data collection.

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Summary Table

Percent discount rate, r	$r = 0.1 + 2 \times$ per capita GDP growth rate 10 percent representing the “global average” opportunity cost of capital
Marginal abatement cost	• Calculated for pair-wise comparison of equivalent activities • Duration and temporal production profiles matched for the primary outputs. If two different life-years, the shorter-life item is replaced until the end of life of the longer-life item. If the shorter-life item has any life remaining, a residual value is assigned. • GHG emissions undiscounted, costs discounted using a mid-year assumption. The first year in discounting is the year of the production of the primary output.
Residual value	A fraction of the capital cost equivalent to the fraction of the remaining years. Residual values are assigned to all plants and items of equipment that come on stream during the study period with remaining life in the terminal year (2032), or to the remaining life of the shorter-life equipment in the last replacement period in pair-wise comparison for marginal abatement cost calculations.
Switching prices	Calculated for scenarios as well as pair-wise comparison. Both the implicit value of CO_2e and costs are discounted at the same discount rate r. • For pair-wise comparison used in marginal abatement cost calculations, the price of carbon that would make the lower CO_2e option financially the same to the investor as the higher CO_2e alternative. • For scenario comparison, the price of carbon that would make the net present values of costs in two scenarios with different overall GHG emissions the same.
Scenario building	Vintaging and exogenous constraints are applied. Subject to these, the objective function is cost minimization. Switching carbon prices and total costs across years are computed.
Rebound effect	Only the direct rebound effects will be modeled using price elasticities. They will be included to the extent that credible data are available. Otherwise non-inclusion of the rebound effect will be noted.
Lifecycle emissions	Upstream emissions will be included as data become available. Non-inclusion of upstream emissions for lack of data will be noted.
Transaction costs	Particularly for those interventions for which associated transaction costs are known to impede adoption (energy efficiency improvement measures being one example), they will be included to the extent that data are available. Barriers to adoption will be discussed.