MIT Joint Program on the Science and Policy of Global Change

A Forward Looking Version of the MIT Emissions Prediction and Policy Analysis (EPPA) Model

Mustafa Babiker, Angelo Gurgel, Sergey Paltsev and John Reilly

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Henry D. Jacoby and Ronald G. Prinn,
Program Co-Directors

For more information, please contact the Joint Program Office

Postal Address: Joint Program on the Science and Policy of Global Change
77 Massachusetts Avenue
MIT E40-428
Cambridge MA 02139-4307 (USA)

Location: One Amherst Street, Cambridge
Building E40, Room 428
Massachusetts Institute of Technology

Access: Phone: (617) 253-7492
Fax: (617) 253-9845
E-mail: globalchange@mit.edu
Web site: http://mit.edu/globalchange/

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Mustafa Babiker[*†], Angelo Gurgel[*], Sergey Paltsev[*], John Reilly[*]

Abstract

This paper documents a forward looking multi-regional general equilibrium model developed from the latest version of the recursive-dynamic MIT Emissions Prediction and Policy Analysis (EPPA) model. The model represents full inter-temporal optimization (perfect foresight), which makes it possible to better address economic and policy issues such as borrowing and banking of GHG allowances, efficiency implications of environmental tax recycling, endogenous depletion of fossil resources, international capital flows, and optimal emissions abatement paths among others. It was designed with the flexibility to represent different aggregations of countries and regions, different horizon lengths, as well as the ability to accommodate different assumptions about the economy, in terms of economic growth, foreign trade closure, labor leisure choice, taxes on primary factors, vintaging of capital and data calibration. The forward-looking dynamic model provides a complementary tool for policy analyses, to assess the robustness of results from the recursive EPPA model, and to illustrate important differences in results that are driven by the perfect foresight behavior. We present some applications of the model that include the reference case and its comparison with the recursive EPPA version, as well as some greenhouse gas mitigation cases where we explore economic impacts with and without inter-temporal trade of permits.

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[*] MIT Joint Program on the Science and Policy of Global Change, Cambridge MA 02139. Author's contact e-mail: gurgel@mit.edu.
[†] Saudi ARAMCO, Dhahran, Saudi Arabia, 31311.

1. INTRODUCTION

This paper documents a dynamic forward-looking multi-regional general equilibrium model developed at the Joint Program on the Science and Policy of Global Change of the Massachusetts Institute of Technology (MIT). The model was built from the latest version of the recursive-dynamic MIT Emissions Prediction and Policy Analysis (EPPA) model. The most important new feature of the forward-looking dynamic version of the EPPA model is the perfect foresight behavior, represented by full inter-temporal optimization. It means agents are able to anticipate future changes when making consumption, savings, and investment decisions.

The forward-looking feature of the model makes it possible to better address economic and policy issues such as borrowing and banking of GHG allowances, efficiency implications of environmental tax recycling, endogenous depletion of fossil resources, international capital flows, and optimal emissions abatement paths among others. For example, in a recursive structure agents cannot look ahead to see resource depletion and hence would, if allowed, produce and consume these resources at marginal cost of production until they suddenly ran out of them. Forward-looking agents look ahead and see the implications of over consuming depletable resources and hence allocate these scarce resources optimally over time. The recursive EPPA model has adopted a variety of approaches that mimic forward looking behavior, or at least overcome some of the problems created by its myopic behavior. For the resource depletion issue, producers are, through parameterization of the production function, limited as to how much of the resource they can extract in a year, and this slows the rate of production and creates rents on the resource that have the effect of slowing consumption. Banking and borrowing are particular aspects of forward looking behavior that are important in modeling climate policies. In the recursive EPPA model these features are handled through forcing the model to generate a CO_2 price path that rises at the rate of interest, a theoretical result of what happens when a forward looking agent optimally allocates allowances through time. These approaches are meant to accommodate some aspects of forward-looking behavior in the recursive setup, or at least avoid obvious pitfalls associated with myopic expectations. However, they do not fully treat forward looking behavior.

Forward-looking (perfect foresight) behavior means that a model solution represents an optimal allocation of resources over time given policy constraints. The implication is that we generally expect the forward-looking version to simulate lower costs of a carbon policy than we would get with the recursive-dynamic structure because agents have the additional flexibility to adjust saving and consumption over time. However, as discussed further below, the forward-looking model also had to be simplified in some regards to make it computationally feasible and so it is not directly comparable in all respects to the recursive model. Economists typically consider forward-looking models a significant advance over the recursive structure because in reality agents expectations about the future affect current behavior. However, for policy purposes the tradeoff of less structural detail and the assumption of perfect foresight over all time (as opposed to uncertain expectations of what might happen in the future) leaves open the question of which formulation gives more realistic answers. Some problems simply demand the forward looking structure to get at basic issues, while for others the recursive structure may be more realistic. We thus see these two versions as complementary.

The forward-looking dynamic model was designed with the flexibility to represent different aggregations of countries and regions, different horizon lengths, as well as the ability to accommodate different assumptions about the economy, in terms of economic growth, foreign trade closure, labor leisure choice, taxes on primary factors, vintaging of capital, data calibration, and so on. The first obvious use of the forward-looking model is to understand the differences that myopic and perfect foresight behaviors create in terms of response to greenhouse gas mitigation policies. In this respect, the forward-looking model provides a complementary tool for policy analyses, to assess the robustness of results from the recursive EPPA model, or to point out important differences in results that are driven by the dynamic behavior. For purposes of such comparison, we created a version of the forward-looking model calibrated to follow a macroeconomic path similar to the original EPPA recursive model.

The "forward-looking dynamic" and "recursive dynamic" terminology refers to the solution approach which can also be interpreted as different representations of the expectations of economic actors. In the recursive version of the EPPA model, decisions about production, consumption and investment are made only on the basis of prices in the period of the decision, and this is often referred to as "myopic" expectations. Investments (which are converted to capital in the next period) are made as if input costs and output prices will remain unchanged in the future. In the recursive EPPA, savings and total consumption are fixed shares of income and so consumers do not alter their saving and consumption on expectations of future returns on investment or on expectations of changes in the price of consumption in the future. In a forward-looking model, optimization over time means that decisions today about production, consumption and investment are based on expectations that are realized in the model simulation. Thus, economic actors are characterized as having "perfect" expectations—they know exactly what will happen in the future in all periods of time covered by a modeling exercise. As modeled, consumers equate the marginal utility of consumption through time—this feature of an optimizing through time results in a phenomenon sometimes referred to as consumption smoothing because anticipated shocks in consumption are smoothed out by altering savings. This is a "substitution" effect. Agents also look ahead and change savings in anticipation of changes in investment opportunities. This is an "income" effect because, for example, more savings today in anticipation of higher returns creates more future income.[1]

The present report documents the details about the forward looking version of the EPPA model. Section 2 outlines an overview of the model. In section 3 we discuss the structure of the model, including the dynamic process and its differences from the recursive EPPA. Section 4 presents an application of the model including the reference case and greenhouse gas mitigation cases.

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[1] Rutherford (1999) provides a comparison of the general behavior of a model formulated as a recursive and forward-looking structure.

2. OVERVIEW OF THE MODEL

Similar to the recursive-dynamic version of the EPPA model, the forward-looking version simulates the evolution of the economy through time. It is capable of producing forecasts of macro and sectoral economic flows as well as of greenhouse gases and other key air pollutants emitted by economic activities. A primary use is to investigate the effectiveness and economic cost of policies to reduce GHG emissions. Some applications of the recursive version of EPPA are Jacoby *et al*. (1997), Jacoby and Sue Wing (1999), Reilly *et al*. (1999), Ellerman and Sue Wing (2000), Babiker *et al*. (2000a), Babiker *et al*. (2000b), Babiker *et al*. (2000c), Viguier *et al*. (2003), Webster *et al*. (2002), Webster *et al*. (2003), Reilly *et al*. (2002), Babiker *et al*. (2002), Babiker and Eckaus (2002), McFarland *et al*. (2004), Paltsev *et al*. (2003), Yang *et al*. (2005), Jacoby *et al*. (2006), Reilly *et al*. (2006), Kasahara *et al.* (2007), U.S. CCSP (2007), and Paltsev *et al*. (2007).

The EPPA model is a computable general equilibrium (CGE) model, which represents the circular flow of goods and services in the economy. The forward looking version is identical to the recursive-dynamic EPPA model in terms of the database and the structure of the model, including the representation of production technologies, trade flows, parameters and greenhouse gas inventories are as described in Paltsev *et al*. (2005) except as detailed below.

An important aspect of CGE models, and the most important difference between the EPPA recursive and EPPA forward-looking models as noted above, is the degree to which the model captures the dynamics of the economy through time represented by savings-investment decisions. In the recursive version, savings and investments are based only on the previous and current period variables. The forward-looking model, in contrast, has saving and investment decisions determined by a life-time optimization behavior that takes account of all future economic conditions as simulated by the model. Thus, the solution implies that agents represented in the model know the future with certainty and act on that knowledge.

The formulation of the forward-looking version of EPPA adopts the Arrow-Debreu framework, where the competitive equilibrium is determined by optimization decisions of consumers and producers. Each region of the model has a representative agent which maximizes welfare through the intertemporal allocation of income across consumption in different periods. The model has a complete representation of markets, which all clear simultaneously in equilibrium. The benchmark equilibrium is calibrated to match Global Trade Analysis Project (GTAP) data (Dimaranan and McDougall, 2002). The model solves in five year intervals starting at 2005. The horizon of the model is variable. In general a very long horizon is desirable in forward-looking models to avoid effects of terminal conditions, which by necessity are somewhat arbitrary, on the near term projections which are of most interest. However, solving the model can become numerically infeasible when the horizon is long and there are many regions and many sectors. Thus, computational limits become a practical consideration in choosing the model time horizon, and that choice then depends on the research application. With respect to horizon and region aggregation, three versions of the forward looking dynamic model have been evaluated: (a) a long-term version that solves for a horizon through 2100 with 15 regions and is meant to drive the climate model and handle issues related to stabilization of greenhouse gas concentration; (b) a short-term version that solves for a horizon through 2050 with 15 regions and is meant to address mitigation policy issues; and (c) a short to medium term two-region version (a single country and rest-of-the world) that currently solves for a horizon through 2070 and is meant to address mitigation policy issues at national level and with more focus on advanced energy supply technologies. **Table 1** presents the regions, technologies and resources available in the forward-looking EPPA.

Table 1. Countries, Regions, and Sectors in the MIT EPPA Forward-Looking Model.

Regions[†]	Sectors	Factors
United States (USA)	Non-Energy	Capital
Canada (CAN)	Agriculture (AGRI)	Labor
Japan (JPN)	Services (SERV)	Crude Oil Resources
European Union+ (EUR)	Energy-Intensive Products (EINT)	Natural Gas Resources
Australia & New Zealand (ANZ)	Other Industries Products (OTHR)	Coal Resources
Former Soviet Union (FSU)	Energy	Shale Oil Resources
Eastern Europe (EET)	Coal (COAL)	Nuclear Resources
India (IND)	Crude Oil (OIL)	Hydro Resources
China (CHN)	Refined Oil (ROIL)	Wind/Solar Resources
Higher Income East Asia (ASI)	Natural Gas (GAS)	Land
Mexico (MEX)	Electric: Fossil (ELEC)	
Central & South America (LAM)	Electric: Hydro (HYDR)	
Middle East (MES)	Electric: Nuclear (NUCL)	
Africa (AFR)	Electric: Solar and Wind (SOLW)	
Rest of World (ROW)	Electric: Biomass (BIOM)	
	Electric: (NGCC)	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	

[†] Specific detail on regional groupings is provided in Paltsev *et al*. (2005)

3. EQUILIBRIUM STRUCTURE AND DYNAMIC PROCESS

The forward-looking EPPA model is conceptually built on the classical Ramsey economic growth model. In this way, the model attempts to represent infinitely lived agents who maximize the present value of welfare from consumption, considering the trade-off between present and future consumption. Nevertheless, unlike the conventional Ramsey formulation, the forward-looking EPPA model is multi-regional and does not assume balanced growth paths, *i.e.* economic growth rates are allowed to vary across regions and over time. This latter feature is particularly crucial in applied modeling work since in the real world countries are usually not on steady growth paths and hence it is important that an applied model allow for both transitional dynamics and different rates of growth among regions.

3.1 The Optimization Problem

The utility function employed in the model is a constant intertemporal elasticity of substitution function (CIES). The model is solved so that representative agent in each region maximizes this utility function, subject to a budget constraint, technology and the evolution of capital stock in the economy. The representative agent in each region is endowed with an initial stock of capital, labor, and energy resources. Set r denotes the different regions and set t denotes time. Equation (1) represents the utility function:

$$U = \left[\sum_{t=0}^{T} \left(\frac{1}{1+\rho} \right)^{t} C_{rt}^{\ 1-\theta} \right]^{\frac{1}{1-\theta}} , \tag{1}$$

where C_{rt} is the aggregate consumption in region r and time t, ρ is a time preference or discount rate, θ is the inverse of the elasticity of intertemporal substitution and T is the terminal period[2].

The budget constraint can be thought of as the balance of income and expenditure over the horizon, represented by equation (2):

$$\sum_{t=0}^{T} p_{rt}^{C} C_{rt} = \sum_{t=0}^{T} w_{rt} \overline{L}_{rt} + p_{r0}^{K} K_{r0} + \sum_{t=0}^{T} \sum_{e} p_{ert}^{R} \overline{R}_{ert} - p_{T+1} K_{T+1} , \tag{2}$$

where p_{rt}^{C} is the price of aggregate consumption in region r and at time t, w_{rt} is the wage rate, $\overline{L}_{rt}$ is the labor endowment in efficiency units, p_{r0}^{K} is the initial price of a unit of capital, K_{r0} is the initial stock of capital, p_{ert}^{R} is the rate of return on energy resource in energy sector e (coal, gas and oil), $\overline{R}_{ert}$ is the energy resource supply, p_{T+1} is the price of the post-terminal capital and K_{T+1} is the stock of capital in period $T+1$. All prices are discounted by interest rate, *i.e.* they are present value prices.

The lifetime budget constraint means that the present value of consumption should be equal to the present value of wage income, the initial value of capital stock, the present value of resources being used to produce energy, less the value of post-terminal capital.

At each period t, an imbalance in a region's budget constraint accounts for capital flows (or foreign savings and investments) among regions, which may be interpreted as real assets in terms of a CGE model. In other words, capital flows are allowed among regions, in response to differences in real rate of returns. It means that the closure of the model regarding the balance of payments requires the capital flows to be equal to the current account deficit (or surplus), and they also will be equal to the differences between aggregate expenditures (private and public consumption plus investments) and aggregate income (returns to labor, capital, energy resources and tax revenue) as shown below:

$$kflow_{rt} = p_{rt}^{C} C_{rt} + p_{rt}^{I} I_{rt} - \left(w_{rt} \overline{L}_{rt} + r_{rt}^{K} K_{rt} + \sum_{e} p_{ert}^{R} \overline{R}_{ert} \right) , \tag{3}$$

where $kflow_{rt}$ is the capital flow to region r at time t, p_{rt}^{I} is the price of a unit of investment and r_{rt}^{K} is the capital rate of return.

According to this closure rule, if one country has a current account deficit, there must be a compensating current account surplus in other countries. A further important implication is that in every region any excess of aggregate expenditure over aggregate income today must be paid

[2] As numerical models cannot be solved for an unlimited number of periods, we impose a terminal condition to approximate the infinite horizon problem. For more discussion see Paltsev (2004) and Rutherford (2005).

back by the region in the future so that there is no net change in indebtedness over the model horizon. These conditions can be represented by the following relations:

$$\sum_r kflow_{rt} = 0, \quad and \quad \sum_t kflow_{rt} = 0 \ . \tag{4}$$

The budget constraint in (2) also can be written as an intertemporal budget constraint, considering a rate of return over the assets the agents possess today determining the value of assets tomorrow:

$$p_{rt}^C C_{rt} + p_{rt}^I I_{rt} + kflow_{r,t+1} = w_{rt}\overline{L}_{rt} + r_{rt}^K K_{rt} + \sum_e p_{ert}^R \overline{R}_{ert} + (1+i_t)kflow_{rt} \ , \tag{5}$$

where i_t is the rate of return at time t.

The foreign trade closure rule allows countries to temporarily run foreign accounts imbalances in response to, for example, a greenhouse gas mitigation policy as long as that imbalance is made up for in later years. The recursive EPPA uses a much simpler closure rule, fixing the foreign accounts exogenously and gradually phasing out any existing capital account imbalance. This feature of the forward-looking model provides an avenue of adjustment that is not available to agents in the recursive model.

Physical capital in the forward-looking model evolves in the economy through the creation of new capital from investments, considering a constant depreciation rate at each period. The capital accumulation equation is represented as

$$K_{r,t+1} = (1-\delta)K_{rt} + I_{rt} \ , \tag{6}$$

where δ represents the depreciation rate.

The maximization of (1) subject to (5) and (6), assuming for simplicity initial zero capital flows, generates first order conditions:

$$\left(\frac{1}{1+\rho}\right)^t \frac{\partial U(C_{rt})}{\partial C_t} = p_{rt} \ , \tag{7}$$

$$(1-\delta)p_{r,t+1}^K + r_{rt}^K = p_{rt}^K \ , \tag{8}$$

$$p_{rt} = p_{r,t+1}^K \ , \tag{9}$$

$$p_{rt} = (1+i)p_{r,t+1} \ , \tag{10}$$

where p_t represents the price of aggregate output, p_{rt}^K is the price of one unit of capital stock at period t and $p_{r,t+1}^K$ is the price of one unit of capital stock at period $t+1$. These prices arise as Lagrange multipliers (shadow prices).

3.2 MCP formulation

As actually implemented in the model, the above optimization problem is converted into a market equilibrium formulation using the mixed complementarity problem (MCP) algorithm (Mathiesen, 1985; Rutherford, 1995), and solved numerically using the PATH solver of the General Algebraic Modeling System (GAMS) software (Brooke *et al*., 1998). The MCP formulation takes the first order condition equations in the non-linear optimization problem along with their dual forms and represents the entire system as a set of simultaneous equations and inequalities. In Mathiesen's interpretation of Arrow-Debreu market equilibrium, the resulting MCP formulation can be described by three classes of equations: the zero profit, market clearance and income-expenditure balance conditions. These market equilibrium conditions are in turn defined from microeconomic theory using the duality concept in production and consumption theories (Paltsev, 2004).

In the following we briefly illustrate the structure of our forward-looking model in the MCP format, focusing on the key elements.

The zero profit condition means that economic profits should be equal to zero in equilibrium for any sector that produces a positive quantity of output or, if profit is negative, there is no production at all. Such a condition can be represented mathematically by the following relation[3]:

$$\textit{profit} \geq 0,\ \textit{output} \geq 0,\ \textit{output}^{*}(\textit{profit}) = 0. \tag{11}$$

The market clearance condition implies that a positive price exists for any good with supply less than or equal to demand, or the price will be zero if the good has an excess of supply. This condition can be represented mathematically by the relation:

$$\textit{Demand-supply} \geq 0,\ \textit{price} \geq 0,\ \textit{price}^{*}(\textit{demand-supply}) = 0. \tag{12}$$

The income balance condition means that total expenditure should be equal to the total value of endowments for each agent. This condition should be satisfied both inter-temporally and over the life time. Inter-temporally, for each agent current income plus borrowing should equal current expenditure plus savings. Over the agent's lifetime, the present value of all future incomes should equal the present value of all future expenditures.

Suppressing the region subscript r, the translation of these three conditions produces the following key complementarities relations in the forward-looking model:

(1) The zero profit conditions:

a) The aggregate consumer price index is equal to the unit cost of aggregate consumption in equilibrium. This zero profit condition is associated with the level of aggregate consumption according to:

$$E_t^C(p_{it}, p_{jt}) - p_t \geq 0,\ \ C_t \geq 0,\ \ [E_t^C(p_{it}, p_{jt}) - p_t]C_t = 0, \tag{13}$$

where E_t^C is the unit expenditure function, p_t is the consumer price index and C is the aggregate consumption level.

b) The price of capital in the next period is equal to the unit cost of aggregate investment. This zero profit condition is associated with the level of aggregate investment according to:

$$E_t^I(p_{it}, p_{jt}) - p_{t+1}^K \geq 0,\ \ I_t \geq 0,\ \ [E_t^I(p_{it}, p_{jt}) - p_{t+1}^K]I_t = 0, \tag{14}$$

[3] The symbol * denotes complementarity between variables. Given an expression as $x^*y = 0$, where $x \geq 0$ and $y \geq 0$, it means that $x_i y_i = 0$ for all $i = 1, \ldots, n$. The variables x_i and y_i are called a complementary pair and are said to be complements to each other.

where E_t^I is the unit investment cost function, I_t is the level of investment and p_t^k is the price of capital.

c) The price of capital at time t must be equal to its returns (per unit of capital) plus the price of capital at next period netted for depreciation. The zero profit for capital accumulation is associated with the level of capital stock according to:

$$r_t^K + (1-\delta)p_{t+1}^K - p_t^K, \;\; K_t \geq 0, \;\; [r_t^K + (1-\delta)p_{t+1}^K - p_t^K]K_t = 0, \tag{15}$$

where K_t is the level of capital stock and r_t^k is the rate of return on capital.

d) The price of output from sector *i* is equal to its unit cost. This zero profit condition is associated with the level of production according to:

$$E_{it}^Y(p_{jt}, p_t^F) - p_{it} \geq 0, \;\; Y_{it} \geq 0, \;\; [E_{it}^Y(p_{jt}, p_t^F) - p_{it}]Y_{it} = 0, \tag{16}$$

where E_{it}^y is the unit production cost function, Y_{it} is the level of output and p_{it} is the output price.

(2) The market clearance conditions:

a) Supply equals demand in each commodity market. This condition is associated with a positive output price in equilibrium according to:

$$\begin{aligned}&\sum_j D_{ijt}^{ID}(p_{jt}, y_{it}) + D_{it}^C(p_{it}) + D_{it}^I(p_{it}) + D_{it}^M(p_{it}) - D_{it}^X(p_{it}) - y_{it} \geq 0, \;\; p_{it} \geq 0, \\ &[\sum_j D_{ijt}^{ID}(p_{jt}, y_{it}) + D_{it}^C(p_{it}) + D_{it}^I(p_{it}) + D_{it}^M(p_{it}) - D_{it}^X(p_{it}) - y_{it}]p_{it} = 0,\end{aligned} \tag{17}$$

where *D(.)* are the compensated demand functions, and where the superscripts *ID* denotes intermediate demand, *C* final demand, *I* investment, *X* exports and *M* imports.

b) Supply equals demand in each primary factor market (labor, land, and energy resources). This condition is associated with positive prices for each fully employed factor according to:

$$\sum_j D_{jt}^F(p_t^F, y_{jt}) - F_t^F \geq 0, \;\; p_t^F \geq 0, \;\; [\sum_j D_{jt}^F(p_t^F, y_{jt}) - F_t^F]p_t^F = 0, \tag{18}$$

where D_{jt}^F are factor demand functions, F_t^F is factor supply, and P_t^F is the price of factor service (wages and resource rents).

c) Supply equals demand for capital accumulation. The capital accumulation process is associated with a positive price for capital according to the complementarity relation:

$$I_t + (1-\delta)K_t - K_{t+1} \geq 0, \;\; P_t^k \geq 0, \;\; [I_t + (1-\delta)K_t - K_{t+1}]P_t^k = 0. \tag{19}$$

(3) The income-expenditure balance conditions

a) The present value of the stream of incomes over the agent's lifetime equals the present value of the agent's expenditures over her lifetime. This lifetime income balance is associated with the agent's lifetime welfare index. The agent's income-expenditure balance is given by:

$$p_0^K K_0 + \sum_{F,t} p_t^F F_t^F - p_{T+1}^K K_{T+1} = \sum_t P_t C_t, \tag{20}$$

which is equivalent to equation (2) in the optimization problem.

b) The sum of agent's income and her borrowings in any current period must equal the sum of her expenditures and savings. This period-by-period balance is associated with the period welfare index for the agent. This intertemporal income-expenditure balance, which is equivalent to that in equation (5) of the optimization problem, is given by:

$$P_t\, C_t + E_t^I I_t + S_t = \sum_F p_t^F F_t^F + r_t^K K_t + B_t, \tag{21}$$

where S is saving and B is borrowing.

The equations system (13) to (21) represents an abstract version of the model in MCP. Except for capital accumulation, investment activity and welfare, the implementation of the forward-looking model employs the same functional forms used in the recursive EPPA model (for documentation, see Paltsev *et al.*, 2005).

The next subsections focus on addressing some practical issues in the implementation of the forward-looking version of EPPA.

3.3 The infinite horizon and the terminal condition

The optimization problem posed by the numerical model is necessarily restricted to a finite horizon. The primary issue raised is that the representative agent has no incentive to accumulate capital beyond the finite horizon, and thus has the tendency to consume all income and invest nothing in the last period. This final period behavior has repercussions for earlier periods as agents look forward and see the value of investment reduced because it will only be used through the terminal year. Often simpler models address this problem by extending the horizon of the model to hundreds of years and then a fairly arbitrary terminal condition can be assigned, and it will have little effect on the near term solution. For a model of our complexity we find it infeasible to solve the model for hundreds of years, and with a shorter horizon the formulation of the terminal condition requires greater care. The solution is to require an investment level in the final period that approximates the level that would be obtained in the infinite horizon problem. In this way, the solution of the finite horizon problem is very close to the solution of the infinite horizon problem.

The terminal condition we use assigns a post-terminal growth rate to investments. The growth rate of investment in the terminal period is required to be equal to the growth rate of consumption in that period, as shown by the equation:

$$\frac{I_{rT}}{I_{rT-1}} = \frac{C_{rT}}{C_{rT-1}}. \tag{22}$$

The equilibrium condition of the infinite horizon problem is balanced growth—the economy and all sectors growing at the same constant rate. As described by Rutherford (1998), this condition assures a balanced investment growth without imposing a specific capital stock target or a specific exogenous growth rate in the post-terminal period. It means that, after a policy shock, the model can determine a different growth path. With an exogenously specified rate of growth of investment in the final period, the model would be forced to return to that growth rate by the end of the period, and that would have consequences for estimates of policy costs in earlier years.

Comparison of policies that have different implications for growth can also require evaluation of welfare difference in the post-terminal period. If the horizon is long enough, the discounted value of these difference may be unimportant, but experimentation with the model showed significant differences when the horizon was truncated to 50 to 70 years. We thus create an index that computes an estimate of the infinite horizon welfare as follows. First we formulate the aggregate index as a two period problem, the period from present to the model horizon, and the period beyond the horizon of the model,

$$Welfare = \left[(1-\beta)U^{1-\theta} + \beta U_T^{1-\theta}\right]^{1/1-\theta}, \tag{23}$$

where θ is, as defined previously, the inverse of the elasticity of intertemporal substitution, $Welfare$ is defined as the welfare index over the infinite horizon; U is life-time welfare over the horizon of the model, and U_T is the annual welfare in the last period (T) of the model that with an appropriate estimate of β, the share weight of the post-horizon welfare, is used to approximate welfare in the post-T period. For interest rate r we approximate β by using the GDP growth rate g in the formula:

$$\beta = \frac{\dfrac{(1+g)^T}{(1+r)^T} \cdot \dfrac{(1+g_T)}{(r-g_T)}}{\sum_{t=0}^{T} \dfrac{(1+g)^t}{(1+r)^t} + \dfrac{(1+g)^T}{(1+r)^T} \cdot \dfrac{(1+g_T)}{(r-g_T)}}, \tag{24}$$

where $\dfrac{1+g_T}{r-g_T} = \sum_T^{\infty} \dfrac{(1+g_T)}{(1+r)} \cdot \dfrac{(1+g_T)^t}{(1+r)^t}$.

The first term of the numerator of (24) is the final period growth discounted from T to today. This discount factor is multiplied times the discounted growth factor from T to infinity. The denominator is the sum of growth over the horizon (t=0 to T) plus the numerator.

3.4 Calibration

The calibration of the forward-looking EPPA model follows in several ways the same process as the recursive model, except for the treatment of economic growth, the evolution of capital stock, and the depletion of fossil resources. In common with the recursive version of EPPA, the GTAP base year data we use are for 1997. We have adjusted parameters to match historical data through 2005, as in the original recursive version of the model. In the forward-looking model we use the initial benchmarking to 2005 to essentially simulate the full data set we need so that the model can be simulated with 2005 as the base year, and 2010 as the first forecast year. If we simulated with 1997 as the actual base year of the model then future policy changes would affects outcomes that are now history. The initial benchmarking to create 2005 as a base year avoids this conflict with reality.

One of the more important aspects of the calibration of the forward-looking model is the consistency among capital stock, capital earnings, the interest rate, growth rate of the economy, and the rate of depreciation. Two general problems arise: One is that some of these variables are poorly measured. The second is that because of the business cycle a particular base year may not reflect a longer run equilibrium that is consistent with observed average growth rates. For example, the capital stock is, in general, a poorly measured variable, and estimates of it frequently are not compatible with the observed capital earnings, prevailing interest rates, investment levels, and assumed depreciation rates which themselves are poorly measured. By incompatibility we mean that the apparent rate of return on capital appears too high or too low, or that the level of investment recorded in the data, if sustained would lead either to abnormally high or abnormally low growth for some time. In other words, the data would seem to imply that the economy is far from a long run equilibrium growth path. While better measured, capital earning and investment levels for any specific year can be far from equilibrium levels because of the presence of business cycles, and so these levels are then not the right ones to use to benchmark long run growth. So to the extent the implied equilibrium growth path is far different than the historical growth experience of the economy, it seems more likely that estimates of one or more of these variables is in error or indicates short-run disequilibrium reflecting business cycle behavior. The usual approach is to use estimates for those variables whose values are thought to be more reliable and infer the values of the remaining variables from the first order conditions for capital and investments in equations (8) to (10).

We start by accepting the steady state real interest rate as known (as 4% per year in developed countries and 5% in developing countries). From (9) and (10) we can determine the initial level of the price of one unit of capital:

$$p_{t+1}^{K} = p_t^{K}(1+\bar{r})^{-1} = p_t \Rightarrow p_t^{K} = (1+\bar{r})p_t . \tag{25}$$

Assuming a 5% and 7% depreciation rate per year in developed and developing countries, respectively, the initial rate of return of capital can be found by substituting the values of p_t^K, p_{t+1}^K, p_t and p_{t+1} from equation (25) into equation (8):

$$\bar{r}^K = \bar{r} + \delta . \tag{26}$$

Based on the returns to capital (or capital earnings) observed in the base year (RK_0), the initial capital stock can be obtained from:

$$K_0 = RK_0 / \bar{r}^K . \tag{27}$$

Assuming that an economy is in equilibrium, investment should cover the depreciation and the growth rate of the economy. Thus, the total investment at the initial period can be calculated as:

$$I_0 = K_0(g+\delta) , \tag{28}$$

where g is the benchmark growth rate of the economy. The benchmark growth is an “average” growth rate for the initial period, recognizing that growth in any single year may be distorted by business cycle behavior of the economy. Note also that I_0 is likely to be inconsistent with the observed investment in the initial year. Thus, we adjust the initial investment level in the data to be equal to I_0 balancing the initial accounts with a corresponding change to the endowment of the representative agent. This assures that the growth rate in early periods will be consistent with recent observation.

Finally, it is necessary to define the value of the intertemporal elasticity of substitution in Equation (1) and the time preference parameter ρ. We adopt the value of 0.5 as the inter-temporal elasticity of substitution. The time preference parameter is then determined from the relation:[4]

$$\rho = \frac{1+\bar{r}}{(1+g)^{1-\theta}} - 1 . \tag{29}$$

3.5 Some key features of the dynamic process in the model

The evolution of the economy in the forward-looking version of EPPA involves a number of features. Capital accumulation is one of them, and its evolution, as shown before, is a result of the optimization process of the model. Other sources of growth are: the increase of labor supply and its productivity over time, the changes in energy productivity, the evolution of natural resources stocks and the availability of "backstop" energy-supply technologies. The changes in energy productivity and the "backstops" follow basically the same approach as in the recursive EPPA (Paltsev *et al.*, 2005). The others dynamic features are detailed below.

3.5.1 The economic growth path

In addition to its rich representation of regions, commodities and time horizon, a distinguishing feature of the forward-looking EPPA is its modeling of the economic growth dynamics. Together with the capital accumulation, the growth in labor supply and productivity are crucial to determine the growth paths of the economies in the model. The usual approach in forward-looking CGE models is to specify exogenous growth rates for population and labor productivity. In addition to that approach we have introduced the possibility to endogenously determine the growth path of labor productivity needed to produce a pre-specified GDP growth path, taking into account all the other endogenous factors affecting growth. A major reason for including this feature is that we wanted to make a controlled comparison with the recursive EPPA in terms of energy use, GHG emissions, and response to GHG policy without having differences in reference GDP being a confounding factor. To endogenously estimate the labor productivity growth needed to generate a pre-specified GDP growth we add the following equation to the model:

$$w_{rt} L_{rt} \lambda_{rt} + r_{rt}^{K} K_{rt} + \sum_{e} p_{ert}^{R} R_{ert} = \{ w_{r0} L_{r0} + \bar{r}_{r0}^{K} K_{r0} + \sum_{e} p_{er0}^{R} \bar{R}_{er0} \} (1 + g_{rt}) , \tag{30}$$

where λ_{rt} is the endogenously estimated labor productivity growth factor and g_{rt} is the exogenously specified GDP growth rate of the economy. As noted above, in the current versions

[4] This benchmarking is implicitly embedded in the initial calibration of the model to a balanced growth path, ensuring consistency among the values of $\bar{r}$, g, ρ, θ and δ (Rasmussen and Rutherford, 2001).

of the forward-looking EPPA, the g_{rt} rates used to drive the growth path are taken from the reference scenario simulated by the recursive EPPA model. This approach facilitates comparison of results produced by the forward-looking EPPA with those produced by the recursive EPPA. The relationship in Equation (30) can be eliminated for other applications. Also note that Equation (30) only operates in simulations that establish a reference case for the model, *i.e.* absent GHG policy. As noted earlier, how consumption shifts through time in response to a GHG policy is one of the interesting questions that a forward-looking model can address. Consumption shifting provides another avenue of adjustment not present in the recursive model, and being able to begin from identical reference GDP paths in both versions allows us to see directly how important this avenue of adjustment is for a given GHG policy, and what we may be missing in the recursive model.

3.5.2 The fossil fuel resources depletion

The forward-looking version of EPPA treats fossil fuel resource inputs in a similar way to the recursive model. In both models resources are subject to a depletion based on physical production of fuel. The amount of resource used to produce fuel in a period is subtracted from the total reserves of that resource, reducing its total supply and in turn endogenously affecting its price. In both models, resource extraction is controlled by an elasticity of substitution between the fossil fuel resource and the bundle of other inputs that is calibrated to match a medium term price elasticity of supply of the produced commodity (see Paltsev *et al.*, 2005). Nevertheless, in the recursive model the myopic behavior creates a risk of over extraction whereas in the forward-looking model this risk is avoided by the fact that the full extraction path is determined simultaneously taking into account future prices and demands for the produced fossil fuel.

The depletion module in the forward-looking EPPA is represented by adding the following equation to the model:

$$R_{ert} = \overline{R}_{er} - \sum_{tt=0}^{t} D^{R}_{tt,r,e}(P^{R}_{tt,r,e}, y_{tt,r,e}), \tag{31}$$

where $\overline{R}_{er}$ is the exogenously specified amount of conventional reserves inclusive of any future additions from exploration and $D^{R}_{t,r,e}(.)$ are the amounts of the resource depleted through production from the initial time period *tt* up to the current period *t* of the model. The non-conventional reserves (shale oil) have a similar depletion representation in the model.

A key conclusion of the Hotelling model of depletion is that resource rent will rise at the interest rate (Hotelling, 1931). The "perfect foresight" representation in the forward-looking model should drive the resource rent path toward such a profile. Attempts to evaluate whether the actual resource price for oil rises at the discount rate often have concluded there is little evidence to support this theoretical result. In the forward-looking EPPA, the actual depletion path may vary from the Hotelling results because of additional aspects of the model such as the specification of multiple grades of the resource (*i.e.* quasi backstops) and limits on production as represented by the regional production functions that produce Ricardian rents as well as Hotelling rents. For example, a key conclusion of a pure Hotelling model is that the lowest cost resources should all be produced first, but clearly that can not explain why relatively expensive oil deposits in the North Sea, Alaska, and elsewhere are being produced while there remain very inexpensive deposits in the Middle East and Asia. The production function approach that, through the elasticity of substitution, limits expansion of production of lowest cost reserves thus allows multiple resource grades to be produced at the same time. The forward-looking EPPA model creates the possibility to examine more completely the implications of forward-looking behavior on resource use that more realistically includes other constraints and considerations than does a simple Hotelling framework.

3.5.3 Vintaging of Capital Stock

The recursive EPPA model adopts a vintaging scheme of capital where a share of the capital produced in each period, set at 30% in standard cases, is vintaged. Each vintage is distinguished by age and technology, frozen as a Leontief technology at the input shares that were optimal when it was put in place. Five separate age classes are carried over and each is subject to depreciation. The remaining capital remains malleable. In the forward-looking version with the full account of all regions, it is computationally infeasible to incorporate such a detailed vintaging scheme. A simpler putty-clay type formulation is adopted where 30% of the initial capital stock in each sector is frozen (non-malleable) and is sector-specific, with two types of production activities for each commodity being specified, new vintage and extant production. The new vintage production employs the malleable portion of capital (the putty) and has the usual nested technologies and substitution characteristics. The extant production employs the non-malleable portion of capital (the clay) and uses technologies that allow for very limited substitutability among inputs. In each period new investment produces malleable capital out of which 30% will be locked in as non-malleable during the next period. The new additions to the stock of non-malleable capital in each sector for the start of the next period are allocated via a transformation activity to each sector in direct proportion to the amount of malleable capital added in each sector for the current period. Stocks of capital accumulate subject to usual depreciation and in each period each unit of capital produces one unit of capital service to the corresponding production sector. The energy-efficiency characteristics of the non-malleable capital are updated with a lag to capture the differences in energy efficiency across the different ages of capital stock. This approach captures some of the key aspects of vintaging—limiting the ability to redeploy capital across sectors and limiting the ability to substitute away from energy in the short term—while reducing the computational burden of maintaining distinct multiple vintages. The intention is that the single stock of vintaged capital in each sector approximates the average response of the five distinct vintages of the recursive model. As a result forward-looking behavior will take into consideration the fact that investment in, for example, period 5 will continue to operate with its characteristics semi-frozen until it fully depreciates.

3.5.4 Foreign Trade

Much of the structure of international trade in the forward-looking model is the same as that in the recursive EPPA model. In particularly, all goods (except for crude oil, and biofuels[5]) are modeled as differentiated products (Armington goods) with bilateral trade calibrated to the 1997 flows using nested CES functions, where the top nest controls substitution between domestic and foreign and the bottom nest controls substitution across the different origins of foreign goods. One aspect of the CES function is that it is share-preserving and calibration would imply that bilateral trade patterns are not affected by the differentiated future patterns of economic growth across world regions and countries. To address such a potential shortcoming we adjust the CES coefficients in the forward-looking model along the baseline to reflect the differentiated regional patterns of economic growth. The adjustment used is to scale each region bilateral trade coefficients by the growth rate of that region relative to the growth rates of its trading partners for each commodity and each time period. The growth-weighted adjustment scheme has the advantage of keeping global trade growth at pace with overall economic growth along the baseline, and with this adjustment the solution time of the model was greatly reduced.

3.6 Other Developments in the Model

Some additional features included in the forward-looking model are intended to better represent some aspects of the economy and can be turned on or off, depending on the goals of the research. These features include a representation of labor leisure choice, factor taxes and consumption taxes.

3.6.1 Labor-leisure choice

The recursive EPPA model treats labor supply as completely exogenous (except for special versions of the model). We have introduced a labor-leisure choice in the forward-looking EPPA. Among other reasons, this feature makes it possible to evaluate the implications of changes in labor taxes on labor supply. The modeling of labor-leisure choice introduces some small changes in the optimization problem described before, without changing its principles. The utility function now becomes a function of "full" consumption (Z_{rt}), which accounts for consumption of goods and services and consumption of hours of leisure (l_{rt}). The possibility of substitution between aggregated consumption of goods and leisure is controlled by an elasticity of substitution $\sigma = 1/(1-\eta)$ according to functional relation:

$$Z_{rt} = \left[\alpha C_{rt}^{\eta} + (1-\alpha) l_{rt}^{\eta}\right]^{1/\eta} \quad . \qquad (32)$$

The calibration of the relation in (32) follows the same procedure as in Babiker *et al.* (2003), with the benchmark leisure-labor ratio of 0.25, implying α of 0.2, and with the elasticity of substitution between consumption and leisure, σ, set to equal one. Such calibration yields an uncompensated own-price labor supply elasticity of 0.25, an estimate that is consistent with the empirical literature (Yang *et al.*, 2005).

[5] Biofuels are not included in regionally disaggregated versions due to the need for computational efficiency.

3.6.2 Capital and labor taxes

The recursive EPPA model does not distinguish labor and capital tax revenues from the total value of labor and capital inputs and endowments. This is because the GTAP database (Hertel, 1997; Dimaranan and McDougall, 2002), on which the EPPA model is calibrated, does not separate the factor taxes from the factor input flows. As discussed in Gurgel *et al.* (2006), despite the attempt to improve the representation of factor taxes in GTAP 6, this task is still largely incomplete in GTAP.

The forward-looking version of EPPA includes an option to explicitly represent these taxes in the benchmark dataset. To do so, factor taxes were estimated following the same procedure in Babiker *et al*. (2003) and Gurgel *et al*. (2007). To introduce these taxes into the model we split the gross factor earnings between tax revenue and net flow of factor services and move the tax revenue to the representative agent as part of his income (a lump sum recycling of government tax revenues to the representative agent). Also, the consumption taxes in EPPA were re-estimated, and the income-expenditure balance is maintained by lump sum transfer of the tax revenues to the consumer. **Table 2** shows the tax rates on factor and consumption that are currently used in the forward-looking EPPA.

Table 2. Tax rates

	Tax Rate			Region coverage (in terms of GDP share) for available data		
Region	**Consumption**	**Labor**	**Capital**	**Consumption**	**Labor**	**Capital**
USA	4.7%	29.5%	37.6%	100%	100%	100%
CAN	12.6%	33.4%	44.3%	100%	100%	100%
MEX	8.5%	17.5%	6.8%	100%	100%	100%
JPN	6.9%	28.4%	42.3%	100%	100%	100%
ANZ	13.2%	25.3%	41.9%	100%	90%	90%
EUR	17.4%	39.7%	36.8%	100%	99%	99%
EET	17.4%	31.5%	15.5%	84%	74%	74%
FSU	18.8%	25.6%	38.0%	69%	69%	69%
ASI	11.3%	11.7%	23.9%	100%	100%	100%
CHN	9.3%	1.0%	4.8%	100%	100%	100%
IND	4.5%	3.1%	10.7%	100%	100%	100%
IDZ	6.8%	1.2%	21.9%	100%	100%	100%
AFR	12.2%	12.5%	46.5%	47%	43%	47%
MES	1.4%	-	11.9%	43%	0%	54%
LAM	5.7%	9.0%	15.2%	83%	83%	83%
ROW	19.0%	9.9%	24.6%	51%	45%	51%

Source: Gurgel *et al*. (2007)

4. REFERENCE SCENARIO AND POLICY ILLUSTRATION

In this section we present the results from the 15-region version model from 2005-2050 for a reference run and a policy run that caps greenhouse gas emissions. For the policy run we consider a scenario where all regions engage in efforts to reduce GHG emissions in order to achieve a radiative forcing stabilization level of 4.7 W/m^2, which when other greenhouse gases are accounted for results in stabilization of a CO_2 concentration at 550 parts per million by volume (ppmv), as described by the U.S. Climate Change Science Program (CCSP, 2007). We compare our results from the forward-looking model with those obtained from the recursive version of EPPA.[6] However, as noted in the previous section, the computational demands of the forward-looking model necessitates making some trade offs in terms of the length of the horizon, the number of regions and sectoral and technology details. To computationally accommodate the 15-region forward-looking version, we had to reduce the number of technologies and perform other simplifications in the original structure of the recursive EPPA model. In particular, we collapsed the household transportation sector into the general consumption of the household and removed advanced technologies including bio-fuel production, the natural gas combined cycle electricity generation with carbon capture and storage (NGCC-CCS) and without CCS (NGCC). To focus on the difference forward looking behavior makes in the model, we then also removed these technology options and the disaggregated household transportation sector from the recursive model and reran the CCSP scenarios. The economic and energy results thus differ from those reported in CCSP (2007) even though they are generating the same emissions profiles for GHGs.

4.1 Reference Case and Comparison with Recursive Model

The reference scenario simulates the forward-looking model with the same parameter values for economic growth, energy efficiency, and technology costs as in the recursive EPPA model. Comparisons of trajectories for key indicators in the forward-looking and recursive models are provided below.

4.1.1 Benchmarking GDP Growth in the Reference

The percentage point differences in annual GDP growth rates between forward-looking and recursive models are shown in **Table 3**. Given the calibration procedure described in Section 3.4, we expect these deviations to be small. Most of the deviations are smaller than 0.1 percentage point, which means that the GDP growth rate in the forward-looking model is 0.1 percentage point greater or smaller than in the recursive model. In general the largest deviation occur in the first period of simulation (2005), due to endogenous adjustments in the forward-looking model to calibrate to initial data for the capital stock, growth rate, depreciation rate and flow of capital services. Otherwise, the regions in the forward-looking model follow closely their corresponding

[6] In other exercises, Paltsev *et al.* (2007) and Gurgel *et al*. (2007) have used the 2 region version of the model to investigate in more detail proposed U.S. Congressional Bills for reducing U.S. greenhouse gas emissions and explore the differences of results between forward-looking and recursive modeling.

growth rates in the recursive model, keeping the GDP growth rates and values almost the same in both models. The results thus demonstrate the success of the calibration process of forcing growth rates in the forward-looking model follow those of the recursive model, and that the procedure provides appropriate macroeconomic scenarios for comparing of policy results from the two alternative modeling strategies.

Table 3. GDP growth rates: deviations between the forward-looking and recursive models (percentage points).

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
USA	0.32	-0.07	0.01	-0.09	-0.07	-0.06	-0.02	-0.06	-0.02	0.02
CAN	0.02	-0.18	0.01	-0.07	-0.05	-0.07	-0.02	-0.06	0.04	0.03
MEX	0.11	0.02	-0.06	0.06	0.01	0.00	0.06	0.06	-0.01	0.07
JPN	-0.49	-0.03	0.08	-0.05	0.07	0.00	-0.03	-0.01	0.00	-0.02
ANZ	0.12	-0.02	-0.09	-0.06	0.03	-0.02	0.01	0.00	0.07	0.24
EUR	0.12	-0.01	-0.11	0.04	-0.03	-0.08	-0.06	-0.04	-0.02	-0.03
EET	-0.03	-0.01	-0.05	0.05	0.01	0.08	0.01	-0.01	0.06	0.11
FSU	0.19	-0.10	-0.02	0.04	-0.03	0.04	-0.01	0.04	0.05	-0.04
ASI	0.14	0.01	-0.01	-0.01	-0.01	0.03	-0.01	0.03	0.09	0.21
CHN	0.08	-0.15	0.10	0.02	0.14	0.21	0.10	0.08	-0.04	-0.13
IND	0.35	0.01	0.12	0.23	0.20	0.29	0.34	-0.14	0.10	-0.16
AFR	0.26	-0.24	0.04	-0.01	-0.01	0.07	0.09	-0.11	0.06	0.12
MES	0.28	0.01	0.04	-0.14	0.07	0.12	0.02	-0.04	0.07	0.05
LAM	-0.03	0.14	-0.03	0.05	0.03	0.06	0.07	0.09	0.03	0.21
ROW	0.15	0.00	0.10	0.18	0.10	0.28	0.39	-0.27	-0.06	0.19
World	0.08	-0.03	-0.01	-0.01	-0.01	-0.01	0.00	-0.03	0.00	0.02

An interesting diagnostic is the labor productivity growth rate in the forward looking model since that is the variable being adjusted in order to benchmark it to the recursive model (**Table 4**). The comparison shows that in order to reproduce the growth rates in the recursive model, the labor productivity must be somewhat lower in the forward-looking model. The productivity growth rates in the recursive model are treated largely as a variable tuned to produce what are considered reasonable paths of GDP growth consistent with recent history. It is hard to directly compare these with measured rates of labor productivity growth because the simplified concept in EPPA differs from those used in typical historical estimates. For example, labor growth is simply a lagged growth in population reflecting approximate labor force age and participation rates, whereas actual data on labor productivity would separately consider actual participation and unemployment. However, if anything, the labor productivity growth rates in the recursive model are high compared with direct estimates of historical growth. Thus, the fact that in the forward-looking model the productivity rates required to match a reasonable rate of growth in GDP are lower suggests that the forward-looking structure offers a more realistic treatment. The likely reason that productivity growth required for a given GDP growth is lower with the forward-looking model is that the capital stock (through saving and investment) can adjust to take full advantage of labor productivity growth.

To better understand the benchmarking of GDP growth in the forward-looking model we also run it under two alternative assumptions about labor productivity and then compare global consumption and investments levels among different models and assumptions. First we set the labor productivity in the forward-looking model to be equal to the labor productivity in the recursive model, and denominate it as *Dynamic - recursive productivity*. A second assumption is to assign labor productivity in the forward-looking model as a simple average of the labor productivity obtained in the forward-looking version where growth matches the recursive model. We call this version as *Dynamic - average productivity*. The original version which reproduces the growth rates from the recursive model through adjustments in the labor productivity is denominated *Dynamic - adjusted productivity*.

Table 4. Comparison of labor productivity increase rates (%) in the forward-looking (dynamic) and recursive models.

Region	Model	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
USA	Dynamic	3.2	3.3	3.4	3.3	3.2	3.2	3.2	3.1	3.0	3.0
	Recursive	3.3	3.9	4.1	4.1	4.1	4.0	3.9	3.7	3.6	3.5
CAN	Dynamic	3.2	3.4	3.4	3.4	3.3	3.3	3.2	3.2	3.1	3.0
	Recursive	3.5	4.0	4.1	4.1	4.1	4.0	3.8	3.7	3.6	3.4
MEX	Dynamic	3.4	3.3	3.4	3.5	3.5	3.6	3.7	3.6	3.6	3.5
	Recursive	3.2	4.8	5.3	5.6	5.6	5.6	5.5	5.3	5.2	5.0
JPN	Dynamic	1.2	2.0	2.2	2.2	2.4	2.5	2.6	2.6	2.6	2.6
	Recursive	0.7	2.3	3.0	3.3	3.4	3.4	3.4	3.3	3.2	3.1
ANZ	Dynamic	3.4	3.6	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.2
	Recursive	3.9	4.5	4.6	4.6	4.6	4.4	4.3	4.1	4.0	3.8
EUR	Dynamic	2.7	3.1	3.1	3.1	3.0	3.0	3.0	3.0	2.9	2.9
	Recursive	2.0	3.2	3.6	3.8	3.9	3.9	3.8	3.7	3.6	3.4
EET	Dynamic	4.2	3.7	3.7	3.7	3.7	3.8	3.8	3.8	3.8	3.8
	Recursive	4.6	5.1	5.3	5.3	5.2	5.1	5.0	4.9	4.7	4.6
FSU	Dynamic	3.2	3.3	3.6	3.8	3.9	3.8	3.8	3.8	3.7	3.5
	Recursive	4.8	4.9	4.9	4.8	4.7	4.6	4.5	4.3	4.2	4.0
ASI	Dynamic	2.1	2.4	2.7	2.9	3.1	3.3	3.4	3.5	3.5	3.6
	Recursive	3.5	4.5	4.9	5.1	5.1	5.0	4.9	4.8	4.6	4.5
CHN	Dynamic	4.3	4.3	4.6	4.6	4.7	4.8	4.8	4.7	4.6	4.5
	Recursive	9.0	8.1	7.6	7.2	6.9	6.6	6.3	6.0	5.8	5.5
IND	Dynamic	6.2	5.2	5.3	5.4	5.4	5.4	5.5	5.0	4.8	4.6
	Recursive	9.0	8.4	8.0	7.7	7.4	7.1	6.8	6.5	6.3	6.0
AFR	Dynamic	2.6	2.9	3.3	3.5	3.6	3.7	3.9	3.4	3.3	3.3
	Recursive	3.4	4.4	4.8	4.9	4.9	4.8	4.7	4.6	4.5	4.3
MES	Dynamic	0.7	1.9	2.8	3.2	3.7	4.1	4.2	4.2	4.2	4.1
	Recursive	3.3	4.4	4.8	4.9	5.0	4.9	4.9	4.8	4.6	4.5
LAM	Dynamic	2.3	2.4	2.6	2.8	3.0	3.3	3.5	3.6	3.7	3.7
	Recursive	2.2	4.0	4.8	5.1	5.2	5.3	5.2	5.1	4.9	4.7
ROW	Dynamic	4.2	3.6	3.8	4.0	4.1	4.3	4.5	3.8	3.6	3.6
	Recursive	4.6	5.3	5.6	5.6	5.6	5.4	5.3	5.1	5.0	4.8

Figure 1 presents the world aggregated consumption and investment paths under the alternative versions of the forward-looking model and for the recursive model. Consumption

follows very similar paths in the recursive model and dynamic versions with adjusted productivity. However, when both the forward-looking and recursive model have similar labor productivity growth, the forward-looking model allocates consumption and investments in a very different way, generating much higher growth than in the other forward-looking versions. In this case, investment in the forward-looking model jumps up in the first period at the expense of consumption, allowing much faster capital accumulation and a greater increase in consumption from 2020 to the end of the model horizon. Such a jump in the first period suggests that the dynamic model is not well-calibrated because the simulated periods differ dramatically from history.

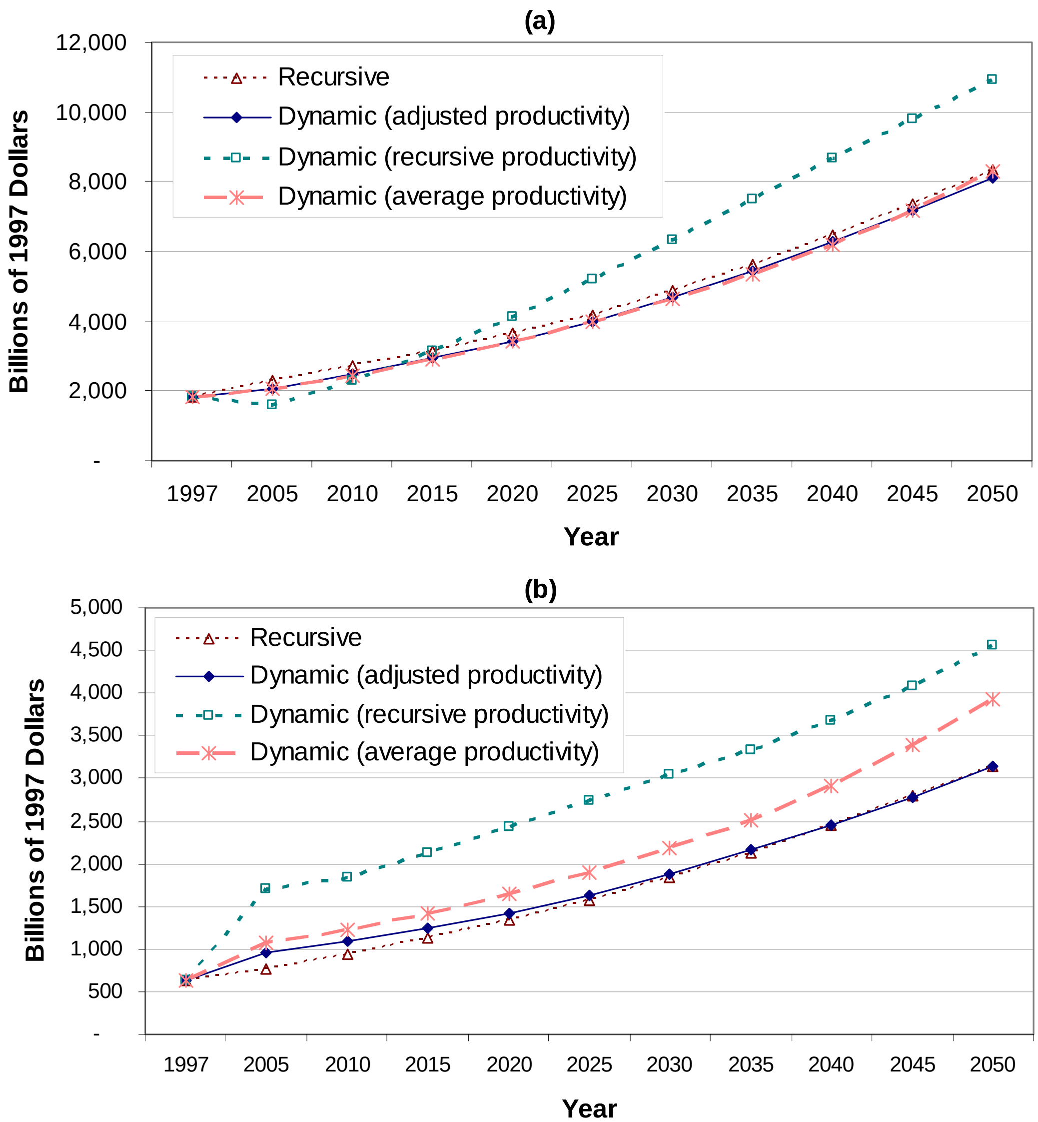

Figure 1. World aggregated expenditures under alternative modeling assumptions: **(a)** consumption, **(b)** investments.

As previously noted, in the forward-looking model investment and consumption are smoothed over time. One aspect of this is that saving and investment will respond to keep the capital-labor quantity and price ratios relatively constant. Thus, with higher increases in labor productivity (as in the *Dynamic - recursive productivity* case), it is optimal to move to a higher savings and investment path so that capital growth keeps pace with labor growth (in productivity adjusted terms). To get to this higher path of savings and investment there is a jump in the short-term. As a consequence, consumption drops in the near term, but recovers and expands in the middle- and longer-term as this investment pays off. When labor productivity is adjusted to reproduce the annual growth rates in the recursive model (*Dynamic - adjusted productivity*), the forward-looking model needs only slightly higher investment levels than the recursive model in initial periods in order to assure that the capital/labor ratio will be balanced.

A feature of the recursive model is that productivity slows somewhat from current rates, and to match the GDP growth in the recursive model growth in productivity for the forward looking model also must slow somewhat. When we replace this pattern with a constant average rate (*Dynamic - average productivity*), investment in the near term increases somewhat relative to the *Dynamic - adjusted productivity* case. Investment in the recursive model is more smoothly connected to historical levels by virtue of the fact that it is a constant share of income. Investment also grows faster in the *Dynamic - average productivity* case. Because labor productivity towards the end of the horizon is higher in the later years for the majority of regions than in *Dynamic - adjusted productivity* case it is optimal to build up a larger capital stock to match the higher effective level of labor. However, consumption does not deviate from the levels observed in the forward-looking version with annually adjusted productivity. This result is the expected consumption smoothing effect: the level of resources (*i.e.* total productivity-adjusted labor) is similar by design over the horizon of these two versions differing only in when they are available. The forward-looking representative agent allocates the total consumption over time in the same way independent of when the resources are available.

As noted above, an important aspect of this comparison is that the consumption and investment paths prescribed by the forward-looking model under adjusted labor productivity are not only similar to those observed at the recursive model, but are also smoother than the others. This implies that the GDP benchmarking strategy provides a labor productivity growth rate that, given the other parameterizations of the model, is most consistent with the historical benchmark data in that investment levels and consumption continue on a fairly smooth path.

4.1.2 Energy Prices and Fossil Fuel Resources

As noted in the previous Section, the macroeconomic baseline was calibrated to be similar between forward-looking and recursive model to allow a better comparison of results from alternative models when we impose a greenhouse policy. Another important aspect of the baseline is the behavior of the energy sectors.

Figure 2 presents the evolution of the world oil price forecasted by the alternative models. Oil prices grow in both models, but the forward-looking model shows a price path of slower increase, due to higher use of shale oil toward the end of the model horizon. This result suggests that the forward looking model does a better job at coordinating the alternative resources and their extraction profiles over the model horizon in order to keep oil prices lower.

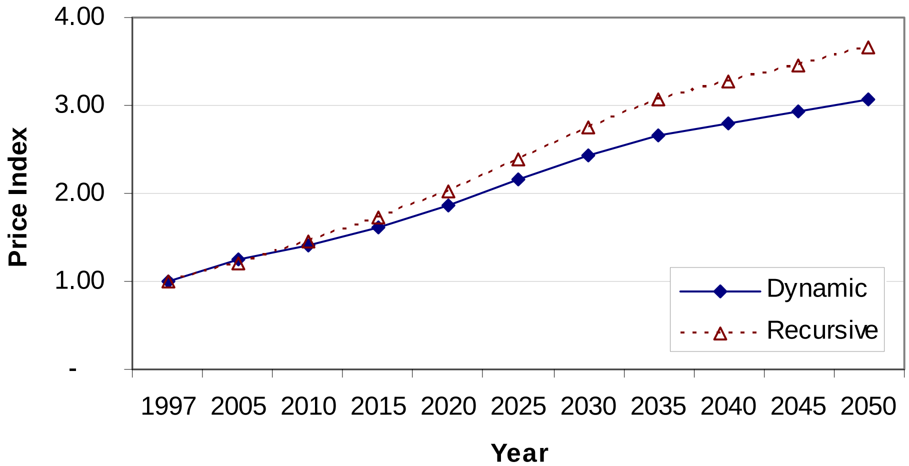

Figure 2. Evolution of the world oil price.

The projected trends in the gas prices for some selected regions are shown in **Figure 3**. As an Armington good, gas has differentiated prices, with the price in each region mainly depending on the availability of resources and demand in that region. We show prices in USA, in the region with highest prices (IND) and the one with lowest prices (FSU). Similar to the oil price case, both models predict very similar price paths, with the recursive model showing a trend of slightly higher gas prices than the forward-looking model. Although the differences in price are small, they imply lower resource depletion rates and better management of the energy supply mix in the forward-looking model compared to the recursive model.

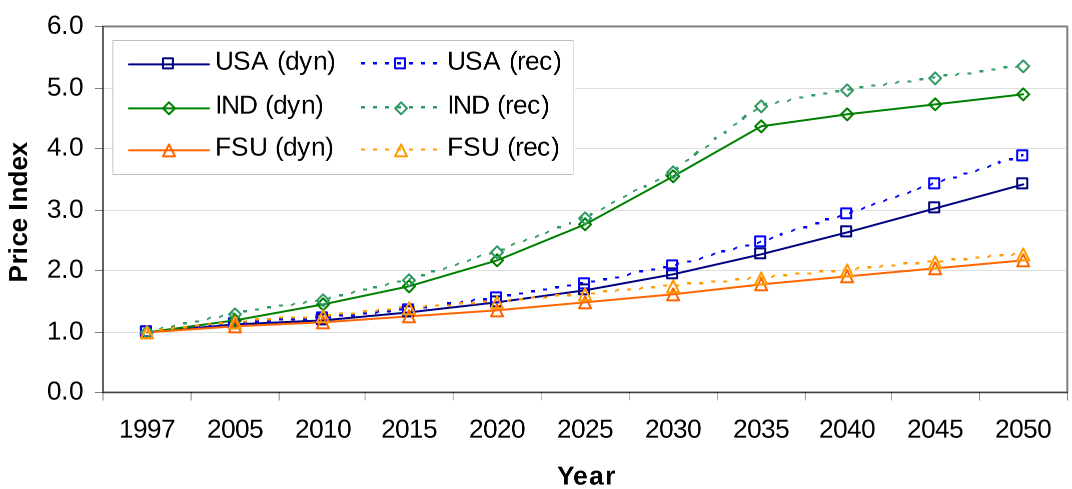

Figure 3. Evolution of gas prices, selected regions.

Coal prices are also differentiated by region, as shown in **Figure 4**. Again we show the prices in USA, the region with highest prices (IND) and the one with lowest prices (EUR). The general trend depicted by the figures show that increases in coal prices are slower than gas and oil prices, which is to be expected given the relative abundance of the world coal resources. Comparing the recursive with the forward-looking model, the differences in prices seem to be negligible for most regions. The highest relative difference in prices is observed in EUR, and it is only in the order of 5% lower in the forward-looking model at the end of the model horizon.

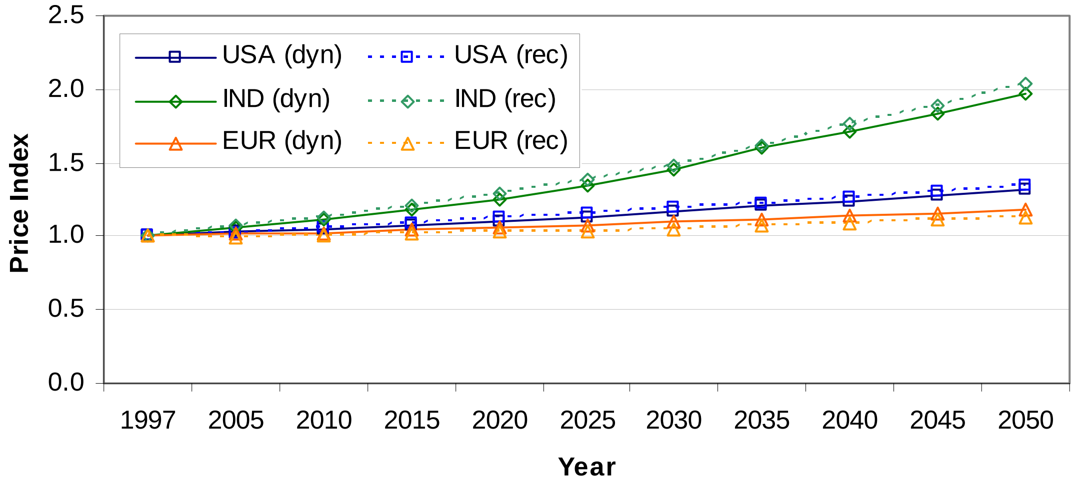

Figure 4. Evolution of coal prices, selected regions.

Figure 5 presents depletion of fossil fuel resources in the world predicted by both models, relative to the resources base in 1997. As pointed out before, coal has a larger resource base, and hence its depletion rate is much lower than that for conventional oil and gas. The figure shows very similar depletion trends in both models, with the recursive model extracting slightly higher amounts of oil and gas than the forward-looking model, which likely reflects the fact that prices are somewhat lower in the dynamic model and thus there is less incentive to produce these resources. The two models show that, by 2050, the reserves of oil and gas resources are reduced to around 70% to 75% of their levels in 1997. These patterns of depletion are consistent with the predicted fossil fuel price trends discussed above. The EPPA specification is not a Hotelling representation where a fixed amount of resource is simply allocated over the model horizon but instead represents an underlying graded resource where expansion of production requires additional costs. Implicitly, then, some share of the resource specified as available in the model is more costly than backstops such as shale oil or gas from coal. Coal also has a very small rent associated with it and so its cost is similarly driven by the supply representation that includes increasing costs as more is extracted. With the forward looking model there is a possibility of reallocating resources over time through Hotelling-like behavior. However, these results suggest that the graded resource feature and backstops appears to dominate the results because the forward-looking model results differ little from the recursive model results.

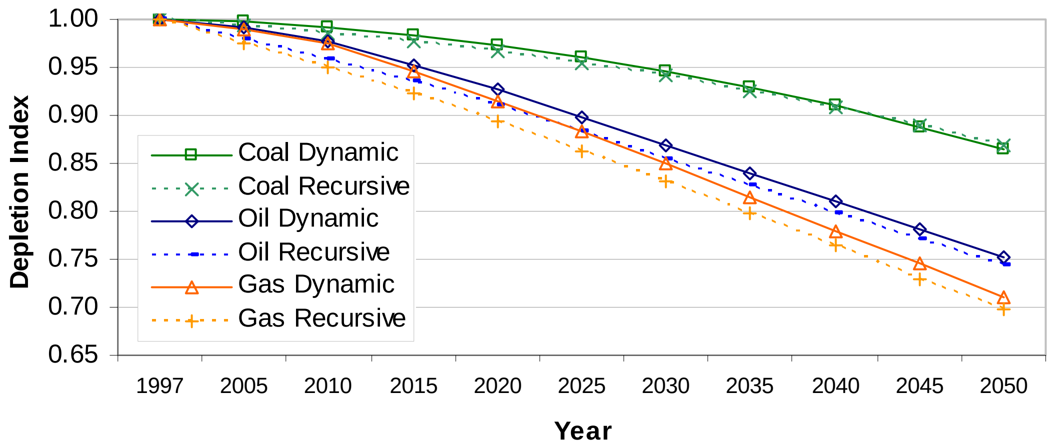

Figure 5. Depletion of fossil fuel resources.

4.1.3 Emissions of Greenhouse Gases

Economic growth and the associated growth in energy consumption are the principal determinants of the level of greenhouse gas emissions in the absence of mitigation policies. **Figure 6** shows the global trajectories of greenhouse gas emissions in the forward-looking and recursive models for our reference scenario. The figure indicates very similar levels of emissions for the two models, with differences becoming visible mostly towards the end of the model horizon. Emissions of CO_2 from anthropogenic activities reach almost 18GtC/yr in the forward-looking model compared to about 17GtC/yr in the recursive version by 2050. Both models produce very similar emissions trends until 2020-2025, but diverge somewhat after that with emissions from the forward-looking model leading to higher levels for all greenhouse gases. The differences in emissions between models are due to differences in energy prices, fuels mix and energy consumption patterns discussed above. In particular, the forward-looking model shows relatively lower prices and thus induces more energy consumption and higher emissions given that the rates of energy efficiency remain unchanged between the two models. Shale oil use is somewhat higher in the forward-looking model contributing to higher CO_2 emissions. In addition, emissions differ depending on the patterns of sectoral growth rates and hence on the structural evolution of the economy in the two models. Here again, this appears to lead to somewhat higher emissions in the forward-looking model because the energy intensive industries grow faster than in the recursive model. However, in the broader view of uncertainty in projections of energy and the economy over the course of 45 years, the difference in emissions due to model structure is relatively small.

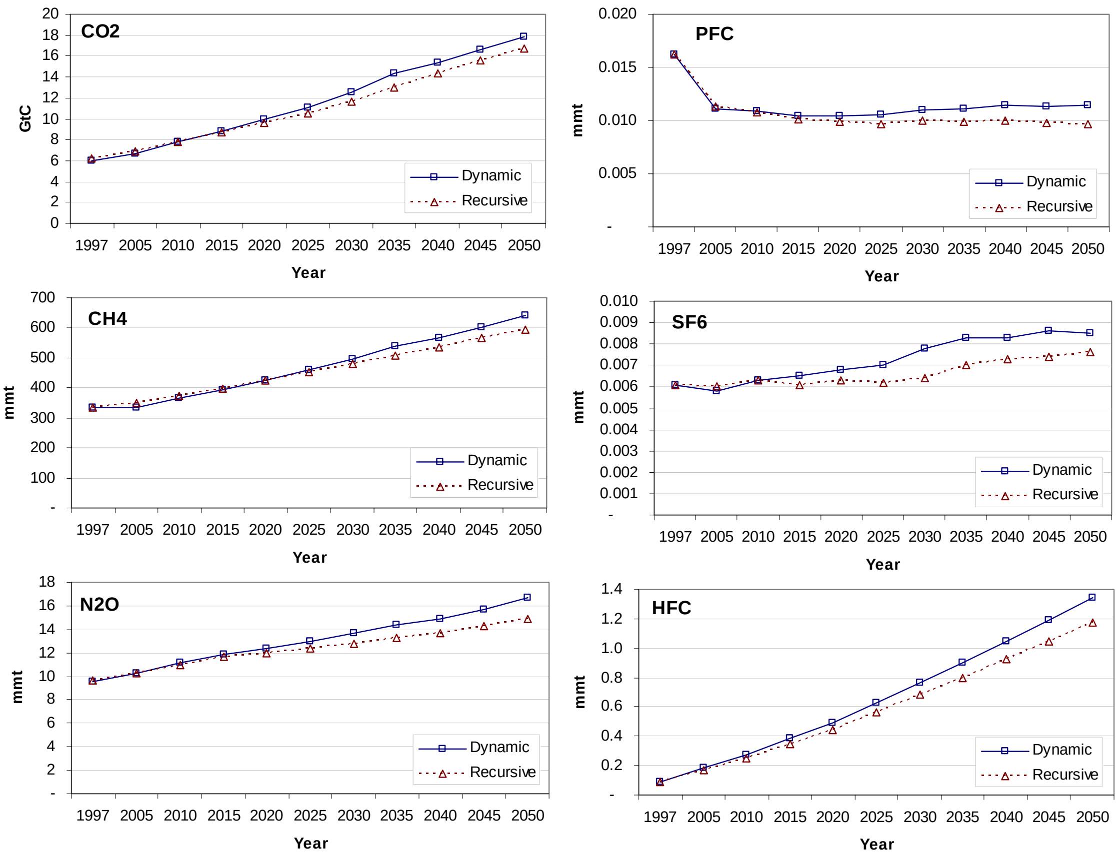

Figure 6. Emissions projections for greenhouse gases (range and comparison with recursive EPPA model).

4.2 Sample Policy Calculation

To illustrate the performance of the forward-looking version of EPPA under a mitigation policy constraint we have simulated a global effort to reduce GHG emissions in order to stabilize CO_2 concentration at 550 ppmv and compared the results of the forward-looking model to those from the recursive model. To achieve such stabilization, all greenhouse gases are subject to reduction through a cap and trade system starting in 2010, with GHG allowances being traded among countries in order to equalize internationally the marginal costs of emission controls. We assume that the initial distribution of allowances is the same used by the IGSM model in CCSP (2007)[7], as a ratio of the emissions in the reference scenario so that in both cases we require the same percentage reduction. This procedure controls for the fact that the recursive and forward-looking model do not have exactly the same emissions in the reference, as our main interest in this comparison is to see whether, when faced with abatement efforts of equal stringency, the costs differ between the two model structures. We also allow trade among some GHG allowances (CO_2, PFC and SF_6) using the GWP equivalents among them, but CH_4 and N_2O allowances are not traded with other gases, to keep our implementation of the policy consistent with that in CCSP (2007).

In the IGSM implementation of the 550 ppmv scenario in CCSP, inter-temporal trade of GHG permits (banking and borrowing) was simulated by manually searching for an initial CO_2 price (with CO_2 prices rising 4% per year) that generated cumulative emissions consistent with stabilization. To provide a comparable recursive scenario we re-simulated the simplified recursive model to again generate a price path that rose at 4% per year and that produced the same level of cumulative emissions through 2050 as in the CCSP (2007) version of the model. We denominate it as *Recursive_Q%* simulation to indicate that the percentage reduction is the same as simulated in the forward-looking model. We compare these results to those obtained from the forward-looking model. In the forward looking model we introduced the same percentage reduction from reference as in the recursive model.[8]

Figure 7 shows the resulting CO_2 prices in the recursive model and in the forward-looking model under the two assumptions about inter-temporal trade of permits. The price paths shows that the strategy used to simulate banking and borrowing in the recursive generates behavior similar to that of the forward-looking model since both rise at about 4%. In the forward looking model the money discount rate is endogenous but depends directly on parameters of the intertemporal consumption function, and those parameters were chosen to be consistent with a

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[7] The IGSM model in CCSP (2007) uses the recursive EPPA but, as noted earlier, we have removed features from the recursive EPPA such as biofuels and NGCC with an without CCS and collapsed household transportation into the household sector to facilitate comparison with the forward-looking EPPA model.

[8] Since the emissions level was higher in the forward-looking reference using the same absolute emissions level would have meant a large emissions reduction, tending to generate higher marginal abatement costs. Our interest here is to compare the two versions when faced with the same abatement level, not necessarily achieving the same level of emissions.

4% annual money discount rate in the base year. While that rate can change over time as economic growth changes, that effect is relatively small within the horizon of the model.

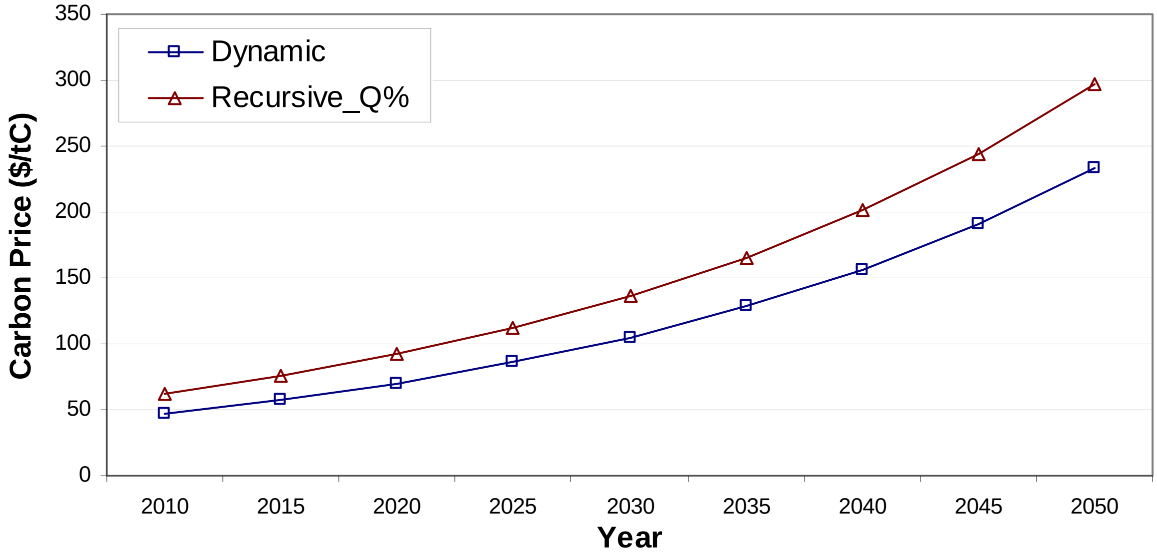

Figure 7. CO_2 prices in the CCSP 550 ppm stabilization scenario.

There is a difference in the initial carbon price. It is 62 $/tC in the recursive model and 47 $/tC in the forward-looking model, and the absolute level diverges over time both increase at 4% per year. While it is not possible to completely identify the reasons for this difference, one of the main reasons appears to be the more rapid penetration of coal electric generation with capture and storage of carbon (IGCC-CCS). The recursive model includes adjustment costs that slow expansion of backstop technologies, but such adjustment costs could not be represented in the forward-looking model. Thus, at least part of this difference is due to simplifications needed in the forward-looking model. However, given that the forward-looking provides greater flexibility by allowing inter-temporal reallocation of consumption and investments as well as greenhouse gas allowances one might expect costs to be lower. Note also, that we were not able to fully control the baselines and so remaining differences in the baseline may have an effect on CO_2 prices. In order to compare the emissions and costs in both models under the same CO_2 price path, we simulate one additional scenario using the recursive model, where we set the CO_2 price equal to that obtained in the forward-looking model. We denominate this simulation as *Recursive_P*.

Figure 8 presents the world GHG emissions in the 550 ppmv stabilization, compared with CO_2 emissions in the reference. The scenario reduces the global emissions in the forward-looking model from 23.5 GtC in 2050 to 12.7 GtC. In the recursive model emissions are reduced in 2050 from 21.4 GtC to 10.8 GtC in the *recursive_Q%* scenario. The difference is because, as discussed previously, we set the policy so that the percentage reduction (33% of cumulative world emissions between 2010 to 2050 from the reference scenario) was the same in both models. The forward-looking model shows flat to slightly rising emissions to be the efficient allocation of the cumulative constraint over the horizon. The GHG emission path from the recursive model is very similar to the forward-looking one, with a somewhat lower emissions level in the second half of the period reflecting the lower reference emissions, and thereby lower absolute level of emissions in the policy case. We notice slightly higher emissions in the scenario *recursive P* so that the cumulative emissions between 2010-2050 decreases by only 29% compared with the 33% reduction in the *recursive_Q%* scenario. Because the forward looking and recursive models are fundamentally different at some level an idealized comparison is not possible. We can compare them through either setting the same percent reduction in emissions or setting the same CO_2 price. Because of the forward-looking optimization behavior, the first option will generate slightly higher prices and the second will mean slightly lower percentage cuts in emissions in the recursive model compared to the forward-looking results.

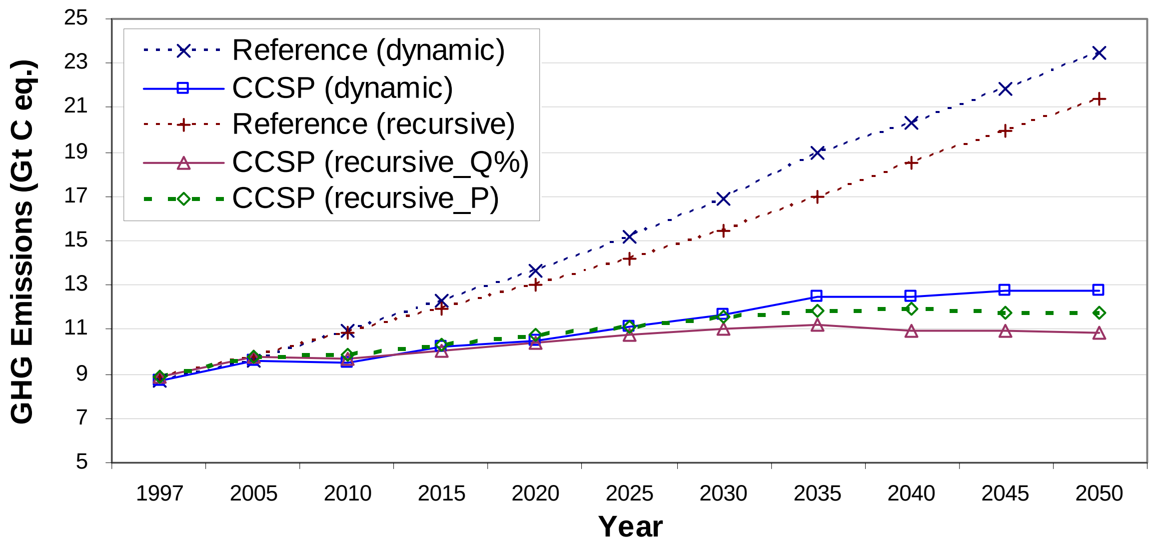

Figure 8. World GHG emissions in the CCSP 550 ppm stabilization scenario.

Figure 9 shows the impact of the 550 ppmv stabilization scenario on the aggregate world consumption, relative to its reference levels. The policy affects consumption through time, increasing slightly the global consumption in the pre-policy period in the forward-looking, and then, decreasing consumption gradually from 0.1% in 2010 to 2.3% by 2050. The *recursive_Q%* simulation shows no change prior to the implementation of the policy, and then shows a continuous decrease in consumption, from 0.3% in 2010 to 2.6% in 2050. It is evident that, under the same percent reductions in greenhouse gases, the consumption losses in the recursive model follow in parallel those in the forward-looking model, being slightly higher likely as a consequence of the somewhat higher carbon prices. However, when the recursive model is faced with the same CO_2 price path, it generates higher losses in the first half of the policy implementation period, but smaller losses toward the end of the model horizon than the forward looking model, reflecting the inability of agents in the recursive model to smooth consumption over time. As a consequence, the discounted losses in absolute dollar terms in the forward-looking model are lower than those in the recursive model, even under the same price path. Also note that the percent reductions in emissions in the forward-looking model are somewhat higher.

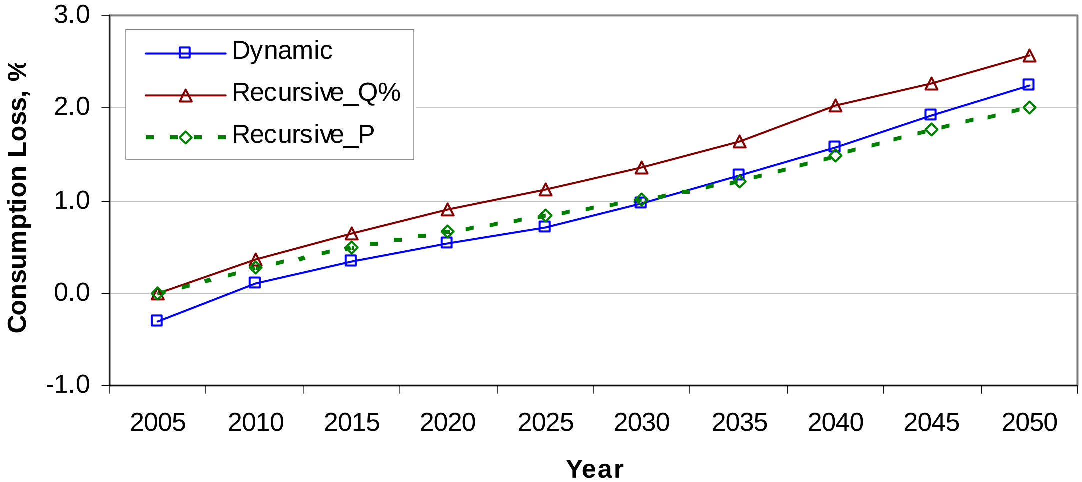

Figure 9. Worldwide loss in consumption in the CCSP 550 ppm stabilization scenario in terms of consumption in the reference.

The changes in consumption from the policies can be summarized by a welfare index calculated from the sum of discounted consumption over the entire model horizon (lifetime). We compute also an infinite horizon welfare index for the forward looking model, as discussed before, which accounts for the changes in consumption in the post-terminal period of the model as shown in **Figure 10** aggregated for world. The lifetime welfare losses are higher in the recursive than in the forward-looking model under similar CO_2 constraints, as consumption changes are larger in the former, although the difference is not that large. This is the result of consumption smoothing in the forward-looking model that results in some gains in consumption before the policy starts on the basis of expected higher prices of energy in the future, and an overall smaller decrease in consumption as we move towards the end of the horizon. However, under same CO_2 prices, welfare losses become slightly lower in the recursive model in percentage terms, although the summed discounted absolute losses are higher. This occurs because, even though we matched GDP between the forward and recursive models, the consumption levels in the reference are somewhat greater in the recursive model. Thus the slightly bigger absolute loss is a somewhat smaller loss in percentage terms. Again, the emissions reductions are smaller in the recursive model when CO_2 prices are similar between models, and so the effect of model structure on estimated costs depends in part on how you normalize the stringency of the policy. Perhaps the most surprising result is the similarity of the consumption losses in the two models.

The welfare losses over the infinite horizon in the forward-looking model, calculated using the changes in consumption in the last period of the model to account for the post-terminal welfare, is considerably larger (a 2.2% decrease) which is a full one percent point greater than the life-time welfare loss. This measure is only indicative of the long-term costs of the greenhouse gas mitigation policy as the actual cost will depend on what the policy is in the post-terminal period and the technologies available to meet emissions constraints. As constructed the infinite horizon measure is simply extending the percentage consumption loss indefinitely, and thus might approximate the costs if the stringency of the policy (*i.e.* percentage reduction below reference that exists in 2050) were to remain indefinitely. To achieve stabilization emissions would need to fall further and so infinite horizon costs would be higher, depending on what one assumes about technological availability. The key lesson is that the costs observed in the truncated time horizon necessary to produce a numerically feasible model should not be misinterpreted as the cost of stabilization. It would, for example, be misleading to compare these costs to estimates of benefits of stabilization that included a much longer horizon.

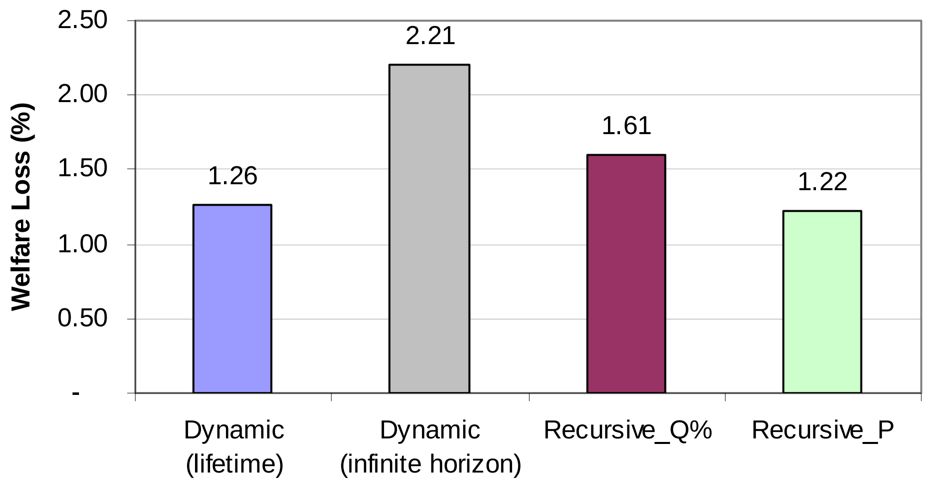

Figure 10. Welfare losses in the CCSP 550 ppm stabilization scenario.

5. FUTURE MODEL DEVELOPMENT

The forward-looking EPPA model has been developed from the recursive MIT EPPA model as an auxiliary and complementary tool to be used in the studies of economics of climate change. It has added the capability to better address important issues, such as optimal allocation of resources over time and inter-temporal trade of greenhouse allowances. The model is being used currently in several applications, including examination of consequences of greenhouse gas policies in U.S., the impacts of recycling of revenue from greenhouse permits, and the importance of representation of backstop technologies in forward looking models. Future developments of the model include efforts to extend the model horizon and emissions forecast for linking with other components of the MIT Integrated Global Systems Model (IGSM).

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