MIT Joint Program on the Science and Policy of Global Change

U.S. Greenhouse Gas Cap-and-Trade Proposals: *Application of a Forward-Looking Computable General Equilibrium Model*

Angelo C. Gurgel, Sergey Paltsev, John M. Reilly and Gilbert E. Metcalf

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This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Abstract

We develop a forward-looking version of the MIT Emissions Prediction and Policy Analysis (EPPA) model, and apply it to examine the economic implications of proposals in the U.S. Congress to limit greenhouse gas (GHG) emissions. We find that the abatement path and CO_2-equivalent (CO_2-e) price in the forward-looking model are quite similar to that of the recursive model, implying that the simulation of banking behavior in the recursive model by forcing the CO_2-e price to rise at the discount rate approximates fairly well the banking result obtained with the forward-looking model. We find, however, that shocks in consumption path are smoothed out in the forward-looking model and that the lifetime welfare cost of GHG policy is lower than in the recursive model, results we would expect to find given that the forward-looking model can fully optimize over time. The forward-looking model allows us to explore issues for which it is uniquely well-suited, including revenue-recycling, early action crediting, and the role of a technology backstop. We find (1) capital tax recycling to be more welfare-cost reducing than labor tax recycling because of its long term effect on economic growth, (2) potentially substantial incentives for early action credits relative to emission levels in years after a policy is announced but before it is implemented that, however, when spread over the full horizon of the policy do not have a substantial effect on lifetime welfare cost or the CO_2-e price, and (3) strong effects on estimates of near-term welfare costs depending on exactly how a backstop technology is represented, indicating the problematic aspects of focusing on short-term welfare costs in a forward-looking model unless there is some confidence that the backstop technology is realistically represented.

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1. INTRODUCTION

Considerable recent attention is focused on developing a U.S. cap-and-trade system for greenhouse gases (GHG). New proposals in the U.S. Congress specify a relatively long horizon—through 2050—on the basis that this would provide greater certainty for investment and planning purposes, and this naturally focuses attention on the role of expectations. Other issues related to greenhouse gas abatement policy such as the effects on growth of using CO_2 auction revenue to reduce taxes on capital or labor, banking and borrowing, the implications of the availability of a backstop technology, or action in anticipation of a policy going into effect also depend on people looking forward and acting differently today because of something that will happen in the future. To fully investigate these issues requires a model where the knowledge of future events is reflected in current decisions. Here we apply a forward-looking dynamic version of the Emissions Prediction and Policy Analysis (EPPA) model to examine U.S. GHG cap-and-trade measures that approximate recent bills under consideration in the U.S. Congress. A recursive dynamic version of EPPA (Paltsev *et al*., 2005) has been used to conduct similar analysis (Paltsev *et al*., 2007). A main interest here is to compare the behavior of the forward-looking and recursive versions, especially with regard to those issues where expectations are particularly important.

The paper is organized in the following way. In the next section we briefly describe the forward-looking model. Section 3 sets out the policy scenarios we investigate, Section 4 reports results of our investigation with the forward-looking model comparing them with results from the recursive model where useful, and Section 5 offers some conclusions.

2. EPPA: FORWARD-LOOKING VERSION

A forward-looking dynamic general equilibrium model optimizes decisions both within a time period (across sectors, regions, goods, and inputs) and across time periods whereas a recursive dynamic model only optimizes decisions within a time period. Both versions of the model use a predetermined path for population growth and labor productivity growth. 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 based 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. The representation of consumers desire to equalize the marginal value of consumption over time is a "substitution" effect where an anticipated shock to the level of consumption in one period causes adjustments in savings in other periods to smooth the consumption change over time. 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. Rutherford (1999) provides a comparison of a behavior of a model formulated in recursive and forward-looking structures.

In reality, consumers and firms look ahead to some degree and make decisions today on the basis of expectations of future events. If, for example, legislation specifies that a cap-and-trade policy is to enter into force five years from the date of passage one might expect that producers and consumers would anticipate the policy and begin changing their decisions as the date approaches. Even without the actual passage of legislation, mounting evidence on the threat of climate change has almost certainly affected some decisions—such as increased attention toward research on lower carbon-dioxide emitting technologies—because the mounting evidence suggests a greater chance that a GHG-limiting policy will be implemented in the future. Once the policy is in place, if investors expect the emissions price to continue to rise, they may choose to build a power plant with lower emissions than are justified by that year's CO_2 price rather than later regret the investment in a higher emitting plant that would be ever more costly to operate because of the rising emissions penalty. In reality, neither producers and consumers nor modelers can perfectly know the future so behavior may lie somewhere between the recursive and forward-looking representations.

The forward-looking EPPA has been designed with flexibility to alter key dimensions such as the time horizon, capital vintaging, and the number of regions, sectors, and technologies explicitly represented. This design approach makes it possible to keep details important for particular applications while limiting the dimensions of the model such that it is numerically tractable. Solving the forward-looking model is computationally demanding because the solution requires simultaneous consideration of all time periods, and some simplifications of the recursive dynamic version are required. The forward-looking version applied here simplifies the EPPA structure[1] in 3 ways:

(1) Instead of the 16 regions of the recursive dynamic version we collapse the model to 2 regions: the U.S. and the Rest of the World. Given the focus on U.S. policy in this study the detail in the ROW is not essential but it does limit our ability to represent differential policies among countries abroad, and it also simplifies international trade considerably.

(2) The model horizon is shortened from 2100 to 2050.

(3) The capital vintage structure is simplified and we do not include adjustment costs associated with rapid expansion of new technologies. These last simplifications would tend to lower the costs compared with the recursive model. One approach in forward-looking models is to vintage initial capital stock and then represent the future capital as malleable because the decision about how to invest in the future remains open. However, if one can make an investment in a future period, as if it can be completely reshaped at no cost in still later periods the importance of the capital rigidity will not be captured. We thus investigate a simplified approach to vintaging that captures key elements of this irreversibility of future investment.

In other ways the model is unchanged from the standard EPPA with the same technological detail as shown in **Table 1**. The underlying Global Trade Analysis Project (GTAP) data (Hertel, 1997; Dimaranan and McDougall, 2002), characterization of alternative technologies, elasticities of substitution, and the like are generally unchanged from the recursive version of the model. The exceptions are two. First, given our interest in comparing the response to GHG policy between the models we benchmark the reference projection of the forward-looking model to match that of the recursive in terms of GDP growth and GHG emissions. Labor productivity and autonomous energy efficiency improvement (AEEI) are adjusted in this benchmarking process.

[1] The recursive version of the EPPA is documented in Paltsev *et al*. (2005); the 15-region forward-looking version of EPPA is documented in Babiker et al. (2007).

Table 1. EPPA Model Details.

Country or Region†	Sectors	Factors
United States (U.S.A)	***Non-Energy***	Capital
	Agriculture (AGRI)	Labor
ROW *Aggregation from standard EPPA*:	Services (SERV)	Crude Oil Resources
Canada (CAN)	Energy-Intensive Products (EINT)	Natural Gas Resources
Japan (JPN)	Other Industries Products (OTHR)	Coal Resources
European Union+ (EUR)	Industrial Transp. (TRAN)	Shale Oil Resources
Australia & New Zealand (ANZ)	Household Transp. (HTRN)	Nuclear Resources
Former Soviet Union (FSU)	***Energy***	Hydro Resources
Eastern Europe (EET)	Coal (COAL)	Wind/Solar Resources
India (IND)	Crude Oil (OIL)	Land
China (CHN)	Refined Oil (ROIL)	
Indonesia (IDZ)	Natural Gas (GAS)	
Higher Income East Asia (ASI)	Electric: Fossil (ELEC)	
Mexico (MEX)	Electric: Hydro (HYDR)	
Central & South America (LAM)	Electric: Nuclear (NUCL)	
Middle East (MES)	Electric: Solar and Wind (SOLW)	
Africa (AFR)	Electric: Biomass (BIOM)	
Rest of World (ROW)	Electric: NGCC	
	Electric: Coal with CCS (IGCAP)	
	Electric: Gas with CCS (NGCAP)	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	
	Liquids from Biomass (B-OIL)	

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

And second, aggregation of the regions in the recursive model to a single ROW region leads to a different response even if parameterization is identical across regions, and where parameters values differ among regions the value that leads to the same response can not be directly calculated as some average of values in the recursive model. We have made an effort to make the ROW behave broadly similarly to the aggregated regions in the recursive model but it is not possible for a single ROW to respond exactly like the disaggregated model. Since our primary interest here is the response of the U.S. to climate policy, any differences in ROW response would affect U.S. response only indirectly through the international trade and capital accounts.

2.1 Equilibrium Structure And Dynamic Process

The forward-looking dynamic EPPA model is conceptually built on the classical Ramsey economic growth approach. In this way, the model attempts to represent infinite lived agents who maximize the present value of welfare from consumption, considering the trade-off between present and future consumption[2]. 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 catch-up across regions.

[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).

The most important difference between the recursive and forward-looking versions of EPPA is the optimization process. In the forward-looking model, a representative agent allocates income across consumption in different time periods in order to maximize welfare[3], which means, in each single period, the representative agent must choose between current and future consumption. Future consumption is purchased through savings. The intertemporal allocation of consumption is governed by a rate of time preference between current and future consumption. The solution of the optimization problem generates an equilibrium where a unit of consumption today is as valuable as one unit of consumption (adjusted for time preference) in the future.

2.2 The Intertemporal Optimization Problem

Here we represent the basic theoretical structure that underlies the forward-looking model. We focus on the general mathematical representation as it relates to reformulating the problem as a forward-looking model and suppress other details of the EPPA model that are unchanged from the recursive formulation.[4] The utility function employed in the forward-looking EPPA is a constant intertemporal elasticity of substitution function (CIES). The 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:

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

where Q_{rt} is a combination of aggregate consumption and leisure in region *r* and time *t*, ρ is a time preference or discount rate and θ is the inverse of the elasticity of intertemporal substitution. This formulation makes labor supply decisions endogenous. We use the term "full consumption" to refer to Q_{rt}, which is represented as:

$$Q_{rt} = \left(\alpha C_{rt}^{\varphi} + (1-\alpha) Z_{rt}^{\varphi} \right)^{1/\varphi} \qquad (2)$$

where C_{rt} is the aggregate consumption at region r and time *t*, Z_{rt} represents leisure time at region *r* and time *t*, α is the weight of consumption in full consumption and $1/(1-\varphi)$ is the elasticity of substitution between consumption and leisure.[5]

The budget constraint can be thought of as the balance of income and expenditure over the horizon, represented by equation (3)[6]:

$$\sum_{t} \left(p_{rt}^{C} C_{rt} + w_{rt} Z_{rt} \right) = \sum_{t} w_{rt} \bar{L}_{rt} + p_{r0}^{K} K_{r0} - p_{T+1} K_{T+1} \qquad (3)$$

[3] Or, more precisely, a discounted flow of consumption (defined here to include final market consumption and leisure) summed over time.

[4] Details included in the model but not explicated treated in this discussion include the endowment of energy resources, taxes applied on primary factors and labor-leisure choice. For a more complete discussion see Babiker *et al.* (2007).

[5] We calibrate this elasticity and the parameter α to be consistent with a labor supply elasticity of 0.25 and a leisure-labor rate of 0.25 in the benchmark, as in Babiker *et al*. (2003).

[6] Although the government sector in each country is present in the model, we omit taxes to simplify the notation.

where p^C_{rt} is the price of aggregate consumption at region r and time t, w_{rt} is the wage rate, $\overline{L}_{rt}$ is the labor endowment in efficiency units, p^K_{r0} is the initial price of a unit of capital, K_{r0} is the initial stock of capital, 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, *i.e.* they are present value prices.

The lifetime budget constraint means that the present value of full consumption should be equal to the present value of wage income and the initial value of capital stock 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 computable general equilibrium (CGE) model. In other words, capital flows are allowed among regions, in response to differences in real rate of returns. Thus the closure of the model regarding the balance of payments requires that capital flows cover the current account deficit (or surplus), and they also should 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). This condition can be represented as:

$$kflow_{rt} = p^C_{rt}C_{rt} + p^I_{rt}I_{rt} - \left[w_{rt}\left(\overline{L}_{rt} - Z_{rt}\right) + r^K_{rt}K_{rt} \right], \tag{4}$$

where $kflow_{rt}$ is the capital flow to region r at time t, p^I_{rt} is the price of a unit of investment and r^K_{rt} is rental price of capital.

This closure rule requires that any current account deficit in one country must be compensated by current account surpluses elsewhere. In addition, this closure rule means that in every region any excess of aggregate expenditure over aggregate income today should be paid off by the region in the future. Thus, it requires no net change in foreign indebtedness over the model horizon. These conditions can be represented by the following relations:

$$\sum_r kflow_{rt} = 0, \quad and \qquad \sum_t kflow_{rt} = 0. \tag{5}$$

From equation (3) we can also derive the condition where the rate of return over the assets the agents possess today determines the value of assets tomorrow:

$$p^C_{rt}C_{rt} + p^I_{rt}I_{rt} + kflow_{r,t+1} = w_{rt}\left(\overline{L}_{rt} - Z_{rt}\right) + r^K_{rt}K_{rt} + (1+r_t)kflow_{rt} \tag{6}$$

where r_t is the real interest rate at time t.

This foreign trade closure rule allows countries to temporarily have foreign accounts imbalanced 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 fixes the foreign accounts gradually phasing out any existing capital account imbalance. This feature of the forward-looking model provides another avenue of adjustment that is not available in 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 by (7):

$$K_{r,t+1} = \left(1-\delta\right)K_{rt} + I_{rt} \tag{7}$$

where δ represents the depreciation rate.

The maximization of (1) subject to (6) and (7), considering initial zero capital flows as a simplification, generates first order conditions:

$$\left(\frac{1}{1+\rho}\right)^{t}\frac{\partial U(C_{rt},Z_{rt})}{\partial C_{rt}} = p_{rt} \tag{8}$$

$$\left(\frac{1}{1+\rho}\right)^{t}\frac{\partial U(C_{rt},Z_{rt})}{\partial Z_{rt}} = \eta_{rt} \tag{9}$$

$$\left(1-\delta\right)p^{K}_{r,t+1} + p_{rt}r^{K}_{rt} = p^{K}_{rt} \tag{10}$$

$$p_{rt} = p^{K}_{r,t+1} \tag{11}$$

$$p_{rt} = (1+i_t)\,p_{r,t+1} \tag{12}$$

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

2.3 MCP Formulation

In the forward-looking dynamic EPPA 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 General Algebraic Modeling System (GAMS) software (Brooke *et al*., 1998). MCP problems are written and solved through three types of inequalities: the zero profit, market clearance and income balance conditions. The equilibrium structure of the EPPA model, defined by these three conditions has been documented by Paltsev *et al*. (2005).

To illustrate the structure of the dynamic model in MCP format, we simplify the notation and remove the subscript r (and the associated complication of including international trade in the representation of the model). The MCP formulation relies on the duality of the consumption and production theories to define unit expenditure and unit cost functions, demand functions for goods, intermediate inputs and primary factors.

The constrained minimization of total expenditure generates:

- $D^{C}_{jt}(p_{jt})$, the compensated demand for good j, where p_{jt} are the prices of goods j;
- $E^{C}_{t}(p_{it},p_{jt})$, the unit cost of aggregate consumption at time t, as a function of the prices of goods i and j (i and j representing the same set of goods).

The minimization of total capital expenditure, subject to the production of one unit of aggregated investment generates:

- $D^{I}_{jt}(p_{jt})$, the compensated demand for good j for investments purposes;
- $E^{I}_{t}(p_{it},p_{jt})$, the unit cost of aggregate investment at time t.

On the production side of the economy, the minimization of total costs of production, subject to the production (y_{it}) of one unit of sectoral output generates:

- $D^{ID}_{ijt}(p_{jt},y_{it})$, the compensated demand for intermediate input j at sector i;

- $D_{it}^{F}(p_t^F, y_{it})$, the compensated demand for primary factors labor (L) and energy resources (R) at sector *i*;
- $D_{it}^{K}(r_t^K, y_{it})$, the compensated demand for capital services at sector *i*;
- $E_{it}^{Y}(p_{jt}, p_t^F)$, the unit cost function for sector *i*, where p_t^F represents the price of factors.

Using these functions, we write the MCP conditions: zero profits, market clearance and income balance. The zero profit condition means that profit should be equal to zero for any sector (including the "sectors" that produce aggregate demand and the aggregate investment) that produces a positive quantity of output or, if profit is negative, there is no production at all. The zero profit condition can be represented by the following relation for every sector:

$$profit \geq 0,\ output \geq 0,\ output^* (-\,profit) = 0. \tag{13}$$

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

$$supply - demand \geq 0,\ price \geq 0,\ price^*(supply - demand) = 0. \tag{14}$$

The income balance condition means that total expenditure should be equal to the total value of endowments for each agent.

We can use these MCP conditions to write the dynamic EPPA model as following. The zero profit conditions are:

a) the aggregate price index is equal to the unit cost of aggregate consumption:

$$p_t = E_t^C(p_{it}, p_{jt}). \tag{15}$$

b) the price of capital in the next period is equal to the unit cost of aggregate investment:

$$p_{t+1}^K = E_t^I(p_{it}, p_{jt}). \tag{16}$$

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, accounting for the depreciation (zero profit for capital accumulation):

$$p_t^K = r_t^K + (1-\delta)p_{t+1}^K. \tag{17}$$

d) the price of output from sector *i* is equal to its unit cost:

$$p_{it} = E_{it}^Y(p_{jt}, p_t^F), \tag{18}$$

The market clearance conditions are:

a) Supply equals demand in each commodity market:

$$y_{it} = \sum_j D_{ijt}^{ID}(p_{jt}, y_{it}) + D_{it}^C(p_{it}) + D_{it}^I(p_{it}), \tag{19}$$

b) Supply (F_t^F) equals demand in each primary factor market:

$$F_t^F = \sum_j D_{jt}^F(p_t^F, y_{jt}). \tag{20}$$

c) Supply equals demand for capital accumulation:

$$K_{t+1} = I_t + (1-\delta)K_t. \tag{21}$$

The total of the stream of incomes over the agent's lifetime is given by:

$$M = p_0^K K_0 + \sum_{F,t} p_t^F F_t^F - p_{T+1}^K K_{T+1}. \tag{22}$$

The equations from (15) to (22) represent an abstract version of the model in MCP. The following topics address practical issues in the implementation of the dynamic version of EPPA.

2.4 The Infinite Horizon and the Terminal Condition

The optimization problem posed by the numerical model is necessarily restricted to a finite horizon. An issue that arises is that the representative agent has no incentive to accumulate capital in the final period, and thus has the tendency to consume all income in the last period of the model, with investment equal to zero. Moreover, this result would have repercussions for earlier periods as agents looked forward and saw that the value of investment was reduced because it was only being used through the terminal year. The solution is to impose a terminal condition in the last period of the model that requires the representative agent to continue to save and invest. The objective is to set the terminal condition such that it approximates the level of investment in the terminal period 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:

$$\frac{I_{rT}}{I_{rT-1}} = \frac{C_{rT}}{C_{rT-1}}. \tag{23}$$

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. Another approach to solving a numerical model of this type is to extend the horizon of the model far beyond the period of interest so that a relatively arbitrary terminal condition, while affecting the solution of years leading up to the terminal year has little or no effect on the period of interest. However, if the period of interest is the next 70 or 100 years, the model horizon might need to be extended to 200 years in the future in this method, greatly increasing the computational demands.

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 includes 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,

$$Welfare = \left[\left(1-\beta\right)U^{1-\theta} + \beta U_T^{1-\theta}\right]^{1/1-\theta}, \tag{24}$$

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 α by using the GDP growth rate (g) in the formula:

$$\beta = \frac{\dfrac{\left(1+g\right)^T}{\left(1+r\right)^T}\cdot\dfrac{\left(1+g_T\right)}{\left(r-g_T\right)}}{\sum_{t=0}^{T}\dfrac{\left(1+g\right)^t}{\left(1+r\right)^t} + \dfrac{\left(1+g\right)^T}{\left(1+r\right)^T}\cdot\dfrac{\left(1+g_T\right)}{\left(r-g_T\right)}} \tag{25}$$

where $\dfrac{1+g_T}{r-g_T} = \sum_{T}^{\infty}\dfrac{(1+g_T)^t}{(1+r_T)^t}$.

The first term of the numerator of (25) 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.

2.5 Calibration

The calibration of the forward-looking EPPA model follows in several ways the same process as version 4 of the recursive model (EPPA 4). In common with the recursive version of EPPA is that we start with base year data for 1997. However, in a forward-looking model policy shocks in the future will change results in any simulated year. Thus, for example, a policy beginning in 2010 would change the economy in 2000 and 2005 compared with a reference case if we treated these years as forecast years. To avoid this rewriting of history with every policy simulation, we use the model in an initial calibration phase to project a simulated benchmark data set for 2005 that matches approximately the recursive dynamic model, which itself has been benchmarked to historical data for these years. Then in further simulations of the forward-looking model we use the simulated year 2005 effectively as the base year of the model. The first simulation year is 2010. This assures that under a policy scenario the economy does not begin adjusting to the policy in what is, in reality, the past.

The most important aspect of the calibration of the forward-looking model, however, is the consistency among capital stock, capital earnings, the interest rate, growth rate of the economy, and the rate of depreciation. 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. By incompatibility we mean that the apparent rental price of capital appears far too high or too low, or that the level of investment 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 an equilibrium growth path. 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. 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. The usual approach is to use estimates for those variables whose values are 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 assuming the real interest rate is 4% per year, a value consistent with observed rates of return. From (9) and (10) we can determine the initial level of the price of one unit of capital (we omit set *r* to facilitate the notation):

$$p_{t+1}^K = p_t^K(1+\bar{r})^{-1} = p_t \therefore p_t^K = (1+\bar{r})p_t \tag{26}$$

Assuming a 5% depreciation rate per year in the U.S. and ROW, the initial rental price of capital can be found by substituting the values of p_t^K, p_{t+1}^K, p_t and p_{t+1} from Eqn. (26) into Eqn. (8):

$$\bar{r}^K = \bar{r} + \delta \tag{27}$$

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

$$K_0 = RK_0 / \bar{r}^K \tag{28}$$

We then calculate the investment level that is consistent with depreciation and a benchmark growth rate of the economy. Thus, the total investment at the initial period can be calculated as:

$$I_0 = K_0(g+\delta) \tag{29}$$

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 inconsistent with 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 as:[7]

$$\rho = \frac{1+\bar{r}}{\left(1+g\right)^{1-\theta}} - 1. \tag{30}$$

3. REFERENCE AND POLICY SCENARIOS

Given our desire to compare results with the recursive version of EPPA (Paltsev *et al*., 2007) we have adopted the same three core policy scenarios, shown in **Figure 1**, which bracket the allowance paths specified in the Congressional proposals. In terms of the policy cost implications, a good summary measure of the different proposals is the total number of tons of CO_2-equivalent greenhouse gases they would allow from 2012-2050. These core cases are 287 billion metric tons

[7] This benchmarking is embedded in the MCP formulation, ensuring consistency among the values of $\bar{r}$, g, ρ, θ and δ (Rutherford, 2001).

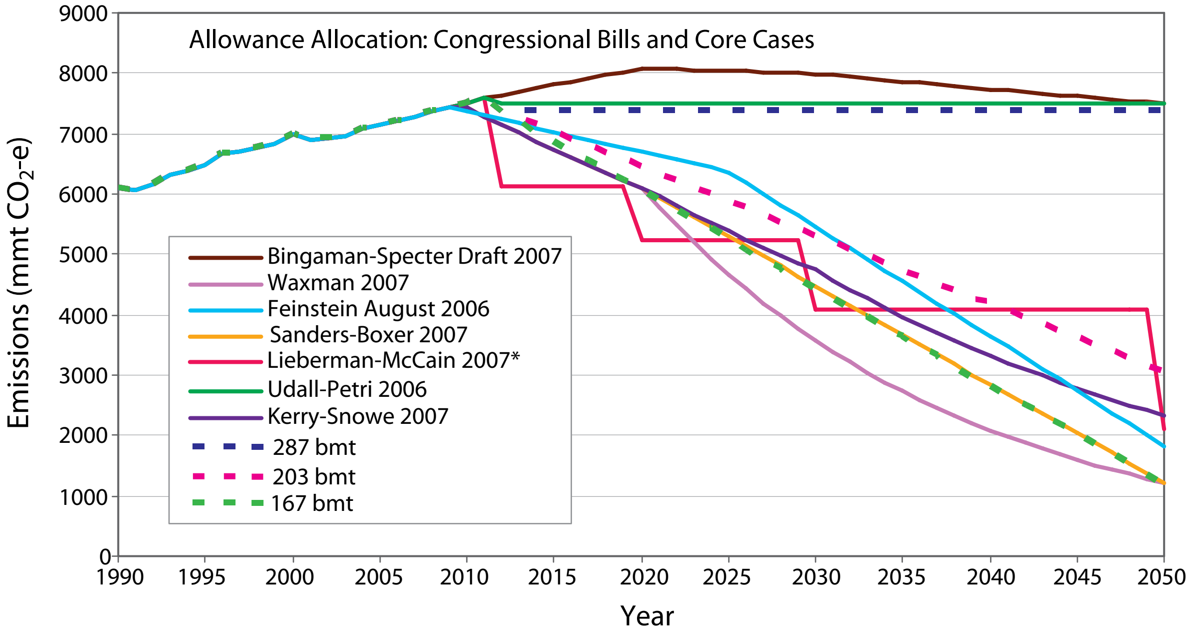

Figure 1. Scenarios of allowance allocation over time.
[* For Lieberman-McCain, this is the allowance path for covered sectors only.]

(bmt),[8] 203 bmt, and 167 bmt, and we use these as labels to designate the scenario results. Because we have an aggregare region ROW, we are not able to represent different policies in different parts of the world as in Paltsev *et al*. (2007). Instead we impose the ROW abatement from reference emissions taken from the recursive simulations for the regions that make up the ROW. For the recursive simulations we assumed Europe, Japan, Canada and Australia/New Zealand adopted a policy in 2015 that gradually brought them to 50% below 1990. Other regions had no policy until 2025, when emissions were then capped at 2015 levels. That cap was tightened further to return to year 2000 level emissions in 2035. An obvious limitation of the aggregate region ROW is that, implicitly, there is an ROW-wide cap in place throughout the 2015-2050 period. Thus, the cuts in the developed regions in early years can be spread across the ROW. This could effect some of the terms of trade results. For example, a relatively tighter policy in a limited number of regions could transmit terms of trade effects to the U.S. and that could shift trading patterns with other regions that had no policy. Such a response would not be picked up in the two-region model.

As with the recursive simulations, for the core cases we assume that all GHGs and all sectors are included in the policy, and that allowances (or any revenue) is distributed in a lump sum manner. We simulate emissions banking in the U.S., but as in the recursive simulations we do not allow banking in the ROW region. This procedure captures some aspects of the fact that some regions are not participating in early periods; *i.e.* if we allow banking, it would imply that developing countries abate in the 2015-2025 period and bank for later years, but without banking the aggregate ROW time path of abatement is consistent with the recursive results and delayed entry of developing countries.

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[8] Or, gigatons.

4. RESULTS

4.1 Comparison of Model Results for the Core Cases

The recursive and forward-looking versions of the EPPA model were designed to be as close as possible in terms of GHG emissions by benchmarking them in the reference case. **Figure 2** compares GHG emissions from the two versions in the reference and core policy cases, and **Figure 3** shows the associated CO_2-e prices. In the recursive-dynamic simulations we set CO_2-e prices to rise at the discount rate to approximate emissions banking behavior. In the forward-looking model, the CO_2-e price path is a result of an explicit optimization rather than a pre-determined path imposed to approximate optimization behavior. A comparison of results of the two versions of the model in Figures 2 and 3 suggest that this approximation in a recursive-dynamic EPPA model works very well in terms of the timing of abatement. Both versions yield very similar paths of emissions and CO_2-e prices under the policy scenarios. The policy-related results are not due to benchmarking, rather the results are similar because of a similar production and consumption structure of the models.

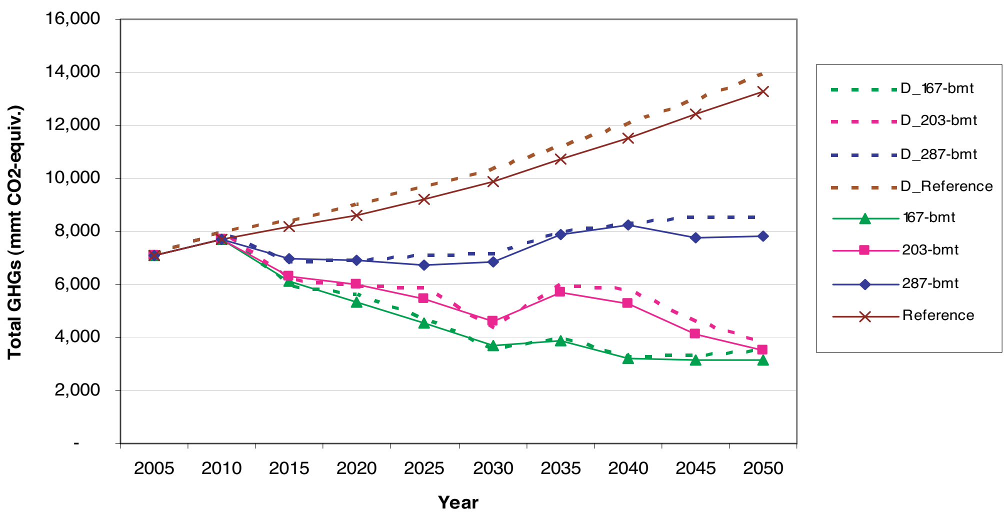

Figure 2. GHG emissions in the recursive (solid lines) and forward-looking (dashed lines) models.

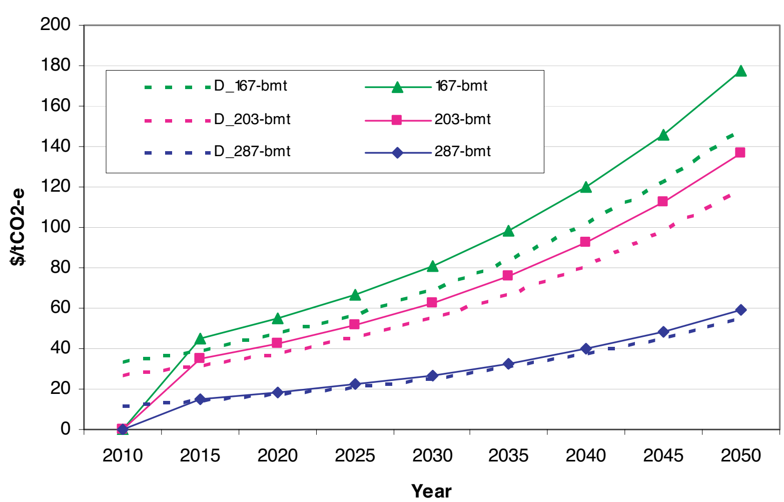

Figure 3. CO_2-e prices in the recursive (solid lines) and forward-looking (dashed lines) models.

Alternative assumptions about expectations as represented in the two model versions do, however, lead to a difference in the welfare results. An important phenomenon represented in forward-looking models is consumption shifting: people look ahead to see relatively abrupt changes in consumption and they try to avoid these shocks by smoothing consumption through time. **Figure 4** shows this response. In the recursive-dynamic model, the changes in policies abroad create shocks to U.S. welfare through unexpected changes in the terms-of-trade. In the forward-looking model, those welfare shocks are smoothed out. Also, note that welfare changes occur in the forward-looking model in 2010 even though the policy is not implemented until 2015. Agents in the model are looking forward and know the policy is coming. They modify their consumption behavior immediately. In this case, looking forward and realizing that consumption will be more expensive in the future, agents increase their consumption in 2010. The result is a welfare (consumption) gain (shown as negative welfare losses in Figure 4) before the policy goes into effect.

In a forward-looking model, economic agents are represented as optimizing over time as well as within any period, we therefore expect the welfare cost of any policy to be less in the forward-looking than in the recursive model. In Figure 4 the time path of welfare loss is lower for most periods in the dynamic than in the recursive model. **Figure 5** shows that the lifetime welfare change is lower for the dynamic model. Lifetime welfare is computed automatically in the forward-looking model and for the recursive model we calculate the Net Present Value (NPV) change using a 4% discount rate consistent with the interest rate in the forward-looking model. The forward-looking model trims about 0.10 to 0.25 percentage points from the welfare loss estimates of the recursive model. Note also that for the 287 bmt case the lifetime welfare change is a benefit for the U.S. This apparent benefit results from the anticipation of the terms-of-trade effects from the ROW region taking on a more stringent policy relative to the U.S. **Figure 6** shows that there are net welfare losses for the U.S. in the 287 bmt case if GHG controls are implemented by the U.S. only. In this case losses are shown by both model versions. Paltsev *et al.* (2007) showed similar terms of trade benefits in the recursive model from implementation of the policy abroad. However, because the abatement costs within the U.S. were somewhat higher the terms of trade benefit was not enough to create a net benefit to the U.S. with the recursive model.

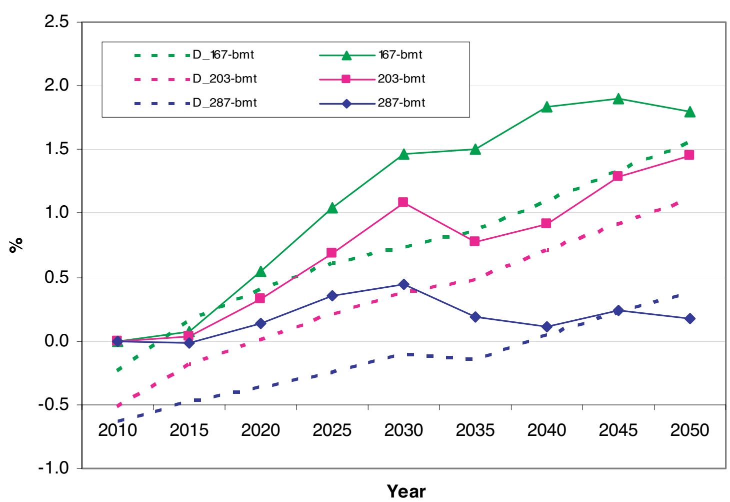

Figure 4. Annual welfare loss in the recursive (solid lines) and forward looking (dashed lines) models.

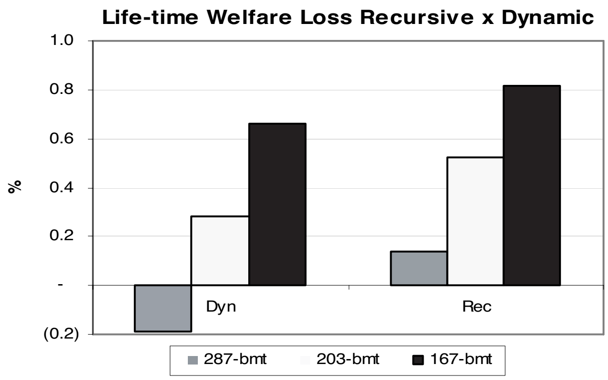

Figure 5. Lifetime welfare change, recursive and forward-looking models.

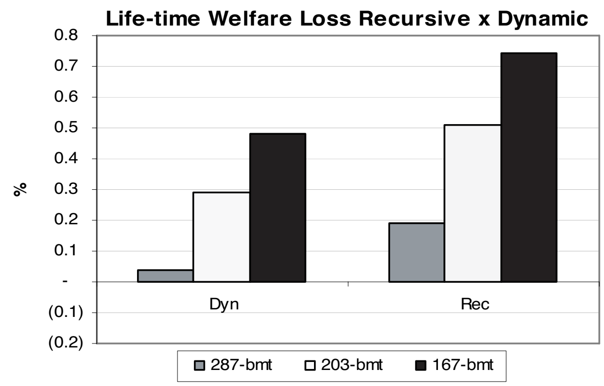

Figure 6. GHG controls implemented by U.S. only.

4.2 Early Action Abatement

One aspect of forward-looking behavior is that, once agents know mitigation measures are coming, they would like to begin abating immediately so long as they can bank allowances for use once the policy goes into effect. Such early abatement can reduce the overall policy cost while achieving the same level of cumulative emissions. Emissions during the policy period (2015-2050) will be somewhat higher, made up for by lower emissions prior to 2015. Many of the Congressional proposals include the possibility of such "early action credits." **Table 2** presents the impacts on emissions in 2010 with and without early action crediting. Without early action credits there are two effects leading in opposite directions. One is the substitution effect on consumption in 2010 knowing that the real price of consumption will rise once the policy is in place. The other, given vintaging, is an incentive to invest in lower emitting technology before the policy is in place or otherwise being stuck with uneconomic capital once the policy comes into effect. We find that latter effect dominating so that there is a slight reduction in emissions in 2010 even without early action crediting. It may be this would be stronger if we were able to vintage the capital stock more completely.

With early action crediting we get substantial reductions in 2010—a 10% to nearly 20% reduction. To create early action credits in reality requires a rather cumbersome effort to establish a baseline level of emissions for those agents who want to claim such credits. To the extent the baseline is too generous credits beyond any real abatement may be granted. On the other hand, if the early action crediting process is narrowly defined to avoid granting credits unless there is certainly real abatement then many opportunities for abatement may be excluded. The nature of the simulation implies that issues of establishing baselines are ideally resolved so it is as if the cap policy began in 2010, and so cannot take into account some of the well-known difficulties of such crediting systems. The 10% to 20% should thus be seen as an upper limit on real reductions that could be achieved through early action crediting.

Table 2. GHG emissions (mmt CO_2-e) in 2010 with and without early action credits.

	Reference	D_287-bmt	D_203-bmt	D_167-bmt
Reference	8,014			
No 2010 credits		8,013	8,012	8,011
2010 credits		7,224	6,669	6,496

Even with the fairly substantial reductions from early action in 2010, **Figure 7** illustrates that it does not have that much effect on the overall abatement level throughout the period. The obvious reason is that abatement during the five-year period represented by 2010 is spread over the entire 2012 to 2050 period. The effect of early action on CO_2-e prices and welfare costs are not shown here but are barely discernible in a graphical representation. Thus, from economic efficiency grounds not much is gained from an early action credit program, even though a quite of lot of effort has gone into defining such programs. The risk with them is that if the baselines are not carefully defined, and a lot of credits are forthcoming, they may be little more than hot air.

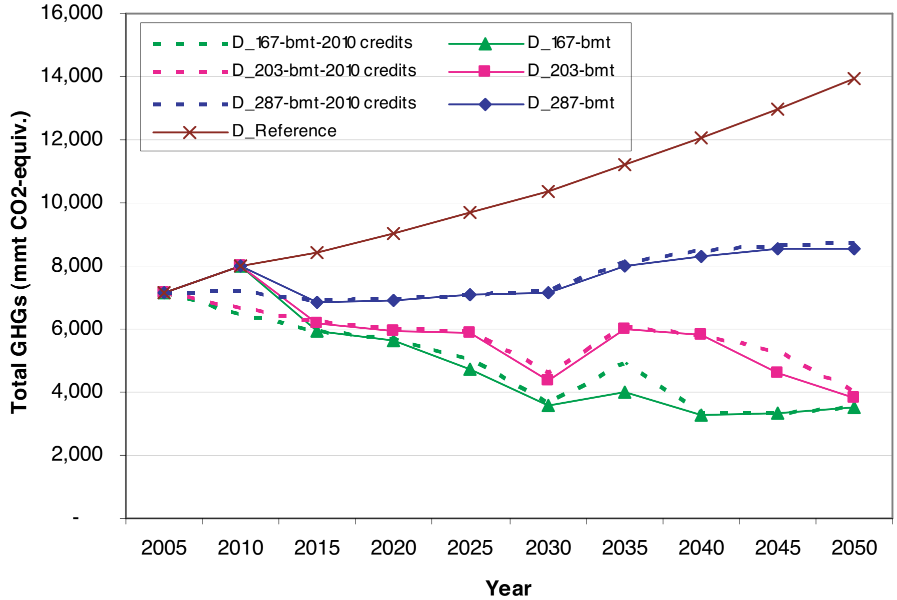

Figure 7. Early action credits; allowed (dashed lines), not allowed (solid lines).

4.3 Revenue Recycling with Forward Expectations

Another area where we might expect the forward-looking model to generate results different from a recursive version is in the effects of revenue recycling. Using the 203 bmt case as an example we compare the forward-looking results with those from the recursive model (**Figure 8**). Both show relatively little effect of reducing the labor tax rate, however, the dynamic results are positive and accumulate whereas the recursive results show almost nothing.[9] The capital tax recycling results show strong effects on growth in both cases. In the forward model, however, additional welfare losses in early years occur as consumption is reduced so that saving and investment can be increased to take advantage of the capital tax cut. Because in the recursive model savings do not respond to investment demand, we instead introduced market capital and residential capital, recognizing that most residential capital (*i.e.* investment in owner-occupied homes) is not subject to capital taxation. This follows an approach that Bovenberg *et al.* (2005) applied in a static setting. We are not completely satisfied with the recursive representation of household capital and are continuing to reformulate it. However, these experiments suggest that

[9] This result for the recursive model is somewhat puzzling. Previous analysis of revenue recycling to labor taxes with a recursive of EPPA showed positive effects (Babiker *et al.*, 2003). We are investigating the recursive formulation further.

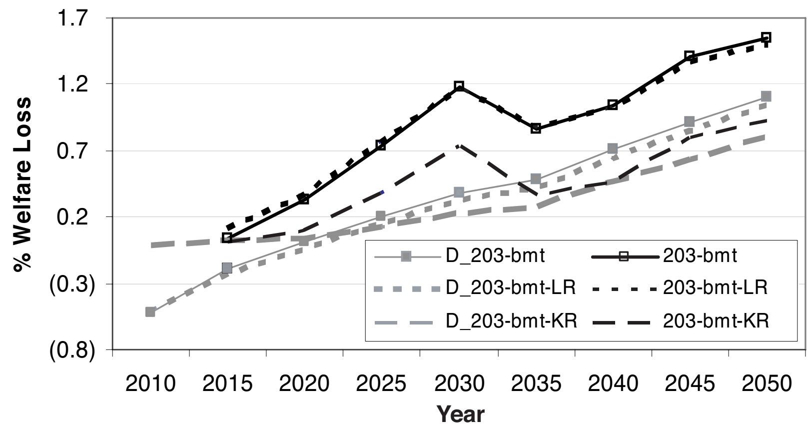

Figure 8. Annual welfare changes with revenue recycling to labor taxes (LR) or capital taxes (KR), recursive and forward-looking model.

it may be useful to consider residential capital as another source for funding increased investment in response to a capital tax cut in the forward model. Being able to shift to more market investment from residential investment appears to make it possible to fund an increase in market investment without the big penalty on near-term consumption. Whether this result would hold up in the forward-looking model needs to be seen.

For comparing welfare change with the recursive model, we have used a lifetime welfare change that is computed only over the model horizon. Lifetime welfare in the recursive model is computed as simply the net present value change in the annual welfare using a comparable 4% discount rate. In comparing lifetime welfare computed this way for capital and labor tax recycling we found little difference between them. The big welfare losses in early years with capital tax recycling were offsetting discounted gains from future years but the growing gain from capital tax recycling—the growth effect—suggested that the finite horizon welfare measure could be misleading. The infinite horizon approximation of the welfare gains from the policies, following the approach described in Section 3.3, are shown **Table 3**. This comparison shows that capital tax recycling improves welfare somewhat more than labor tax recycling. For the 203 bmt case, for example, the lifetime welfare cost without recycling is 0.7%, with capital tax recycling it is 0.53%, and with labor tax recycling it is 0.64%. The small benefits of labor tax recycling in all years end up generating substantial lifetime welfare benefits but they are not as large as with capital recycling where welfare losses in initial years are offset by substantial gains in consumption occurring in later years. The apparent "strong double-dividend" effect of capital tax recycling in the 287 bmt case again results from terms of trade effects from abroad. When there is no policy abroad there is a welfare loss.

One aspect of these results is that the absolute gain from revenue recycling is about the same in all three cases. The reason for this is that the auction revenue, and thus the tax cut, is similar in

Table 3. Welfare changes over the infinite horizon with labor (LR) and capital (KR) recycling in the forward-looking model.

	D_287-bmt	D_203-bmt	D_167-bmt
Lump-sum	0.10	0.70	1.11
LR	0.06	0.64	1.06
KR	(0.02)	0.53	0.95

all three cases. The 167 bmt case generates much higher allowance prices but because the number of allowances is falling over time the auction revenue begins to fall. If long-term policy goal is stabilization of concentrations, allowable emissions must fall very low, and auction revenue would drop off, and in that case revenue-recycling benefits would eventually fall because there was little revenue available.

4.4 Implications of a "Backstop" Technology

Another exercise that makes use of the model with forward expectations is to consider the effect on costs and abatement if a breakthrough is expected in the development of a relatively inexpensive technology. The EPPA model contains explicit technologies that are often mentioned as "backstops" such as biomass energy, wind and solar, carbon capture and storage, etc. By explicitly representing these technologies in terms of the type of energy they supply and their demands on natural resources we find that they are not pure backstops in the sense that term was originally applied—*i.e.* that once these technologies become economic they can replace all fossil fuel use in all sectors, and so they place a cap on the CO_2-e price. In both the recursive and the forward-looking EPPA, the CO_2-e price continues to rise because of limited natural resources or limited ability to substitute the fuel in all purposes. For example, a carbon-free electric generation source does not provide a carbon-free energy source for transportation unless one can develop battery technology that would work in automobiles, airplanes, trucks, and other transport vehicles. However, it is not uncommon in analyses of mitigation costs to assume the invention at some time in the future of a generic "carbon-free backstop" that "caps" the price. The generic backstop represents one way to recognize our very limited ability to see what new technologies might be developed.

The main empirical difficulty in implementing a generic backstop is to guess its cost, but as long we admit to knowing nothing about what it might be, we might as well imagine a number that will yield an illuminating result. For this experiment we assume the backstop cost is $50 per ton CO_2-e and show results for the 203 bmt case. The rationale for this cost is simple: If it were higher than the highest prices observed in the 203 bmt solutions it would be irrelevant. If its cost were very low, then the backstop would come in very soon implying that mitigation of greenhouse gases was a trivial economic issue.

Given the $50 assumption we tested two different approaches to model the backstop. In the first approach we have simply frozen the price once it reaches the backstop level. The interpretation is that the backstop is not available until that date yet it is expected because forward-looking agents can shift consumption in anticipation of it. This is a commonly used approach in CGE models of this type, here termed "backstop price." Operationally, we solve the model without the backstop price, determine when the price is reached, then impose the abatement path obtained without the backstop up to the point of entry and cap the price thereafter.

In our second approach we have generated a backstop technology that uses inputs from the economy to abate emissions. Operationally, we parameterize a production sector that produces emissions allowances at a constant marginal cost using some combination of capital, labor, and intermediate inputs. In this second case, the time of entry is endogenous. The forward-looking agent, knowing there is now a cheaper abatement technology, can adjust abatement prior to its entry. We label this approach "backstop tech". Note that there is no R&D in the model, we are simply representing a "known" technology that is currently unused. (For consideration of the induced technical problem for an individual technology in a CGE framework see Otto and Reilly, 2006.)

Figure 9 shows the price path (a), annual consumption path (b), and lifetime welfare effect (c) for simulations of the backstop price and backstop tech cases. In the case of the backstop price approach, the main avenue forward-looking agents have by which to adjust to existence of backstop is through consumption shifting. When no backstop is expected there is a small welfare gain relative to the reference case before the policy actually goes into effect; people look forward and see consumption becoming more expensive because of the CO_2-e policy and consume now

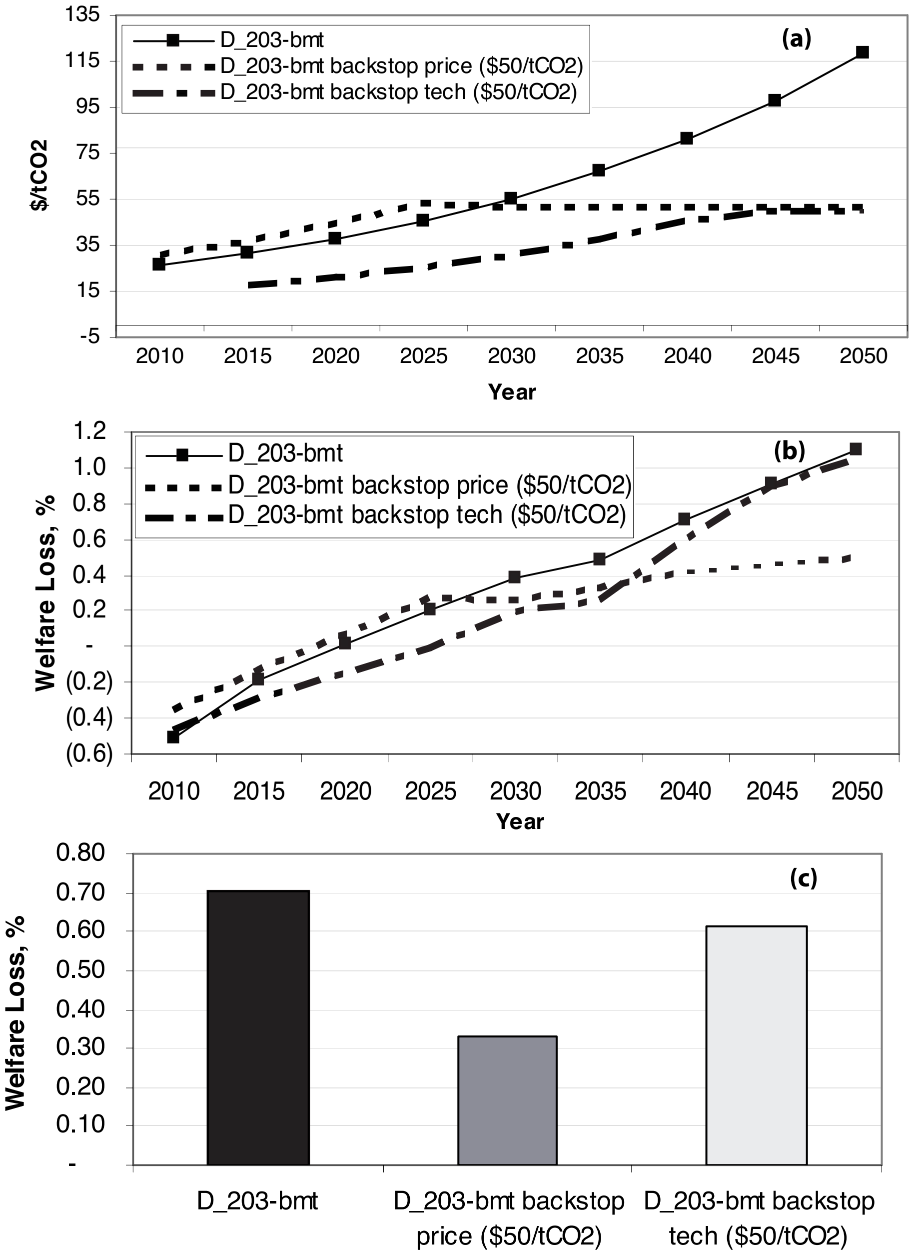

Figure 9. Effects in the forward-looking model of a carbon-free backstop at $50/t$CO_2$-e: **(a)** CO2-e price. **(b)** annual welfare loss and **(c)** welfare loss over the infinite horizon.

while consumption goods are cheaper. Once the policy is in place, the consumption losses rise gradually through time because larger losses in the future are discounted more in comparison with near-term losses. The consumption loss is smoothed through time in discounted terms. In the backstop price case, the constant backstop price means it is falling in discounted terms. When people know the backstop is coming they realize that the flat future CO_2-e price means (in present value terms) a falling cost of future consumption once the backstop enters. They therefore decide to save (and invest) more, cutting back on consumption in the near-term relative to the case without the backstop, to generate higher income in the future when consumption is cheaper.

In the case of the backstop tech approach a main result is that less abatement occurs in the near-term, the CO_2-e price is lower, and the entry of the backstop is delayed. And, even though near term abatement and the CO_2 price is lower than with the backstop price approach, the infinite horizon welfare loss is larger. Here less of the adjustment is forced through consumption shifting because the path of abatement and the near CO_2-e price path can be adjusted in anticipation of the low cost backstop. One aspect of this case is that more of the abatement burden is shifted to the future. Thus, even though the marginal cost of abatement is less in the future than without the backstop the welfare losses approach those of the case without the backstop because greater reductions are required to make up for less abatement in early years.

In much modeling the simple backstop price approach is used. It obviously lacks realism in that inputs are not required for abatement. But that approach has substantial effects on consumption shifting, the optimal abatement path, and overall cost of the policy. Perhaps the main lesson of this exercise is the danger of focusing on consumption losses for a short segment of time in a forward-looking model when the horizon of the model and the policy simulation period is much longer. If interest is focused on consumption change for the first ten years, that estimate can be swung dramatically up or down by different assumptions about a backstop technology. It is worth noting again that the formulation of forward-looking models of this type assume perfect information—that is, when we introduce the backstop it means that agents in the model make decisions today knowing for certain that the backstop will be available at some point in the future at $50 per ton CO_2-e. Obviously, modeling results that apply the backstop concept, specifying a technology of unknown design and resource requirements even if it requires inputs, are inevitably driven by a completely arbitrary assumption of the marginal cost at which it becomes available—whether it is $5, $50, $500, or $5000 per ton. However, our investigation suggests that even assuming we know that cost, exactly how the technology is modeled has important consequences for economic results.

5. CONCLUSION

A forward-looking version of a model is a useful tool to analyze situations where economic agents can look forward and anticipate future changes in economic policy and available technology. For numerical reasons, a forward-looking version of the EPPA model must be simplified in a number of ways. We have tried to retain key features such as vintaging and technology detail. By retaining the similar structure of the model we are able to compare results of the two versions and see how the forward-looking solution changes key results when applied to an environmental policy constraint. Somewhat surprising to us, the forward-looking and recursive versions produce very similar CO_2-e prices and abatement paths. This result leads us to conclude that the recursive EPPA model appears to approximate well the forward-looking result in terms of prices and emissions profiles. This is reassuring to the extent the longer horizon and multi-region recursive structure is necessary because the forward-looking EPPA model of that complexity cannot be solved—some basic results obtained from the recursive structure can be considered fairly robust regardless of whether solved in a recursive or fully dynamic fashion.

Estimates of welfare diverge as one might expect—we see consumption smoothing in the forward-looking model and the additional flexibility of optimizing over time reduces the welfare cost compared with the recursive model. In terms of policy relevance, one might question whether the assumption of perfect foresight moves us closer to or further from reality in estimating policy costs. Pervasive uncertainty, likely revision of policies over time, and unexpected changes in technology suggest the need for a stochastic solution but solving a complex CGE model stochastically is currently beyond available computational resources.

However, for some economic problems that depend critically on expectations the forward-looking solution is necessary in order to better understand economic behavior. We examined three issues: revenue recycling, early action credits, and the role of a potential future backstop technology. With regard to revenue recycling we found that capital tax recycling reduces cost more than labor recycling, and the time path of benefits with capital tax recycling is much different than for labor tax recycling. Welfare in early years falls as more consumption is devoted to savings and investment, and so the capital tax policy is essentially a growth policy where agents give up consumption today for greater consumption in the future. The labor tax recycling benefit is due more to a static reallocation of resources. With regard to early action credits, we find that such provisions, for the policy considered, could reduce pre-implementation emissions by 10 to almost 20%. This is a substantial reduction relative to current emissions, but it ends up not to have much effect on the overall cost of the policy because the banking of these credits is then spread over a long horizon. We do not find extra emissions in anticipation of the policy without early action credits—if anything we see slight reduction from reference as investment decisions anticipate the value of lower emitting technology in the future. Finally, a backstop technology is often included in models of this type. They are often somewhat arbitrary in that little about them is specified, thus there is little on which to base their cost or to describe the inputs and resources required. We found that exactly how they are specified changes results fairly substantially even when the backstop cost is the same. The approximation of “capping” the price to represent a backstop does not capture the fact that when the backstop would be deployed should be an endogenous choice for forward looking agents, and it appears to lead to significant underestimate of the infinite horizon cost, while distorting the near-term estimate of welfare loss as well.

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