When Cost Measures Contradict¹

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Abstract

When regulators put forward new economic or regulatory policies, there is a need to compare the costs and benefits of these new policies to existing policies and other alternatives to determine which policy is most cost-effective. For command and control policies, it is quite difficult to compute costs, but for more market-based policies, economists have had a great deal of success employing general equilibrium models to assess a policy's costs.

Not all cost measures, however, arrive at the same ranking. Furthermore, cost measures can produce contradictory results for a specific policy. These problems make it difficult for a policy-maker to determine the best policy. For a cost measures to be of value, one would like to be confident of two things. First one wants to be sure whether the policy is a winner or loser. Second, one wants to be confident that a measure produces the correct policy ranking. That is, one wants to have confidence in a policy measure's ability to correctly rank policies from most beneficial to most harmful. This paper analyzes empirically these two properties of different costs measures as they pertain to assessing the costs of the carbon abatement policies, especially the Kyoto Protocol, under alternative assumptions about implementation.

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1. Introduction

When regulators put forward new economic or regulatory policies, there is a need to compare the costs and benefits of these new policies to existing policies and other alternatives to determine which policy is most cost-effective. For command and control policies, it is quite difficult to compute costs, but for more market-based policies, economists have had a great deal of success employing general equilibrium models to assess a policy's costs.

Not all cost measures, however, arrive at the same ranking. Furthermore, cost measures can produce contradictory results for a specific policy. These problems make it difficult for a policy-maker to determine the best policy. For a cost measure to be of value, one would like to be confident of two things. First one wants to be sure that the sign is correct. That is, one wants to know whether the policy results in a cost or a benefit to society. Second, one wants to be confident that a measure produces the correct policy ranking. That is, one wants to have confidence in a policy measure's ability to correctly rank policies from most beneficial to most harmful. This paper analyzes empirically these two properties of different cost measures as they pertain to assessing the costs of the carbon abatement policies, especially the Kyoto Protocol, under alternative assumptions about implementation.

The Kyoto Protocol signed in December 1997, established specific emission reduction targets for greenhouse gases that are to be achieved by 2010. While the agreement thus defines precise national objectives for reducing emissions, it leaves open the methodology by which such goals are to be reached. For this purpose the Protocol includes several alternative proposals, including provisions for international emissions trading and credits for reforestation, amongst other possible policies. The open-ended nature of the agreement has provided signatory countries with the opportunity to evaluate which climate change strategy provides the least-cost course of action to achieve the required emission reductions. It has also provoked continuing discussions of the "Cost of Kyoto" in many countries that are assessing the implications of these commitments.

To aid in the decision over the most suitable policy - for both individual nations and the global economy as a whole - economists have developed sophisticated models that simulate the implications of differing approaches. These models provide valuable input into the policy debate, by creating summary measures of the costs and benefits of climate change policies that allow differing strategies to be ranked by objective criteria. However, where it has been possible to compare the metrics used in each of these models, it has been noticeable that they produce different and sometimes contradictory results. This has caused some concern amongst policy-makers who rely on the quantitative estimates produced by these models.

This paper is the second of CRA's two papers for the DOE that investigates cost measures and their resulting values as applied to the Kyoto Protocol. The goal of this research is to provide a theoretical foundation and empirical analysis for determining the most appropriate cost measure for ranking different policies. The previous paper, "Measuring the Costs of Climate Change Policies: Issues in the Interpretations of Common Metrics" provided a critical review of cost metrics in climate change models in current use. This paper undertakes an empirical analysis of why and to what extent current measures differ from the theoretical ideal. This paper analyzes empirically of the numerical differences among the alternative metrics of economic impact, and the determinants of those differences.

This paper is structured as follows. In Section 2, we describe the range of measures that this paper investigates. All of these measures are commonly used in estimating the impacts of a greenhouse gas policy. These measures include:

- Welfare (measured as equivalent variation)
- Direct costs,
- GDP, and
- Present value of future potential consumption.

In Section 3, we describe, in non-technical terms, CRA's economic model that is used to compare the different cost measures. The Multi-Region, Multi-Sector Trade model (MS-MRT) is a dynamic computable general equilibrium model. It is an ideal tool for comparing all these cost measures over a range of implementations of the Kyoto Protocol.

Section 4 outlines the empirical tests that we have undertaken to determine the concrete circumstances in which different metrics can give inconsistent rankings of policies, or significantly different magnitudes of costs

Section 5 provides numerical examples from CRA's MS-MRT model demonstrating the extent to which the various forms of impact estimates can produce different results, even when derived from the same basic model. We demonstrate that:

1. The magnitudes of the measures are not directly comparable in absolute or in relative terms – in particular, GDP, the Direct Cost and the area under the marginal cost curve are annual measures whereas PVC and EV are intertemporal measures;
2. The measures can produce different policy rankings; and

3. The measures can even be directly contradictory.

In the reporting of the results, we turn to the question of what drives these different outcomes.

2. Cost Measures

When evaluating the costs of the Kyoto Protocol, economic models estimate one or more of the following measures: Welfare, Consumption, GDP, and direct costs. CRA's Multi-Sector, Multi-Region Trade model (MS-MRT) can compute all four of these measures and hence is an ideal tool in assessing the differences among them. For this report, MS-MRT computes these measures under different model assumptions and implementation assumptions about the Kyoto Protocol. Table 2.1 summarizes the limitation of each of these metrics.

Table 2.1: Summary of limitations and difficulties with impact metrics

Impact Metric	Limitations or Difficulties
Equivalent Variation (EV)	Imprecision due to approximation of infinite time horizon.
Discounted Present Value of Consumption (DPVC)	Possibility of using inconsistent discount rates Assumes constant marginal utility of income
Discounted Present Value of Direct Cost (DPV of DWL)	Possibility of using inconsistent discount rates Requires highly restrictive conditions to be a measure of welfare Leaves out terms of trade effects Possibility of using inconsistent discount rates
Discounted Present Value of Real GDP (DPV of GDP)	Possibility of using inconsistent discount rates Price index issues Distorted by use of gross, not net investment Oversimplifies relationship between consumption and investment Ignores changes in foreign indebtedness Possibility of using inconsistent discount rates

Equivalent Variation Welfare

In welfare economics, welfare improvements are represented conceptually as increases in individual "utility". Utility is the satisfaction that an individual derives from consuming goods,

services and leisure.² Utility is not simply the sum of the monetary value of all things consumed because individuals derive different degrees of satisfaction from different types of goods. Further, increasing amounts of most goods produce a decreasing rate of increase in an individual's degree of satisfaction. Utility is therefore a *function* of consumption; the function applies different weights to different types of goods, and the utility function usually starts to flatten out as consumption of each good is increased.

Economists do not assign any absolute interpretation to the utility function. Rather, the theories of consumer choice and behavior that have been built on the utility function concept rely only on the *relative* ranking that such a function implies for consumption of alternative "bundles of goods and leisure." Thus, there is no single "correct" utility function, because there will be an infinite set of utility functions that all can equally well explain the same set of choices made by an individual.³ Among the many possible utility functions that can "explain" consumer behavior, it is possible to calibrate one to a monetary unit such as current dollars. When this has been done, it is possible to interpret the welfare impact projected for a policy in terms of its effective impact to current spending power of consumers. This provides a theoretically coherent estimate of the "cost" of that policy to consumers.⁴

The maximum level of satisfaction achievable at any point in time depends on one's income and also on prevailing prices. The economic impacts of a policy are felt by consumers when the policy changes the prices and/or incomes that they face. The monetary measure of the change in an individual's utility due to a policy is equal to the specific amount by which the individual's income would have to be adjusted, after accounting for the policy's anticipated price and income impacts, in order for that individual to be able to achieve a level of utility *equivalent* to today's level. This measure is known as "Equivalent Variation" (EV). Being linked to income, it is stated in monetary terms. By construction, it is measured in current dollars and therefore relatively easy to interpret.⁵

² In the rest of this paper, we will use the term "goods" to refer to all goods and services generally. Leisure will be kept as a separate concept, since some models account for it and others do not.

³ For example, taking one utility function that explains my economic behavior and multiplying it by 2 will provide exactly the same ranking of "Bundles of goods and leisure", though each "bundle" will nominally provide twice the utility. Technically, any function that is a monotonic transformation of a proposed utility function is considered an equally valid utility function.

⁴ This type of utility function is known as a "money metric utility function", and is described mathematically in the appendix.

⁵ There is a similar concept to EV called Compensating Variation. It has a parallel definition except that the necessary income adjustment (i.e., the monetary value of the utility change) is stated in terms of the prices that would hold after the new policy has been brought into force. Since these altered prices are the subject of uncertainty, Compensating Variation is not viewed as a practical alternative to EV. It has primarily theoretical interest, and therefore is not discussed here. The technical appendix does describe it, however.

EV may not be a widely recognized term among laymen, but it is the theoretically correct monetized measure of a policy's impacts to consumer welfare. Conceptually, it tells us an individual's "willingness to pay" to have a policy implemented, or to avoid having a policy implemented (depending on whether the policy will affect the individual positively or negatively).

In this paper, we analyze both the finite EV measure and the approximation to the infinite horizon EV. Infinite horizon EV is approximated by assuming that the economies return to a steady state condition by the terminal period. Then this steady state is projected throughout the rest of time and the infinite sum of impacts is computed and added to the impacts over the finite horizon.

Discounted present value of consumption

The present value of consumption is defined as the net present value of aggregate consumption over the time frame (or horizon) of the model (Equation 2.1). Consumption consists of private spending on goods and services (such as food, housing, and clothing) and public spending on services (such as health, education and welfare). In order to rank policies that affect the welfare of individuals in the future the measure incorporates a rate of time preference that re-values future consumption in today's present value terms. In other words a weighting (or discount rate) is applied to future consumption in order to be able to compare it with the value of current consumption today.

Equation 2.1. Present value of consumption

$$PVC = \sum_{t=1}^T \frac{C(t)}{(1 + w)^{t-1}}$$

where:

$C(t)$ is the aggregate consumption in period t ; and

W is the social discount rate applied to future consumption.

As with EV, a key problem with using PVC as an aggregate welfare measure stems from the difficulties of measuring economic well being over an infinite horizon. It is not yet possible to undertake computations that run to infinity. For this reason so-called 'infinite horizon models' are, in implementation, terminated at some finite point. Problems with measurement arise in determining how to account for the effects of climate change policies that occur after this

specified termination cut-off. In most instances this is dealt with by making an adjustment to consumption that accounts for the change in the value of the capital stocks estimated to exist at the point in time that model calculations are cut off (i.e., the “terminal capital stock”). In climate change models, in particular, it is important that the valuation of terminal capital stock is accurate, as emission limits are known to produce large drops in investment (as high as 2.5 per cent under a “no trading in the US” scenario).⁶ These changes in investment over the shock period can imply very different terminal capital stocks, and hence very different long-term welfare outcomes that need to be accounted for.

Another possible discrepancy between PVC and the underlying welfare measure arises if the chosen intertemporal utility function does not imply a constant discount rate on consumption (or if a different consumption discount rate than that implied by the utility function is used). In this case, PVC will not fully account for preferences regarding the distribution of changes in consumption over time. It is also possible that the discount rate chosen for calculating PVC will not be consistent with the underlying intertemporal utility function. In principle, this discrepancy can make policy changes that reduce welfare measured by the value of the underlying utility function appear to increase the PVC, and vice versa. However, for standard utility functions and the magnitude of impacts of policy changes investigated, this does not appear to be a large problem in practice.

Thus, while there are some potential differences, PVC may serve as a reasonable estimate for a welfare impact. In many cases, it is already used in that manner. It is, nevertheless, not exactly identical to EV.

Discounted present value of GDP

For the MS-MRT model, GDP is computed as the return to factor inputs. GDP is a derived quantity and not a value over which the model optimizes. As with the consumption measure, this is a temporal measure so we take the discounted present value of the sum of these losses to compute a loss for the entire horizon. We then report this single number and compare it to the other cost measures.

Gross Domestic Product (GDP) is defined as the total value of a nation's output that is produced within its borders in a given period of time. Although widely used, GDP changes are perhaps the furthest removed from a formal measure of welfare founded on microeconomics. It is defined as the sum in each calendar year of consumption plus investment plus government spending. Welfare associated with any particular year would be based only on the consumption measure.

⁶ Investment falls because consumers buffer the immediate and largest potential impact on their consumption levels during the near-term periods by reducing investment during that time.

Investment is made in order to assure sustained or even higher future consumption, but it does not provide welfare in its own right. Thus, these widely used measures would not be expected to be inherently sound indicators of the welfare impacts of a policy.

Additionally, GDP changes over time when the output of goods and services change and/or when the prices of those goods and services change. In other words, the nominal GDP measure incorporates movements in prices and it is possible that the measure can increase as a result of a general price rise, even if this price movement is not associated with an increase in output. In order to net out the effect of price changes Real GDP - which is calculated by dividing nominal GDP by the relevant price index - is often used as the preferred output measure. However, it is not easy to formulate theoretically correct price indices, and so even this correction can cause further inaccuracies.

While real GDP is thus superior in policy impact assessment to nominal GDP, there remain three main problems with using either of them to rank climate change policies. These are:

1. It is an annual measure; therefore, there are concerns about the correct discount rate;
2. It is associated with price index and numeraire problems; and
3. It is a measure of gross rather than net income.

We explain each in further detail below.

Direct cost

Dead weight loss is taken to be the integral under the marginal cost of abatement curve plus net imports of carbon permits. It is not practical to construct this curve because of large number of model runs that would have to be made. Therefore, we approximate the integral by assuming that the curve is linear, and thus the integral equals one half the number of tons abated times the marginal cost of abatement. As with the consumption and GDP measures, this is a temporal measure so we take the discounted present value of the sum of these losses to compute a loss for the entire horizon. We then report this single number and compare it to the other cost measures.

The PVC and EV are both firmly rooted in welfare economics. Many energy models, however, are more oriented to making direct estimates of the costs of achieving a particular policy objective. This is particularly true of “bottom up” models that represent energy technologies and their substitutes in specific detail. (DGE models, in contrast, use continuously differentiable production functions that often leave the specific technology choices quite abstract.) The SGM model uses direct cost estimates rather than direct welfare impact estimates as its primary impact metric.

Although direct cost estimates may not be derived from a utility model, they do in fact have a link to the concept of consumer's surplus. This is not a direct link to EV, but as discussed in our first paper, it may serve as a rough approximation.

Area under the marginal cost curve

The usual method for estimating direct costs of achieving a specific emissions reduction is to estimate the marginal cost curve and then calculate the area under that curve up to the reduction target.⁷ The relevant marginal cost curve can be constructed relatively simply from models that can address emissions trading or emissions taxes. The procedure would be to run the model in question to produce estimates of the carbon price associated with different caps on carbon emissions, and to plot the price of carbon against the emission reduction.

A simpler approximation is actually more commonly applied. Rather than plot out the entire marginal cost curve, the analyst will simply obtain an estimate of the marginal cost *at the point of the target emissions reduction*. This is the same as the projected emissions permit price. The estimated total cost for that reduction target is calculated as the $\frac{1}{2}$ the marginal cost times the amount of emissions reduced, based on the assumption that with zero emission reduction marginal cost is also zero. The degree of error in this approximation is greater when the marginal cost curve is more curved over the range of approximation.

The deadweight loss from a tax can also be approximated as $\frac{1}{2}$ the tax rate times the change in quantity purchased as a result of the tax. It is this calculation that we use in our analysis.

⁷ Mathematically, total cost is equal to the area under the marginal cost curve.

3. The Multi-Sector Multi-Region Trade Model

DESCRIPTION OF THE MS-MRT MODEL

The Multi-Sector Multi-Region Trade (MS-MRT) Model is a dynamic, multi-region general equilibrium model that is designed to study the effects of carbon restrictions on trade and economic welfare in different regions of the world. The model includes a disaggregated representation of industries, based on the GTAP4 dataset, so that differences in energy intensities across countries and differences in the composition of industry can be taken into account. It can represent a wide variety of international emissions trading regimes, define trading blocs composed of any grouping of regions, and place any set of constraints on both purchases and sales of emissions permits. The model computes changes in welfare (calculated as the infinite horizon equivalent variation), national income and its components, terms of trade, output, imports and exports by commodity, carbon emissions, and capital flows. It is fully dynamic, with saving and investment decisions based on full intertemporal optimization.

Conceptually, the MS-MRT model computes a global equilibrium in which supply and demand are equated simultaneously in all markets. The model assumes full employment and there is no money. There is a representative agent in each region, and goods are indexed by region and time. The budget constraint in the model implies that there can be no change in any region's net foreign indebtedness over the time horizon of the model. Even though there is no money in the model, changes in the prices of internationally traded goods produce changes in the real terms of trade between regions. All markets clear simultaneously, so that agents correctly anticipate all future changes in terms of trade and take them into account in saving and investment decisions. The MS-MRT model is calibrated to the benchmark year 1995, and solves in five-year intervals spanning the horizon from 2000 to 2030.

In order to capture some of the short-run costs of adjustment, elasticities of substitution between different fuels and between energy and other goods vary with time. The model is benchmarked to assumed baseline rates of economic growth and a common rate of return on capital in all countries. The rate of growth in the effective labor force (population growth plus factor-augmenting technical progress) and the consumption discount rate are computed to be consistent both with the assumed rates of growth and return on capital, and with zero capital flows between regions on the balanced growth path.

In the form used for this study, the MS-MRT model divides the world into eight geopolitical regions (see Table 3.1).

Table 3.1. Regions in the MS-MRT Model

		Member of	
Code	Region	OECD	Annex B
EUR	Europe Union of 15	Yes	Yes
JPN	Japan	Yes	Yes
OOE	Other OECD	Yes	Yes
USA	United States	Yes	Yes
FSU	Eastern Europe and Former Soviet Union	No	Yes
CHI	China and India	No	No
OEC	Oil Exporting Countries	No	No
ROW	Rest of world	No	No

Seven industries are represented in the MS-MRT model structure:

- Five energy forms: coal, crude oil, electricity, natural gas, and refined petroleum products; and
- Two non-energy goods: Energy-Intensive Sectors (EIS), and All Other Goods (AOG).

The MS-MRT model uses an Armington structure in its representation of international trade in all goods except crude oil, and places no constraints on capital flows. Crude oil is treated as a homogeneous good perfectly substitutable across regions. For all other goods, we assume that domestically produced goods and imports from every other region are also differentiated products. Domestic goods and imports are combined into Armington aggregates, which then function as inputs into production or consumption.

The model includes the markets for the three fossil fuels. Electricity is produced using these fuels, capital, labor, and materials as inputs. Crude oil trades internationally under a single world price. Natural gas and coal are represented as Armington goods, to approximate the effects of infrastructure requirements and high transportation costs between some regions. Depletion is assumed to lead to rising fossil fuel prices under constant demand, but the relation between

depletion effects on the supply of oil, gas, and coal and the actual supply of these fuels is ignored. That is, the model does not keep a record of the current stock of each fuel in each time period. World supply and demand determine the world price of fossil fuels. Current energy taxes and subsidies are included in each country's energy prices. The carbon-free backstop, represented as a carbon sequestration activity that requires inputs of non-energy goods, establishes an upper bound on world fossil fuel prices.

NON-TECHNICAL DISCUSSION OF THE MS-MRT MODEL STRUCTURE

This section offers a non-technical discussion of the important elements of the MS-MRT model: production, household behavior/consumer choice, international trade, savings and investment, and carbon restrictions. It relies largely on diagrams to illustrate the nesting structures used in the utility and production functions and the definitions of markets.⁸

Production of the Non-Energy Goods

The MS-MRT model represents non-energy production in two sectors. In producing non-energy goods, the model accounts for regional differences in factor intensities, degrees of factor substitutability, and the price elasticities of output demand in order to trace back the structural change in industrial production that is induced by carbon abatement policies.

All non-energy industries have a similar production structure (see Figure 1). Materials (outputs of the two industries used as inputs in other industries) enter the production function in fixed proportion with a value-added aggregate and an energy aggregate. The value-added aggregate comprises capital and labor. When the energy value share of an industry is small, the elasticity of substitution between the value-added aggregate and the composite energy good is equal to the own-price elasticity of demand for energy. This elasticity determines how difficult or easy it is for a region to adjust its production processes in response to changes in energy prices. Higher values of the energy substitution elasticity imply that a region can more easily substitute value-added for energy as the price of energy increases. This elasticity is time varying to reflect capital stock turnover and the ease of deploying new technology. For OECD countries, this elasticity begins at a value of 0.35 in the year 2000 and rises linearly to 0.6 by 2030; in non-OECD countries, it starts at 0.3 and rises linearly to 0.5 over the 30-year time horizon.

⁸ For a mathematical description of the model, see Bernstein, Rutherford, and Montgomery, "Trade Impacts of Climate Policy: The MS-MRT Model," in review, *Energy and Resource Economics*, 1998.

Figure 3.1: Production Structure for AOG, EIS, and Electricity

Capital and labor are nested as Cobb-Douglas. They may be substituted directly for each other through activities such as the automation of labor-intensive tasks. Therefore, the higher the wage rate, the more attractive it becomes to adopt automation. Labor inputs in this model are measured in efficiency units, so that one unit of labor supply is the same as ten billion dollars of base-year wages.

Labor supply is inelastic. Growth rates in the labor force are exogenously specified, so that the effective labor endowment for each region increases over time with labor force efficiency and population growth along the region's baseline growth assumptions. Labor is regionally immobile, and the labor force is fully employed at all times.

Capital stocks evolve through geometric depreciation of existing capital stocks and new investment of sector-specific capital (within countries). The rates of return on capital are determined in an international market by endogenous levels of lending and borrowing. We assume perfectly competitive capital markets in which the rate of return adjusts so that supply equals demand. The model is calibrated to an equalized net rate of return equal to 5 percent in all regions.

Armington composites enter the material nest, so that intermediate inputs from domestic industry j are imperfect substitutes for imports of good j . Material inputs are complements among each other; all other inputs are substitutes.

Production of Fossil Fuels

The production of fossil fuels requires inputs of the aggregate non-energy good and a fuel-specific factor of production that can be thought of as a sector-specific resource. In solving for the baseline, this resource is used to match the level of fossil fuel production to the U.S. Department of Energy's projections for fossil fuel production (EIA, *International Energy Outlook 1998*) through 2020 and to the IPCC IS2a scenario from 2020 to 2030. This matching is achieved by requiring that this resource be used in fixed proportions ($\sigma_{ff} = 0$) with the aggregate good (see Figure 2). Then, defining the level of available fixed resource for each fuel determines the level of each region's oil, gas, and coal production. After we solve the baseline scenario, we solve the fossil fuel production equations for the non-zero value of σ_{ff} required to arrive at the same fuel prices and fuel production levels. This value for the fuel supply elasticity is used when we solve the model under the carbon abatement scenario. Therefore, the level of production is allowed to vary in the scenario solve.

Figure 3.2: Energy Production Structure for Fossil Fuels – Oil, Natural Gas, and Coal

The value of the elasticity of substitution between inputs $L_{r,t}$ and $M_{r,t}$ and the $Resource_{ff,r,t}$ determines the price elasticity of supply at the reference point.

Household Behavior, Consumer Choice, and the Representative Agent

For each region, there is one infinitely lived "representative" agent who chooses to allocate its region's entire lifetime income across consumption in different time periods in order to maximize welfare. In each period, the consumer faces the choice between current consumption and future consumption that is purchased via savings. The pure rate of time preference between current and future consumption determines the intertemporal allocation of consumption. In equilibrium, the agent is indifferent between consuming one unit of consumption today or consuming the value of one unit of consumption that is adjusted for time preference tomorrow. We employ an intertemporal separable utility function where the intra-period utility from consumption is based on a nested CES function over imported and domestic commodities. The representative agent maximizes utility subject to an intertemporal budget constraint.

The budget constraint equates the present value of consumption demand to the present value of wage income, the value of the initial capital stock, and the present value of rents on fossil energy production, less the value of post-terminal capital. In this formulation savings are determined

implicitly so as to equalize the marginal utility of a unit of investment and current consumption. Savings are used for future consumption.

Current consumption is a CES aggregate of energy and non-energy goods (see Figure 3).

Consumers substitute between the end-use energy aggregate $C_{r,t}^E$ and the industry good aggregate $C_{r,t}^I$ with an elasticity of substitution σ_{end} . This elasticity varies over time to reflect capital stock turnover and the ease of deploying new technology. For OECD countries, this elasticity starts at a value of 0.35 in the year 2000 and rises linearly to 0.6 in 2030; for non-OECD countries, it has an initial value of 0.3 and rises linearly to 0.5 over the 30-year time horizon. This elasticity approximately equals the own-price elasticity of demand for energy because energy represents only a small fraction of total consumption.

Figure 3.3: Consumption Nest

Aggregate end-use energy is composed of the fossil fuel aggregate. The aggregate comprises oil, gas, and coal; these fuels substitute against each other with an interfuel elasticity of substitution equal to σ_{fuel} . Electricity is nested together with the non-energy goods. Each non-energy good in the fuel nest is an Armington composite, in which domestic and imported goods are combined in the manner described below. Purchase of the good is financed from the value of the household's endowments of labor, capital, energy-specific resources, and revenue from any carbon permit sales.

International Trade

Trade takes place in the fossil fuels and in the composite non-energy goods. All bilateral trade flows for the non-energy goods are represented in the MS-MRT model.

On the import side, consumers and industries choose between these domestically produced goods and imports. Demands for imports stem from cost-minimizing producer behavior and utility-maximizing household behavior. For the non-energy goods, an Armington trade structure is used so that the model differentiates between domestic and foreign goods. Therefore, domestically produced goods and imports are imperfect substitutes. Small cost differences across regions for a good do not lead to a total shift in demand from one region to another, and small changes in costs lead to small movements away from existing trade patterns. In addition, the Armington structure accommodates both imports and exports of the same commodity across regions (cross-hauling).

To create the Armington aggregate, imports of each non-energy good from each region substitute against each other with an elasticity of substitution equal to the Armington elasticity, σ_{MM} , and the aggregate import good substitutes against the comparable domestic good with an elasticity of substitution (σ_{DM}) equal to half of σ_{MM} . The Armington elasticity σ_{DM} is set at 4 for this model with two non-energy goods because those composite goods are not likely to be identical across countries.

This elasticity measures how easily imports can substitute for domestically produced goods. The Armington elasticity affects the potential gains in non-Annex I export sales that will occur when lower energy costs give these non-participating countries a competitive advantage. Figure 4 displays this structure. $A_{i,r,t}$ represents either consumer or industry demand for the non-energy good i in region r in time period t . Industries and consumers consume an Armington aggregate of domestically produced goods ($D_{i,r,t}$) and goods imported ($M_{i,s,t}$) from regions $s \neq r$.

Figure 3.4: Armington Nest Trade Structure for Consumption and Production

The models incorporate international markets for all goods. For these goods, we have a global market-clearing condition for the MS-MRT model:

$$\sum_r X_r^j = \sum_r M_r^j \quad \forall t, j \in \{\text{energy goods, non-energy goods}\}$$

The model is closed with respect to international trade through the intertemporal budget constraint. The intertemporal budget constraint for the representative agent in each region requires that the net present value of international borrowing or lending remain equal to the baseline level over the model's time horizon. This implies that any change in capital flows must net to zero (in present value terms) over the time horizon. Since the current account surplus or deficit (equal to the value of net exports) equals net international lending or borrowing, this also implies that the net present value of the change in the current account must be zero over the time horizon. The imposition of an intertemporally balanced trade account is linked to an implicit exchange rate that reconciles the present value of each region's domestic import demands with the present value of its exports.

This budget constraint allows changes in capital flows to play a part in determining the trade impacts of carbon limits. In contrast, the EPPA model assumes a period-by-period balance-of-payments constraint so that the current account deficit or surplus must equal baseline levels in each year. The G-CUBED model imposes a constraint on capital flows, so that a region's net foreign indebtedness can change over the model time horizon. G-CUBED accounts for the effects of changes in indebtedness by calculating GNP, in which interest payments on foreign debt are deducted from domestic output (GDP).

Savings and Investment (Dynamics)

MS-MRT is a fully dynamic general equilibrium trade model. The model structure incorporates forward-looking investment and savings behavior, so that businesses, individuals, and governments anticipate the effects of announced policies that are to take effect in the future. The level of savings and investment in a given period is endogenously determined by entrepreneurs and households that maximize the firm's value and the representative agent's lifetime consumption. Entrepreneurs choose investment levels to maximize the net present value of profits, and savings behavior is determined by intertemporal utility maximization. Therefore, investment dollars are placed in the area where they will receive the highest return.

Physical capital stocks depreciate at a constant geometric rate, and they are incremented by investment from domestic output. The finite horizon poses some problems with respect to capital accumulation. In the absence of any terminal adjustment, agents would consume all capital stock in the terminal period and thus let the value of the capital stock decline to zero after 2030. This would have significant repercussions for rates of investment in the periods leading up to the end of the model horizon. To correct for these effects, we apply an auxiliary equation dealing with the terminal capital stock.

It should be emphasized that we apply this side constraint along with the other economic equilibrium conditions (zero profit, market clearance, and income balance), but the application of this constraint has no implications for investment and consumption activities because these impacts do not enter into the zero-profit conditions for these activities. Instead, we close the model by including a terminal capital stock variable, the quantity of which is determined so that the rate of growth of terminal investment is balanced. That is, the shadow price of the above auxiliary constraint is the price of the terminal capital stock.

Carbon Restrictions

To comply with the Kyoto Protocol, the model places a carbon emissions limit on the participating countries. The model endows these countries with emissions permits that allow them to emit carbon up to the level to which they agreed. In the MS-MRT model, it is assumed that, under the no-trade scenario, the emissions permits are tradable within each Annex I region but not across regions. Under the trading scenarios, emissions permits can be traded among the different blocs: for the Annex I trading scenario, only Annex I countries face carbon limits, and

the permits are tradable across all Annex I countries; for the global trading scenario, all countries face carbon limits, and the permits are tradable throughout the world.⁹

BENCHMARKING AND CALIBRATION¹⁰

This section describes how the MS-MRT model was benchmarked and calibrated. As is customary in applied general equilibrium analysis, the MS-MRT model is benchmarked to economic transactions in a particular year (1995). Benchmark data determine the parameters and coefficients (value shares) of the CES production, demand, and utility functions. Base-year finance statistics indicate the value of payments to capital across sectors and the gross value of capital formation. For calibration, we needed to determine a reference level of emissions growth, GDP growth, energy production, energy, and non-energy trade. This entailed assigning values to key elasticities, such as end-use demand, Armington, oil supply, and the Autonomous Energy Efficiency Improvement (AEEI).

To develop a consistent database for energy and non-energy trade and input-output data, we merged non-energy trade data, input-output data, and input-output coefficients for energy from the GTAP database with data from the International Energy Agency (IEA). (See Babiker and Rutherford [1996] for details.)

For carbon emissions forecasts, the model was calibrated to the projections of both DOE and the International Panel on Climate Change. The reference or business-as-usual (BAU) level growth path for world emissions is taken to be the IPCC's reference scenario IS92A. The IS92A scenario corresponds to the IPCC's baseline (medium growth) scenario, which calls for worldwide carbon dioxide emissions to grow from 6.0 billion tonnes in 1990 to 10 billion tonnes by the year 2020. The reference level emissions growth determines the amount of emissions reduction required to meet the carbon limits called for by any carbon abatement policy.

The energy production and consumption forecasts as well as regional emissions were obtained from the Department of Energy's *International Energy Outlook, 1998*. These forecasts were then calibrated to current EIA data and the IS92A scenario so that energy consumption was consistent with carbon emissions. The business-as-usual GDP growth rates were taken from MERGE (a Model for Evaluating the Regional and Global Effects of greenhouse gas reduction policies), which was developed by Alan Manne and Richard Richels.

⁹ In the MPS/GE framework in which MRT-MS is written, creating a market for carbon permits and imposing a cap on carbon emissions for each country is straightforward. See the web site, www.gams.com, for a description of the MPS/GE modeling language.

¹⁰ For further technical details on how the MS-MRT is benchmarked, see Bernstein, Rutherford and Montgomery, 1998.

Selecting Elasticity Values and Backstop Prices

Selecting elasticity values affects the dynamics of the model and how the model responds under a carbon abatement policy. The choice of values has no effect on the baseline level of energy production and consumption, which is benchmarked through choice of other free parameters so that the chosen baseline is replicated as a market equilibrium. There are several key elasticities that need to be chosen for an MS-MRT simulation, including the oil supply price elasticity, Armington elasticity, end-use demand elasticity, interfuel elasticity of substitution, and the cost of the carbon-free backstop technology.

4. Empirical Tests

It is desirable to know whether or not a change in government policy will improve the aggregate welfare of the individuals within an economy. While this task may at first appear straightforward, it is often complicated by the fact that the benefits and costs of government policy affect individuals in different ways. For this reason it is necessary to have a methodology that can compare these differential impacts.

However, where it has been possible to compare the metrics used general equilibrium models, it has been noticeable that they produce different and sometimes contradictory results. This has caused some concern amongst policy-makers who rely on the quantitative estimates produced by these models.

For a cost measures to be of value, one would like to be confident of two things. First one wants to be sure that the sign is correct. That is, one wants to know whether the policy harms or benefits oneself. Second, one wants to be confident that a measure produces the correct policy ranking. That is, one wants to know the ranking of policies from most beneficial to most harmful.

Looking for reversals and consistency across measures when ranking policies. In modeling what factors (restatement of goal from chapter 1). To answer this question, we proceed through a series of MS-MRT runs where we progress from an idealized to a more realistic setting. For all model runs, the eight region, seven sector database is used (see Chapter 3). In the idealized case, each region has the same growth rate and the growth rate is constant over time. Furthermore, the policy analyzed is a carbon tax of \$100/tonne that takes effect in 2010 and continues through the model horizon. The cases continue to deviate more and more from this case until the final runs where each region experiences different growth rates that change with time. Furthermore, regions must meet an emissions cap that is fixed, but emission trading is restricted.

SENSITIVITY ANALYSIS

The cost metrics can disagree because of the inherent differences in what costs they measure, model structure, and policy scenarios. To separate out the latter two reasons, we make a number of model runs in which we conduct sensitivity analysis on different policy instruments and model characteristics.

On the modeling side, empirical tests are conducted under different assumptions about model horizon, terminal condition, economic growth rates, and elasticities. We vary the model horizon between 30 and 100-years. This allows us to study the effects of model truncation. Running the

model out 100-years is close to running it out to infinity because of the discounting.

Assumptions made about the terminal period in a model are important to the model returning to a steady-state or balanced growth so that infinite horizon welfare can be computed accurately.

Two different terminal conditions are tested to study the impact of this part of the model. For a model to be in steady-state, all regions must grow at the same growth rate, and this rate should be constant over time. For a model to be in balanced growth, consumption in each region must grow at the same rate as investment in that region. Therefore, we compare the results of model runs with exogenous labor growth rates that are either uniform across all regions and over time or growth rates that vary with region and year. Finally, we analyze the sensitivity of the welfare measures to the Armington elasticities.

To understand the importance of policy variables on welfare measures, we consider carbon abatement through taxes, emission caps, and restrictions on permit trading under caps. The taxation policy is designed to produce a steady-state scenario, for it assumes that all regions that adopt the carbon policy face a \$100/tonne tax from the year 2010 until the end of time. Under the permit trading scenarios, we look at no trading among Annex B regions, full trading among Annex B countries, and full global trading among all regions. Emission trading is also restricted and its effects are analyzed to understand the impact on cost measures of having a constrained optimization.

CASES

To conduct the sensitivity analysis, we combined the various policy measures, model inputs, and model structure parameters into five case types as reported in Table 4.1.

Table 4.1 Summary of cases used to analyze cost measures

	Growth Rates	Tax Rate	Caps	Horizon	Terminal Condition
1) Uniform Tax and Growth Rates	Constant	Fixed	NA	30 & 100	SVT and Term. Cap.
2) Uniform Tax Rate; Region Specific Growth Rates	Variable	Fixed	NA	30 & 100	SVT and Term. Cap.
3) Kyoto Protocol Caps; Uniform Growth Rates	Constant	NA	Kyoto	30 & 100	SVT and Term. Cap.
4) Kyoto Protocol Caps; Region Specific Growth Rates	Variable	NA	Kyoto	30 & 100	SVT and Term. Cap.
5) Kyoto Protocol Caps with Trade Restrictions; Region Specific Growth Rates	Variable	NA	Kyoto	30 & 100	SVT and Term. Cap.

These cases are designed to determine why cost measures disagree when analyzing the same policy and why they disagree across policies leading to different rankings. Moving down the table from case one to five, the model structure moves further from the balanced growth framework. Case one is an idealized set up: All regions experience the same growth rate, and this growth rate remains fixed for all time. All regions that participate in carbon abatement experience a constant \$100/tonne tax rate on carbon throughout the entire horizon. In Case five, the growth rates are region specific and each region that signs on to abate its emissions faces its own specific cap. Unlike the cases that employ a fixed tax, the constant emissions caps cause the policy to become increasingly more binding over time.

5. Results of Empirical Analysis

Three analyses are performed

- Under which conditions does the infinite horizon welfare measure in a short horizon model accurately estimate the true value for of the infinite horizon welfare;
- Analysis of factors that contribute to reversal of cost measures within a policy; and
- Analysis of factors that cause cost measures to yield differing rankings across policies.

ACCURACY OF INFINITE HORIZON MEASURE

In this section, we analyze empirical tests that are designed to determine the necessary conditions under which the EV infinite horizon measure in a short horizon model serves as a good estimate for the true value of infinite horizon EV. Ideally, this determination would be made by comparing the true value of the measure of infinite horizon EV with the approximation.

Unfortunately, the true value is unknown. Therefore, we must use an approximation to the infinite horizon EV that we believe is close to the true answer. Because of discounting, costs in later years affect welfare less. This implies that an estimate of EV from a much longer horizon model should serve as a good approximation to the true value of infinite horizon EV. Therefore, as an approximation for the true value of infinite EV, we use the welfare measure that results from running the model over a 100-year horizon. Closeness of these two measures indicates correctness of infinite horizon measure in the 30-year model.

The analysis proceeds by progressing from case 1 to 5 and comparing the estimate for infinite horizon welfare in the 30-year model to the value of infinite horizon welfare in the 100-year model all for the same case. In case 1, we employ idealized forecasts and an idealized policy: all regions are assumed to grow at the same rate for all time and regions that agree to reduce carbon emissions face a \$100/tonne tax on emissions. In Case 2, the growth rates vary by time and region, but the carbon abatement policy is still a \$100/tonne tax on carbon emissions. Then, we move to Kyoto like policies where each region adopts its Kyoto target for all time. In this case, we revert to the earlier assumption about equal and time invariant growth rates for all regions. In the last two cases, we relax this assumption and employ the Kyoto Protocol. Case 5 considers trading restrictions in the permit market.

For each policy scenario, we have tested the calculation of the welfare impacts under several differing assumptions, in order to distinguish which assumptions lead to contradictions in the welfare results. These assumptions have included:

- Horizon of 30 and 100-years
- Terminal condition
- Terminal asset
- Uniformity in growth rates
- Uniformity in carbon abatement policy

Case 1: Uniform Carbon Tax and Uniform Growth Rates

Table 5.1 reports the value of the EV measures from the most idealized case:

- Annex B countries take on a \$100/tonne carbon from 2010 onward; and
- All regions experience the same growth rate, which is constant throughout time.

Table 5.1: EV measures under uniform tax and growth rates

	30-year Horizon		100-year Horizon	
	Finite	Infinite	Finite	Infinite
EU 15	0.14	0.13	0.12	0.11
FSU	-0.75	-0.83	-0.83	-0.90
Japan	0.17	0.17	0.16	0.15
USA	0.09	0.08	0.07	0.07
Other-OECD	-0.61	-0.62	-0.67	-0.67
China + India	0.09	0.11	0.11	0.13
Oil Exporters	-1.78	-1.76	-1.83	-1.80
Rest of World	0.00	0.01	0.01	0.02

In the model run used to generate the results reported in Table 5.1, the terminal condition employed state variable targeting and no assumption was made about each region's share of the terminal assets. Varying these two assumptions, however, leads to little change in the welfare numbers because after the policy comes into effect, all regions return quickly to a new steady-state growth path. Therefore, assumptions about terminal conditions and terminal assets have little effect on the results.

In this idealized case, the infinite horizon computed in the 30-year model is a good approximation to both the within horizon and infinite horizon welfare measures in the 100-year model. This is to be expected since this set up assumes a policy and growth rates that are invariant over time. This differs from the model set up that assumes the Kyoto targets are in

place forever. In this case, the policy becomes more binding – requiring larger and larger percentage reductions in carbon emissions over time.

Case 2: Uniform Carbon Tax and Region Specific Growth Rates

In this case, we relax the assumption of uniform growth rates and instead allow each region to grow at a different rate and allow these rates to vary over time. As Table 5.2 indicates, the relaxation of this assumption causes little degradation in the performance of 30-year model's EV infinite horizon measure. In this case, the estimate is still quite good for all regions except FSU where the estimate is fairly good.

Table 5.2: Welfare Measures in 30 and 100-Year Horizon Models under Uniform Carbon Tax and Region Specific Growth Rates

	30-year Horizon		100-year Horizon	
	Finite	Infinite	Finite	Infinite
EU 15	0.10	0.10	0.08	0.08
FSU	-0.71	-0.75	-0.57	-0.61
Japan	0.15	0.15	0.13	0.13
USA	0.13	0.12	0.11	0.11
Other-OECD	-0.55	-0.55	-0.51	-0.51
China + India	0.25	0.26	0.28	0.29
Oil Exporters	-1.71	-1.69	-1.68	-1.66
Rest of World	0.03	0.04	0.05	0.05

Case 3: Kyoto Protocol Caps and Uniform Growth Rates

In this case, the policy changes dramatically from one of equal and constant tax rates to one where each region must meet its emission cap under the Kyoto Protocol from 2010 to the end of the horizon. Uniform growth rates are reapplied to each region. Table 5.3 reports the EV results from the case in which we assume that there is no permit trading among regions.

In this case, the estimate of infinite horizon welfare that comes from the 30-year model is at most half and for most regions much less than half of costs or benefits that accrue in the 100-year model. Infinite horizon welfare measure for 2030 indicates a loss of less than 0.05% for USA, but in the 100-year version, the loss grows to be almost 0.5%. Possibly even more troubling is the fact that infinite horizon welfare changes sign for the EU.

Table 5.3: Welfare Measures in 30 and 100-Year Horizon Models under Kyoto Protocol and Uniform Growth Rates

	30-year Horizon		100-year Horizon	
	Finite Horizon	Infinite Horizon	Finite Horizon	Infinite Horizon
EU 15	0.04	0.03	-0.37	-0.41
FSU	-0.53	-0.53	-0.88	-0.94
Japan	-0.26	-0.28	-0.68	-0.72
USA	-0.02	-0.03	-0.40	-0.45
Other-OECD	-1.00	-1.01	-1.90	-1.95
China + India	0.11	0.11	0.28	0.27
Oil Exporters	-2.50	-2.50	-3.96	-3.96
Rest of World	-0.04	-0.04	-0.02	-0.04

Comparing the results from Tables 5.2 and 5.3 indicates that the relative importance of uniform growth rates as opposed to a uniform policy over time. Where uniform policy implies that the effect of the policy varies little over time. The fixed carbon tax policy applies the same cost adder on energy consumption for all periods; whereas, the Kyoto Protocol causes the cost of energy consumption to rise over time. Therefore, under the Kyoto Protocol, the model never returns to a steady state condition and hence the estimate for infinite horizon welfare in the 30-year model is poor. In addition, this suggests that there are large problems if one uses a short time horizon model to estimate infinite horizon welfare for a Kyoto like policy.

Case 4: Kyoto Protocol Targets and Region Specific Growth Rates

In this case, the restriction that each region has the same growth rates is relaxed. Each region takes on its own growth rate through 2020 as forecasted by the Energy Information Agency. From 2020 onward, each region is assumed to grow at the same rate as it does from 2015 to 2020. This leads to some extremely divergent economic growths over the 100-year horizon.

These large discrepancies in growth rates cause the welfare measures in the 30 and 100-year models to diverge more than in the previous case of uniform growth rates (see Table 5.5). If the growth rates were made to converge by the end of the 100-year horizon, the differences would narrow. But they would still exceed those that appear in the uniform growth case.

Table 5.4: Welfare Measures in 30 and 100-year Horizon Models under Kyoto Protocol Caps with Unrestricted Permit Trading

	30-year Horizon	100-year Horizon
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	Finite	Infinite	Finite	Infinite
EU 15	0.08	0.06	-0.31	-0.38
FSU	-0.82	-0.96	-5.97	-6.42
Japan	-0.20	-0.23	-0.48	-0.53
USA	-0.04	-0.07	-0.61	-0.68
Other-OECD	-0.96	-0.98	-1.79	-1.85
China + India	0.36	0.37	0.82	0.77
Oil Exporters	-2.50	-2.46	-4.16	-4.16
Rest of World	0.03	0.03	0.14	0.10

Case 5: Kyoto Protocol Targets with Trade Restrictions and Region Specific Growth Rates

This case further distorts the scenario by imposing trade restrictions on permit trading. For this case, only Annex B countries adopt carbon limits. These countries are allowed to trade permits among themselves. But no country may satisfy more than 30% of its obligation through the purchase of permits. This causes the model to become further from a steady state condition by the terminal year. Hence the estimate of infinite horizon welfare in the 30-year model is the worst of all the cases. Now, the FSU and the EU experience positive welfare in the 30-year model and negative welfare impact in the 100-year model (see Table 5.5). The welfare measures, in general, diverge more in this case than in the previous ones.

Table 5.5: Welfare Measures in 30 and 100-year Horizon Models under Kyoto Protocol Caps with Restricted Trading

	30-year Horizon		100-year Horizon	
	Finite	Infinite	Finite	Infinite
EU 15	0.06	0.05	-0.11	-0.19
FSU	0.36	0.17	-6.09	-6.45
Japan	-0.05	-0.07	-0.42	-0.46
USA	-0.06	-0.09	-0.51	-0.61
Other-OECD	-0.81	-0.83	-1.85	-1.92
China + India	0.29	0.30	0.82	0.78
Oil Exporters	-2.13	-2.09	-4.03	-4.03
Rest of World	0.03	0.04	0.15	0.11

Effect of Terminal Condition on EV Measures

Much has been written about the importance of terminating these economic models correctly so that one can have confidence in the results and the welfare measures. We analyze the effect of the terminal condition on the predictive powers of the EV measure of infinite horizon welfare in the 30-year model. We consider two different terminal conditions (see Appendix for summary on each).

Applying either terminal condition yields poor results for prediction powers model. The EV Infinite from either version of the 30 yr model is a poor estimator of the EV infinite or EV finite for the 100 yr. Model For the 100 yr. Model, the method of termination matters little as the EV measures for each model are nearly identical

Therefore, to make use of infinite horizon estimate, must assume that is one of a constant tax after the terminal year where the tax equals the

Table 5.6 Welfare Measures in 30 and 100-year Horizon Models Under Different Terminal Conditions

	State Value Target				Target Terminal Capital Stock			
	30-year Horizon		100-year Horizon		30-year Horizon		100-year Horizon	
	Finite	Infinite	Finite	Infinite	Finite	Infinite	Finite	Infinite
EU 15	0.08	0.06	-0.31	-0.38	0.12	0.11	-0.31	-0.38
FSU	-0.82	-0.96	-5.97	-6.42	-0.57	-0.68	-5.97	-6.42
Japan	-0.20	-0.23	-0.48	-0.53	-0.15	-0.18	-0.48	-0.53
USA	-0.04	-0.07	-0.61	-0.68	-0.02	-0.04	-0.61	-0.68
Other-OECD	-0.96	-0.98	-1.79	-1.85	-0.92	-0.95	-1.79	-1.85
China + India	0.36	0.37	0.82	0.77	0.35	0.36	0.82	0.77
Oil Exporters	-2.50	-2.46	-4.16	-4.16	-2.58	-2.55	-4.16	-4.16
Rest of World	0.03	0.03	0.14	0.10	0.02	0.03	0.14	0.10

These large differences suggest that in order to better compare the effect of terminal conditions, we need to devise a policy in which the impacts of the policy in the final year are similar to the impacts that would be present in the post horizon. A policy that maintains carbon prices close to their value in the terminal year is one way to come closer to this idea. Therefore, we ran the model for the 100-year horizon that assumes the carbon prices are nearly constant from 2030 onward.

Table 5.7 compares the difference in welfare measures under the two different terminal conditions and the two different policies: Kyoto forever and Kyoto to 2030 and then constant carbon tax afterward. The absolute differences between the welfare measures under the Kyoto+Fixed Tax policy are significantly smaller than under the Kyoto Forever policy. Much of the remaining difference is caused by the large differences in regional growth rates. Implementing converging growth rates would ameliorate this problem.

Looking at the results within the Kyoto+Fixed Tax policy, one sees that for all regions the absolute difference in the columns under the Kyoto+Fixed Tax heading are smaller under the state value targeting. Therefore using this method of model termination causes the infinite horizon welfare measure from the 30-year model to be closer to the 100-year model's estimate for infinite horizon welfare. These results support the work of Lau, Pahlke and Rutherford (see Appendix).

Table 5.7 Welfare Measures in 30 and 100-year Horizon Models Under Different Terminal Conditions

	State Value Targeting		Terminal Capital Targeting	
	Kyoto+Fixed Tax	Kyoto Forever	Kyoto+Fixed Tax	Kyoto Forever

	Finite	Infinite	Finite	Infinite	Finite	Infinite	Finite	Infinite
EU 15	-0.03	-0.04	-0.15	-0.22	-0.07	-0.07	-0.18	-0.25
FSU	-1.65	-1.71	-6.44	-6.80	-1.94	-2.00	-6.72	-7.07
Japan	-0.04	-0.04	-0.37	-0.41	-0.08	-0.09	-0.42	-0.46
USA	-0.09	-0.10	-0.42	-0.52	-0.13	-0.14	-0.46	-0.56
Other-OECD	-0.21	-0.22	-1.01	-1.09	-0.24	-0.25	-1.04	-1.13
China + India	0.27	0.28	0.54	0.49	0.28	0.29	0.55	0.50
Oil Exporters	-1.17	-1.14	-1.96	-1.96	-1.09	-1.06	-1.87	-1.87
Rest of World	0.06	0.07	0.12	0.08	0.06	0.07	0.11	0.07

REVERSALS ACROSS MEASURES

Reports cases in which cost measures disagree in sign. That is, for a given policy, two cost measures that are used to measure the impact of a policy on a region disagree as to whether the policy yields benefits or imposes costs. Several variants of cases one through five were run. The following tables present some of the representative examples from cases two, three, and five where cost measures disagreed.

In almost all cases, finite and infinite horizon EV and discounted present value of consumption agreed in sign and generally were of similar magnitude. Discounted GDP however disagreed in several instances.

The problem with the GDP measure appears to depend little on the terminal condition used, emissions policy, or growth rates. Changes to these model inputs or model structure affect in which regions reversals are seen and the magnitude of the reversal, but making these changes fails to eliminate reversals. The GDP measure even gives contradictory results under the idealized policy of constant carbon taxes.

Extending the model horizon, however, causes many of the reversals to disappear. This suggests that terminal condition affects GDP greatly.

Deviating further and further from the ideal model set up leads to more reversals. Table 5.10 shows that the welfare measures disagree for Japan under a carbon abatement policy where all regions adopt carbon caps and permits can be traded among all regions. But restrictions are placed on emissions trading.

Table 5.8 Uniform carbon tax and region specific growth rates (100-year horizon)

Region	Regions Taxed	DPV of GDP	EV Finite	EV Infinite	DPV of Consumption
China + India	All	-0.58	0.05	0.05	0.04

Rest of World	All	-0.12	0.06	0.06	0.06
USA	Annex B	-0.06	0.11	0.11	0.11

Table 5.9: Kyoto Protocol Caps and Uniform Growth Rates (30-year horizon)

Region	Scenario	DPV of GDP	EV Finite	EV Infinite	DPV of Consumption
EU 15	Global Trading	0.03	(0.00)	(0.01)	(0.00)
Rest of World	AB Trade w/ Restrictions	0.23	(0.00)	(0.01)	(0.00)

Table 5.10: Reversal in Cost Measures under Kyoto Protocol Caps with Trading Restrictions and Region Specific Growth Rates (30-year horizon)

Region	Trading Limit	DPVGDP	EV_FIN	EV_INFC	PCTPDVC
Japan	30%	-0.19	0.01	-0.01	0.01
USA	10%	-0.20	0.02	0.00	0.01
	30%	-0.13	0.03	0.02	0.03

In general, there are three key problems with using the GDP measure to determine the net costs of a policy:

- It is an annual measure;
- It is associated with price index and numeraire problems; and
- It is a measure of gross rather than net income.

In addition, with MS-MRT, there is the additional problem that the model does not optimize over GDP so it is not surprising that at times it fails to yield the correct policy implication. Below, we explain the three key problems in further detail.

Annual measure

Due to the lag between the time when emissions of greenhouse gases occur and the appearance of any possible effects that the accumulation of these pollutants may have on the global climate, the true costs of current emissions may not be felt for some time yet to come. Policies that attempt to limit greenhouse gas emissions are thus by their very nature intertemporal while GDP, is measured annually. For this reason GDP comparisons may not aid decisions that seek to rank climate change policies, which are known to affect both current and future generations. For

example, it is not uncommon for economic models to find that the change in GDP is positive in one period and negative in the next. In such an instance it is not possible to conclude that the policy is unequivocally superior to an alternative course of action, where that action may lead to a negative GDP change in this period but a positive GDP change the period following.

GDP may also be increased over a period of time by shifting resources from consumption to investment, or vice versa. Depending on whether resource allocation is optimal in the baseline, this shift may increase or decrease underlying economic welfare. This is seen in two kinds of results. One is a “buffering” of consumption during an economic downturn, by means reduced saving and investment, which can maintain GDP and consumption for some period of time, but at the expense of a smaller capital stock which eventually leads to lower productive capacity and output in the future. The other is a result of some policy stimulus, such as an investment tax credit, which boosts investment, possibly at the expense of consumption, and translates into a larger capital stock at some future point in time. Evaluating overall welfare effects requires including both the changes in consumption during the models time horizon with changes the capital stock at the end of the model horizon in an overall measure to determine whether the shifts between consumption and investment increase or decrease intertemporal welfare.

In short, the GDP measure provides no guidance as to the appropriate weightings (or discount rates) to apply to future changes in GDP and can only provide annual, and thus temporal, results for an essentially intertemporal problem.

Price index problems

As outlined above, movements in the general price level may influence nominal GDP changes. For this reason, Real GDP is the preferred measure as it removes the effects of inflation. However, in order to net out price movements, nominal GDP must be divided by a relevant price index, the choice of which is inherently problematic. In particular, models that do not include an explicit utility function must use a constructed price index, which implies a specific evaluation across commodities and time. In models that do include a utility function the ideal price index can be taken directly from the temporal expenditure function, but in these instances the results are very sensitive to the choice of numeraire.

In simulations performed with MRT, GDP reversals appear most frequently when policies that produce significant changes in capital flows are investigated, or when there are large changes in international prices for non-energy goods. GDP reversals due to changes in capital flows occur because of shifts in investment as comparative advantage changes due to shifts in energy costs. In addition, the changes in international capital flows complicate welfare comparisons because the change in net foreign indebtedness must also be taken into account. A surge of investment in a developing country financed by foreign investment will increase GDP in the short and long

run, but that portion of the capital stock will now belong to agents outside the economy in question – who will have claims on output of the economy. Capital inflows imply that an increasing amount of the productive assets of an economy are owned by agents located outside the economy. The resulting obligations to service the debt come out of resources that could otherwise provide consumption to residents of the economy in question. GDP measures the value of goods and services produced in the economy – the level of economic activity – not the income of residents of the economy, and therefore can give a distorted picture of resident welfare in the presence of capital flows. Use of GNP measures, which do account for repatriated profits, earnings of foreign workers, and debt service, should be investigated to address this issue.

Valuation of imports and exports provides a thornier problem, if the intention is to mimic welfare changes. The ideal measure would incorporate in GDP terms of trade gains or losses that occur because of changes in prices of imports and exports, but this is literally impossible if “Real GDP” is defined by fixed price weights. With fixed price weights, the same prices are used to evaluate Real GDP in the baseline and policy cases, and in every year, no matter how a policy changes those prices.

In some models, with endogenous imports and exports, changes in terms of trade will cause changes in quantities of imports and exports, and these changes will register in measures of “Real GDP.” However, the choice of price weights will affect the magnitude and the sign of the contribution of these changes in quantities of imports and exports on GDP.

These measurement issues are related to the manner in which changes in terms of trade result in different amounts of goods being available for final demand in the economy in question. For, if the price of imported oil falls, but all other prices remain the same, a smaller amount of other goods will need to be exported (or a larger amount of goods can be imported) to produce balance of payments equilibrium. The reduction in exports, all else constant, increases goods available for domestic use, and therefore welfare. Capturing these changes in real GDP requires some subsidiary calculations, either of the correct price index or a fundamentally similar calculation of changes in quantities. Models that calculate imports and exports endogenously will return to balance of payments equilibrium, by increasing some imports and decreasing some exports. This should lead to an increase in Real GDP whenever the price of an imported good falls. Whether Real GDP is evaluated at base period prices (before the fall in the price of imports) or current period prices (after the fall in the price of imports) will affect the magnitude of the calculated change. The standard Paasche-Laspeyres comparison will then apply -- if quantity increases for a good whose price has fallen, and quantity decreases for a good whose price has increased, the increase in Real GDP will be smaller than if quantity increases for a good whose price increases and decreases for a good whose price decreases.

Gross versus net income

GDP is a measure of gross income, in the sense that they do not take account of the depreciation of capital. When policies lead to large reductions in investment for a sustained period of time, they lead to lower levels of capital stock and reduced capital consumption allowances (CCA). As a result, GDP falls because of both contemporaneous reductions in investment and lower CCA. This effectively double-counts the reduction in investment and produces a larger percentage reduction in GDP than in net national income. GDP also fails to account for net interest payments on foreign debt, so that if a policy causes a significant change in foreign debt, GDP will inaccurately measure the change in real income for residents of a country.

REVERSALS IN POLICY RANKINGS

In this section, we highlight a few instances where using different cost measures leads to different policy rankings. Over all the cases, the EV and consumption measures generally yielded the same policy rankings. The discounted present value of GDP and direct costs, however, disagreed with the EV and consumption measures and at times disagreed with each other. Proceeding from case 1 to case 5, we report representative instances where the measures lead to different policy rankings.

Uniform Carbon Tax and Uniform Growth Rates

Under this highly idealized case, policy rankings were consistent across all cost measures. This stands to reason since there are only two different policies and scenario is close to a balanced growth solution.

Kyoto Protocol Caps and Uniform Growth Rates

Replacing the uniform carbon tax with Kyoto like policies causes GDP to produce a different policy ranking from that of the welfare and consumption measures (see Table 5.11). In four out of the eight regions, GDP ranks the Annex B trading policy ahead of the global trading policy whereas the other cost measures give the reverse ranking.

Table 5.11: Kyoto Protocol Caps and Uniform Growth Rates (30-year horizon)

Region	Scenario	DPV of GDP	EV Finite	EV Infinite	DPV of Consumption
USA	AB Trade w/ Restrictions	-0.67	-0.39	-0.44	-0.39
	Global Trading	-0.56	-0.44	-0.46	-0.44
Oil Exporting Countries	Annex B Trade	-2.29	-2.79	-2.78	-2.79
	Global Trading	-2.65	-2.54	-2.55	-2.54
Rest of World	Annex B Trade	0.26	0.06	0.05	0.06
	Global Trading	0.11	0.36	0.34	0.36

Table 5.12 shows that increasing the model horizon to 100-years fails to eliminate the problem.

Table 5.12: Change in policy rankings by cost measures under uniform growth rates with KP targets (100-year horizon)

Region	Trading Scenario	DPV of GDP	EV Finite	EV Infinite	DPV of Consumption
Oil Exporters	Annex B	-2.29	-2.79	-2.78	-2.79
	Global	-2.65	-2.54	-2.55	-2.54
Rest of World	Annex B	0.26	0.06	0.05	0.06
	Global	0.11	0.36	0.34	0.36
USA	Annex B w/ Restr.	-0.67	-0.39	-0.44	-0.39
	Global	-0.56	-0.44	-0.46	-0.44

Uniform Carbon Tax and Region Specific Growth Rates

Moving to region specific growth rates leads to a reversal in rankings. Interestingly, this occurs in both the 30-year and 100-year horizon model. Table 5.13 shows this reversal under the 100-year horizon model. GDP produces completely different impacts. Even in the policy where only Annex B regions are taxed, the DPV of GDP for the rest of world region changes by twice as great a percentage as do the welfare and consumption measures.

Table 5.13 Reversal in policy rankings under a uniform carbon tax and region specific growth rates (100-year horizon)

Region	Regions Taxed	DPV of GDP	EV Finite	EV Infinite	DPV of Consumption
Rest of World	All	-0.12	0.06	0.06	0.06
	Annex B	0.11	0.05	0.05	0.05
USA	All	0.11	0.24	0.24	0.24
	Annex B	-0.06	0.11	0.11	0.11

Kyoto Protocol Caps under Unrestricted Trading; Region Specific Growth Rates

Moving to the more realistic case of emission targets and timetables and region specific growth rates leads to much more divergence. Discounted present value of direct costs and GDP disagree with the welfare and consumption measures for the USA; whereas only the discounted present value of direct cost yields a different ranking for the EU. As shown in earlier tables, discounted present value of GDP yields different rankings for China+India and the rest of world regions.

Table 5.14: Kyoto Protocol – Unrestricted Trading

	Trading Scenario	DPV of DC	DPV of GDP	EV Finite	EV Infinite	DPV of Cons.
EU 15	No Trade	10.06	0.07	0.08	0.06	0.08
	Global	12.40	0.14	0.12	0.12	0.12
USA	No Trade	64.80	-0.29	-0.04	-0.07	-0.05
	Global	49.17	-0.13	-0.10	-0.10	-0.10
China + India	No Trade		0.56	0.36	0.37	0.37
	Global	-42.43	0.40	0.89	0.86	0.88
Rest of World	No Trade		0.17	0.03	0.03	0.03
	Global	-8.40	0.07	0.13	0.13	0.13

Summary

The reversals all occur when either the direct cost or GDP or both measures disagree with the welfare and consumption measures. Changing the model horizon or terminal condition generally has little impact on these reversals. The reversals seem to be inherent to the regions and their position in the global market – exporter or importer of goods and permit buyer or seller.

6. Conclusion

The results in section 5 clearly illustrate the difficulties facing modelers and policy makers as they attempt to determine the optimal implementation of carbon abatement policies. For many cases, the different cost measures produce contradictory results. Under certain circumstances, the measures fail to agree on whether a specific policy is a winner or loser. More contradictions arise when one compares the policy rankings that arise from each cost measure.

This analysis highlights a few helpful points in how the model should be structured and how to select the best measure. The model should have a long-term horizon. Using a short-term model leads to poor estimates of infinite horizon welfare under Kyoto Protocol. The model is far from steady state in 2030. Furthermore, the choice of terminal condition is important. We find that the state value targeting is superior to having a constraint on terminal capital.

The theoretically consistent welfare measure in MS-MRT is Equivalent Variation being analyzed. The empirical results bear this out. Ideally we would like to measure welfare over the infinite horizon – but we need to truncate at some finite point, but 30 years is too short. Our experiments show that for a 30-year horizon an estimate of post-horizon welfare loss is required, but current methods differ greatly from results of 100-year horizon runs. Therefore, better choice is to extend the model horizon to obtain a better understanding of welfare impacts.

This analysis finds the dead weight and GDP cost measures troubling. The measure of direct cost or dead weight loss suffers from the following problems.

- Direct cost is an annual measure and cannot therefore, fully take account of the intertemporal nature of climate change issues.
- It relies on the change in consumer's surplus as an accurate measure of the overall change in welfare. Consumer's surplus (and for the same reasons producer's surplus) will only provide an accurate representation of welfare loss (or gain) under certain specific conditions.
- Estimation of Direct Cost from a single marginal cost estimate is further prone to error because it may be a poor approximation of the true total cost if marginal costs are highly nonlinear.
- Fails to capture terms of trade effects.

Some of the specific conditions alluded to above are often not met when analyzing a carbon abatement policy. Direct cost works well when terms of trade effects are small. This is far from

the case in a Kyoto like policy. In addition, this measure fails when markets are restricted or command and control is used in place of market based policy instruments. In both cases, the price increase of energy does not reflect all the loss. One also has to consider price changes in other goods. Finally, for countries that do not adopt carbon limits, there is no measure of direct cost when looking at the marginal cost curve of carbon abatement.

The GDP measure suffers from the following problems.

- It is an annual measure.
- There are price index issues.
- It is distorted by use of gross, not net investment.
- It oversimplifies relationship between consumption and investment.
- It ignores changes in foreign indebtedness.

Some of these problems lead to the contradictory results we reported in section 5. Investment component leads to differences: Non-Annex B countries that sell permits actually reduce industrial output from baseline levels. Therefore, investment shrinks, but consumption increases. Therefore, welfare measures improve for much of the non-Annex B under global trading regimes, but GDP declines. However, the GDP measure misses the terms of trade and investment impacts that lead to the country being better off since it now has more money for consumption than it would have had if it used the permits for producing goods domestically. Under no trade, these countries increase their investment since their industries are now more competitive relative to the Annex B regions. This increase in investment for domestic production though is less than the carbon revenue that they collect in the global trading scenario.

7. Appendix: Terminal Condition, Finite and Infinite Horizon

The creation of theoretical, economic models in the late 1960's, which, for the first time, allowed model horizons to stretch to infinity, was a step change in the development of economic modeling techniques. The inclusion of dynamics in this manner withdrew the difficulties associated with the unbounded nature of the 'future' and the associated problems of disentangling consumer behavior from the incentives provided at the end of a specific time period.

However, while these models are theoretically satisfying, numerical techniques are not yet sophisticated enough to solve models that run to infinity. For this reason all applied versions of infinite horizon models are, in implementation, finite horizon truncations. Given that these models are implemented through finite truncations of an infinite horizon, it is possible that shifting the end (or terminal) period may lead to different solutions.

This is particularly a problem when a policy is imposed in a manner that varies throughout the time horizon. In particular, if carbon limits are imposed in such a fashion that carbon prices are still increasing at time T , welfare in the post-horizon period may not be discounted away even if the horizon is distant.

The following section investigates this issue further. We begin by discussing the end of the horizon and the numeric techniques that are most commonly used to approximate infinity. This discussion leads naturally into a description of how welfare is measured beyond the time horizon. Finally, the section concludes by looking at a new approach for formulating welfare calculations that is suitable for short time horizons as well as models that incorporate endogenous growth.

Approximating the infinite horizon

Most infinite-horizon models are differentiated from finite-horizon formulations in that the reference run ends in a steady state. That is, the policy simulation shocks the economy out of equilibrium, and the model then proceeds to compute a transition path to a new steady state. The new steady state is reached within finite time, and the length of this transition period is endogenous. By contrast, finite horizon models end at a set period and are not required to finish in steady state.

For this reason the terminal period of an infinite horizon model is characterized by an equilibrium where all quantities grow at the same rate and where gross investment is determined by the size of the capital stock, the exogenous growth rate and the capital depreciation rate.

Most methods for approximating the infinite horizon derive from the seminal article by Barr and Manne (1967). In this article the authors assume that the post-terminal period is characterized by:

1. tastes and technological coefficients that are identical to those at date T ;
2. no essential input requirements that the economy cannot produce for itself; and
3. the economy expands at a constant, exogenous, geometric growth rate (g).

Calculating utility within the time horizon and beyond

Although the model contains a finite horizon date (say T), this does not require the utility function to be insensitive to consumption after that date (i.e. the period T to infinity). If, as started above, we assume that the economy grows at a constant geometric growth rate (say g), then we can obtain a 'salvage value' for the terminal capital stock. In other words, we can express utility that arises from consumption that occurs after the time horizon, directly as a function of consumption at time T . This is explained in some mathematical detail below.

Time is idealized in infinite horizon models into discrete time periods: $0, 1, 2, \dots, T$. The model is terminated at the end of the time horizon (T), and assumptions are used to represent the economy after this point.

In addition, aggregate labor and all prices decline over time according to the discount rate, while investment is constrained so that the capital stock increases by the growth rate (less any depreciation).

With these formulations of the economy we can calculate post-horizon utility by separating the intertemporal utility function into two parts, the first sums utility over the time horizon of the model ($t < T$), and the second sums utility associated with the post-horizon period (T to infinity) and gives an increased weight to terminal period consumption. This is shown below:

Calculating utility within the time horizon

The present value of lifetime utility for the representative agent can be formulated as:

Equation 1: Present value of utility

$$u = \sum_{t=0}^{\infty} \left(\frac{1}{1+p} \right)^t u(C_t)$$

where: u present value of utility
p rate of time preference
C_t consumption at time t

The individual coefficients can be calculated directly from consumption so that utility within the time horizon can be expressed as:

Equation 2: Present value of utility within the time horizon

$$U = \sum_{t=0}^{T-1} \left(\frac{1}{1-\rho} \right)^t \log(C_t)$$

Calculating utility beyond the time horizon

Utility that occurs post-horizon is derived from the value of the capital stock at time T. In other words, a “salvage value” for the terminal capital stock may be established through the assumption that the entire economy expands at the rate g subsequent to date T. That is, the utility of post-terminal consumption can be expressed directly as a function of the consumption received at date T.

In order to incorporate this we need to calculate the coefficients in a slightly different fashion that adds an additional weight to terminal period consumption.

For t=T-infinity, consumption can be expressed as:

Equation 3: Post-horizon consumption

$$C_t = \log(C_T (1+g)^{(t-T)})$$

Substituting this back into equation 1, and adding in utility under the time horizon gives us the following equation:

Equation 4: Utility with an increased weight on terminal period consumption

$$U = \sum_{t=0}^{T-1} \left(\frac{1}{1+\rho} \right)^t \log(C_t) + \sum_{t=T}^{\infty} \left(\frac{1}{1+\rho} \right)^t \log(C_T(1+g)^{(t-T)}) = \sum_{t=0}^T \beta_t \log(C_t) + \text{Constnt}$$

The closer the solution, in both the baseline and policy cases, at time T is to a steady state growth path in which consumption in fact grows at a constant rate g , the more accurate the approximation.

This terminal condition serves two purposes: to make sure that solving the model does not produce spurious terminal effects, and to provide a complete measure of welfare changes. The first effect could be dealt with through transversality conditions, which force investment and capital stock to be maintained through the final period and prevent disinvestments before the terminal date. The second correction is fundamental. Policies may lead to changes in the terminal capital, and growth prospects of the economy, that are ignored in a model where welfare effects are truncated.

An alternative approach to approximating the infinite horizon: State variable targeting

This approach (developed by Lau et al (2000)) does not require an ex ante specification of the growth rate and is therefore suited for models with endogenous growth and/or short horizons. The technique involves including the post-terminal capital stock as an endogenous variable. The addition of an extra variable requires another equation. For this reason investment growth is constrained to equal the growth rate of output (or some other “stable” quantity variable). This constraint imposes balanced growth in the terminal period but does not require that the model achieve steady state growth. Using this approach we do not have to specify capital stock in the post-terminal period or a specific growth rate for the terminal period. Accuracy of the correction still depends on whether the model is back to balanced growth, so that longer time horizons should reduce errors.

The state variable targeting approach as outlined in Lau, Pahlke and Rutherford (2000) provides a method for approximating infinite horizon models that may be more appropriate for short-time horizons (and is more appropriate for incorporating endogenous growth). The technique involves including the post-terminal capital stock as an endogenous variable. The addition of an extra variable requires another equation. For this reason investment growth is constrained to equal the growth rate of output (or some other “stable” quantity variable). This constraint imposes balanced growth in the terminal period but does not require that the model achieve steady state growth. Using this approach we do not have to specify capital stock in the post-terminal period or a specific growth rate for the terminal period.

This method (see Lau, Pahlke and Rutherford, 2000) relies on time-separable utility functions. The infinite horizon is decomposed into two distinct optimization problems: one problem defined over the period $t=0$ to $t=T$, and a second problem defined over the period $t=T+1$ to infinity. Rutherford (2000) suggests that in a complementarity formulation we can include the post-terminal capital stock as an endogenous variable.