

Exploring Policy Options with a Behavioral Climate-Economy Model

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Abstract

Many integrated energy-economy-climate models have been developed to address climate change policy. While these models are quite varied in scope, most share a common core of economic optimization and equilibrium assumptions. By contrast, system dynamics models of energy-economy interactions focus on disequilibrium dynamics, with behavioral decision rules and explicit stocks and flows of capital, labor, resources and money.

This article tests climate policies using a system dynamics model that includes many features missing from economic models. Among these are endogenous technological change and boundedly rational decision making. Energy requirements are embodied in capital, and energy production capacity depends on explicit capital stocks. The search for optimal policies is decoupled from other decisions, and uses criteria that are fair across generations. Earlier experiments with the model, briefly reported here, indicate that these features greatly alter policy outcomes.

The model is used to test a family of emissions permit and tax policies like the Kyoto Protocol under a range of assumptions. Uncertainty is included in the analysis through Monte Carlo simulation. Results suggest that nearly all policy options are a net benefit, and that the landscape for policy choice is more forgiving than generally supposed. However, implementation remains a critical issue, and the viability of tradeable permits is questionable. Carbon tax policies are found to outperform fixed emissions permits in nearly all circumstances.

The model used in this article is available at www.sd3.info.

Introduction

The climate change debate has spawned many integrated climate-economy models (Dowlatabadi 1995; Parson and Fisher-Vanden 1995; Weyant 1999). The motivation for these models is the need to identify an efficient distribution of the burdens of climate change along with efforts to avoid it. A diverse set of models has developed around various aspects of this question. Modelers are continuously improving the representation of biogeophysical cycles, adding regional and sectoral detail, testing new policy instruments, and developing better numerical methods for model analysis.

In some ways, though, most integrated models are convergent. This is particularly evident (and potentially troublesome) in their social and economic systems, where there is probably more structural uncertainty than in the physical systems of climate or greenhouse gas cycles. Similarities among models can be attributed to the roots of integrated models in the economic tradition of energy modeling. Specifically, many integrated models share the following assumptions, at least in their central scenarios:

- discount rates on utility or cost and benefit flows that give a higher weight to the welfare of current generations and richer regions,
- exogenous population with demographic transition to equilibrium
- exogenous, declining rates of economic growth (in cost-benefit models) or factor productivity (driving economic growth in general equilibrium models),
- autonomous energy efficiency improvement or carbon intensity reduction,
- exogenous energy production technology,
- consumer and producer optimization with full information and, frequently, perfect foresight,
- instantaneous equilibration of factor inputs to optimal levels,
- no positive feedback mechanisms in the economy (other than capital accumulation),
- no human disturbance to the environment other than climate, and
- infinite, linear sinks for carbon.

Obviously, not all integrated models fit the characterization above perfectly. Of the well-known models, William Nordhaus' original DICE model (Nordhaus 1994) is probably the purest example of the standard paradigm. In the base case of the DICE model, assumptions about discounting, rationality, exogenous population growth and technological change, limited potential for greenhouse gas abatement, low susceptibility of human systems to climate interference, and an optimistic model of the carbon cycle combine to suggest that little should be done to limit climate change (Fiddaman 1995).

Some of these assumptions are puzzling in the context of the history of global modeling. Most surprising is the common assumption that technology (factor productivity) growth will slow to zero in the next century. Because population growth also stops and there are diminishing returns to capital investment, the economy comes into equilibrium in about a century. The end of growth is a technical convenience for optimization models as it minimizes the difficulty of terminal

valuation of the system state, but it contradicts the assumption of inexorable technological progress that was the foundation of much of the critique of World3 and World Dynamics by Nordhaus and others (Nordhaus 1973). The practical implication for climate policy is that low growth minimizes pressure on the climate system, and discounting for time preference overwhelms growth, driving the importance of future generations' welfare to zero.

The FREE model

The model used here, FREE (Feedback-Rich Energy-Economy model), incorporates several important features that are currently not addressed by other models. These include:

- a disequilibrium energy-economy system, with adjustment and perception delays, embodiment of energy requirements in capital, and resource depletion,
- inclusion of endogenous technological change and other positive feedback effects which may lead to lock-in of the energy-economy system to particular supply and end-use technologies,
- explicit behavioral rules, rather than myopic or intertemporal optimization, for decision making,
- separation of the search for optimal social policies from savings, factor allocation, and other decisions, and
- an equitable approach to the valuation of impacts on current vs. future generations.

To facilitate exploration of these new structures, other aspects of the model are kept simple. The model contains no regional or sectoral disaggregation, and uses simple models of the carbon cycle and climate. With appropriate parameters, the model may be reduced to a form that behaves much like simpler neoclassical models, as in Senge (1978).

Model Description

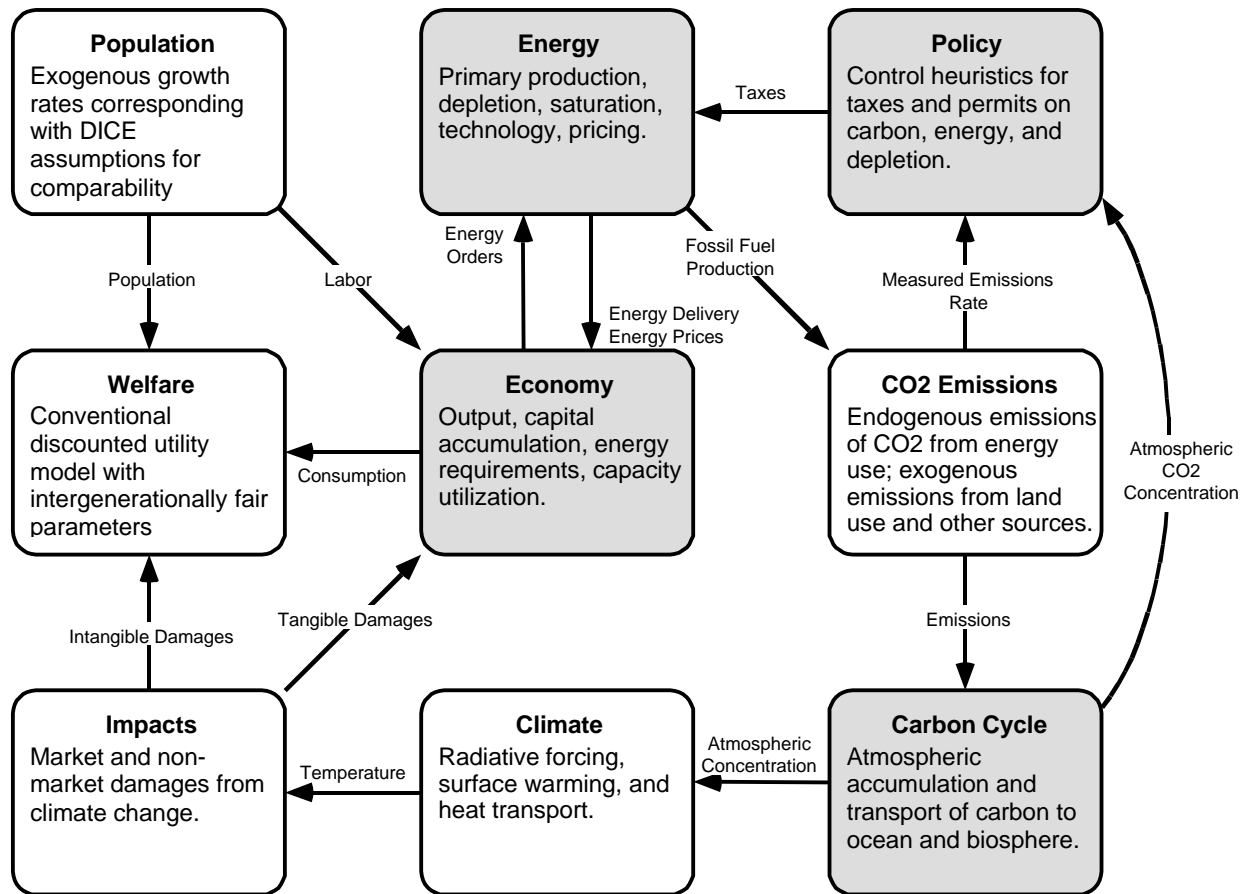
The nominal time horizon of the model is 1960-2100. However, for optimization purposes, runs are typically extended to 2300 to reduce horizon effects. The historical period of the model is relatively long compared to most, which typically replicate only a decade or two of history. The comparatively long historical period proved useful for calibration and testing of energy supply-demand interactions. One of the insights from the process is that many models neglect structural and behavioral rigidities in energy use and as a result have unrealistic short-term responses that would be revealed by testing the models in circumstances like the oil shocks of the 70s and 80s.

The FREE model represents the global energy-economy system and, in a more limited fashion, global biogeophysical processes. The majority of structure in the model is endogenous. Generation of economic output, investment, energy supply and demand, depletion, and energy technology development are tightly coupled to one another. The carbon cycle and climate are also fully endogenous, but are coupled to the rest of the model somewhat more sparsely. Carbon and energy tax policies are formulated as endogenous feedback control rules, rather than exogenous inputs.

For simplicity, many features have been omitted from the model. There is no regional or sectoral disaggregation (except in the energy sector). Non-energy natural resources are ignored. While the energy sector includes several distinct energy sources, energy conversion activities (such as the generation of electric power from thermal fuels) are omitted. A number of economic structures that contribute to disequilibrium are omitted, such as sectoral labor pools and cash reserves. Inventories and backlogs are omitted, as they equilibrate quickly relative to the model horizon. In a way the model can be regarded as a hybrid between disequilibrium system dynamics energy models (Sternan 1981) and economic equilibrium optimization models; this difficult marriage facilitates comparison of the two approaches through parameter changes.

The model can be divided into nine subsystems that have relatively sparse interactions. Figure 1 illustrates the sector boundaries, internal activities, and external relationships.

Figure 1: Sector boundary diagram



Shaded sectors incorporate substantially new structures; other subsystems are conventional or very simple.

The fundamental behavior of the model can be summarized by a few feedback loops (Figure 2). The reinforcing process of capital accumulation drives economic growth (augmented by exogenous population and factor productivity growth). Climate change acts like a weak balancing loop that restrains growth. Economic activity requires energy input; which leads to carbon

$CDU =$ cumulative discounted utility $L =$ population

$r =$ rate of time preference $U =$ utility of representative individual

With the rate of time preference $\rho = 0$, the welfare of all generations is weighted equally. Any $\rho > 0$ represents a preference for current welfare—pure myopia. With $\rho = .03$, the weight to future welfare declines by half in only 23 years, and climate damages in 2100 are only 5% as important as present costs of emissions reductions.

In the simulations presented here, intangible or non-market environmental services are neglected, so an individual's utility is purely a function of consumption, given by Eq. 2. If $\theta = 1$, utility simplifies to the logarithm of consumption.

$$U = \frac{\left(\frac{c}{c_0}\right)^{(1-\theta)} - 1}{1-\theta} \quad \text{Eq. 2}$$

$c =$ consumption per capita

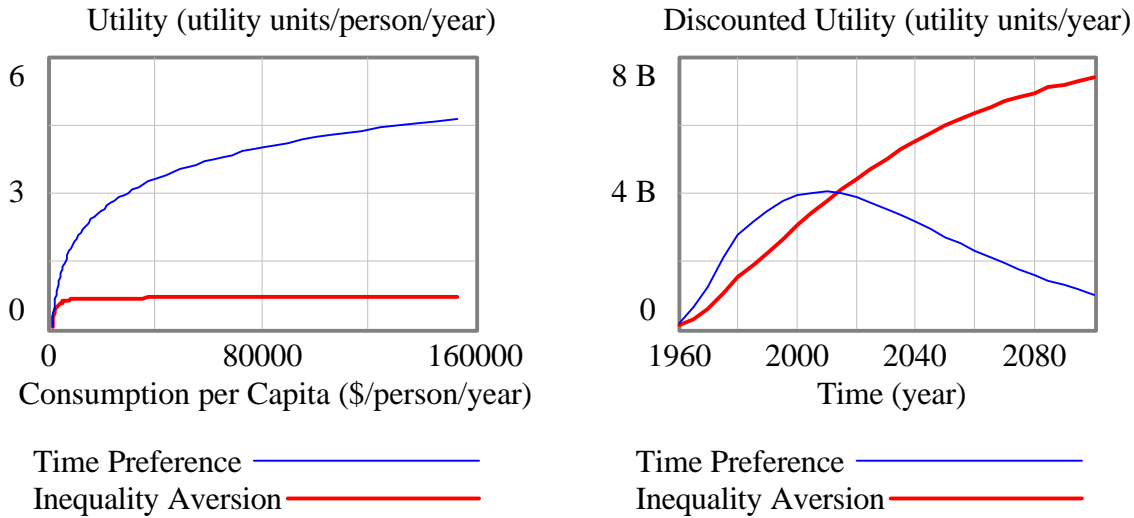
$\theta =$ rate of inequality aversion

With this formulation, the marginal utility of an additional unit of consumption declines with increasing wealth, so that an equivalent absolute increase in consumption yields more utility for a poor individual than for a rich one. With higher values of θ , diminishing returns set in more rapidly.

Models using this welfare framework, like DICE, often choose a positive rate of time preference of about 3% and a rate of inequality aversion of 1 (Nordhaus 1994). Because such models typically assume that growth rates of population and economic output decline to near zero in the next century, the flow of discounted utility inevitably declines to zero as well. The primary motivation for this parameter choice is correspondence with observed rates of return (Manne 1994). This is a poor basis for the choice of parameters, as the model of behavior used to make this choice assumes perfect foresight and neglects structure (such as demographic disaggregation) that is extremely important in real-world savings decisions. Intergenerational allocation of resources is not part of a consumer's normal decision making process, so markets do not adequately reflect intergenerational issues (Schelling 1995). Even in the absence of structural uncertainty, it is difficult to see how historical evidence discriminates between fair and unfair parameter choices, as the two generate nearly identical historical trajectories for interest rates.

Many economists and philosophers reject pure time preference on ethical grounds (Ramsey 1928; Cline 1992). The author concurs, so the FREE model uses parameters that are consistent with history but fair to future generations. The rate of time preference is set to 0, so that the welfare of all generations is weighted equally. The rate of inequality aversion is set to a higher value (2.5), so that the needs of current (poorer) generations are of greater urgency. In this case, the flow of discounted utility does not decline, even if population and economic growth cease.

Figure 3: Effects of discounting on welfare



The Time Preference simulation uses $\rho = .03$, $\theta = 1$ (as in DICE). The Inequality Aversion simulation uses $\rho = 0$, $\theta = 2.5$ (the base case of the FREE model). The left panel shows the flow of utility of an individual as a function of the flow of consumption per capita. The right panel shows the total flow of utility to the population, discounted for time preference, as a function of time. With positive discounting for time preference, the flow of discounted utility tends toward zero as economic growth slows.

Deterministic Policy Analysis

The principal policy instruments in the model are permits and taxes on carbon and energy use. Figure 4 illustrates the response of the model to a carbon tax of \$100 per ton. The tax is phased in smoothly (using a five-year time constant) beginning in 2002, so that it is essentially constant by 2020. In response to the tax, welfare (shown here as the flow of discounted utility, lower right panel) rises and falls several times. Surprisingly, the first impact of the tax is a slight increase in welfare, which occurs because total energy system costs decrease significantly. Costs fall because the carbon tax suppresses energy demand, reducing the need for new investment in coal, oil and gas production, and depressing capacity utilization, so that only the most efficient capital is used. The increase in consumption is an artifact of the implicit fungibility of consumption and investment goods in the model (the two are not distinguished) that would disappear with a more detailed treatment.

After about 2005, welfare falls, because productivity losses mount and the initial savings in energy investment are replaced by higher investment requirements in noncarbon sources. Productivity falls because the shift in energy prices leads to suboptimal capacity utilization in the goods producing sector until the energy intensity embodied in the capital stock can adjust. The marginal product of capital falls, diminishing investment. With reduced capacity utilization and investment, output grows more slowly than it does with no tax. The model is actually optimistic about the potential for adjustment as the capital lifetime is only 15 years; in reality much energy

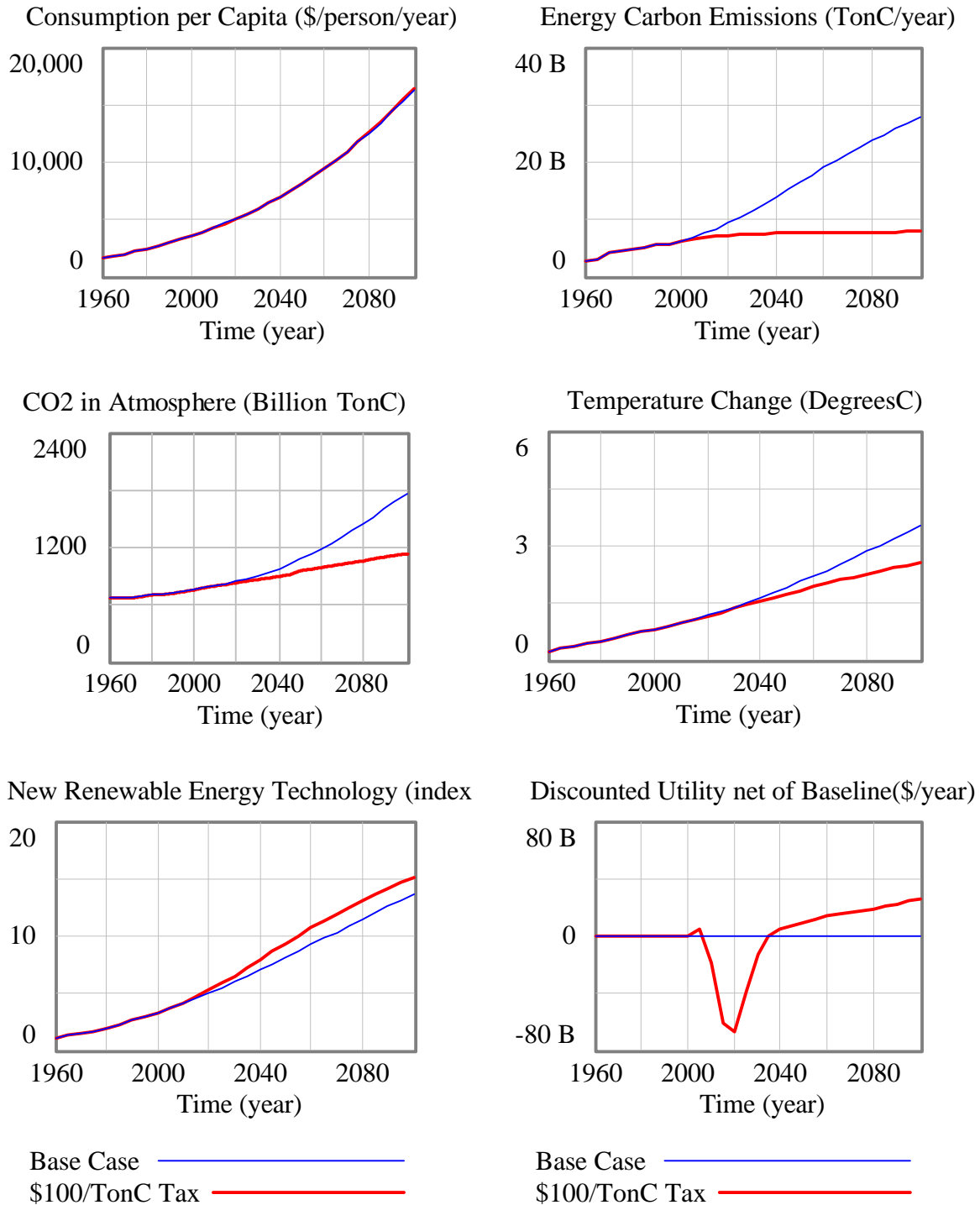
consuming capital is very long lived (like the housing stock) and tied to settlement patterns that change on time scales of many decades.

After 2035, welfare rises above its baseline level, due to a combination of factors. Most of the adjustment costs from changing energy prices are past; substitution of capital for energy offsets most of the effects of higher prices and productivity and capacity utilization return to their normal levels. The benefits of reduced climate change begin to be felt. Reduced climate damages improve returns in the goods producing sector, leading to greater investment. Savings in the energy sector from earlier realization of learning curve benefits for noncarbon sources (lower left panel of Figure 4) reduce the cost of the shift away from fossil fuels, which is inevitable anyway due to depletion of oil and gas.

The tax stabilizes emissions above the current rate of roughly 6 billion tons carbon per year, at 8 billion tons carbon per year in 2100 (vs. 28 with no tax). Because emissions are more than double natural uptake, carbon continues to accumulate in the atmosphere and a doubling of the stock over preindustrial levels is narrowly avoided. As a result there is substantial climate change; the threefold emissions reduction lowers warming only from 3.5 to 2.5 degrees Celsius.

The cumulative effect of the carbon tax on welfare (the area under the discounted utility curve) is still slightly negative in 2100; the breakeven point is reached almost exactly 100 years after the tax is initiated. By the end of the simulation in 2300, the accumulated benefit is \$4.6 trillion in current consumption terms. While this is a huge absolute number it is small compared to accumulated output over the same period. In fact the difference in trajectories for consumption (top left panel of Figure 4) is almost imperceptible.

Figure 4: Behavior with and without \$100/TonC carbon tax



Note that the flow of discounted utility shown here is converted to its 1995 consumption equivalent by dividing the flow of utility by the marginal utility of a unit of consumption in 1995.

Optimal carbon taxes

A useful starting point for policy analysis is to identify an effective carbon tax policy in deterministic runs of the model using best-guess parameters. For simplicity, a constant tax, implemented gradually as above, is used in the tests presented this section. The criteria for policy selection is maximization of welfare (cumulative discounted utility) over the simulation period. The conventional wisdom from simple integrated models—which are frequently derived from DICE—is that abatement efforts in the near term should be limited, with modest carbon taxes on the order of 10-50 \$/TonC (Nordhaus 1994, 2001; Yohe and Wallace 1996; Nordhaus and Boyer 1998; Keller 1999).

Fiddaman (1997) explores a range of scenarios, starting with a parameterization that behaves much like the DICE model (Table 1). In this case, the optimal carbon tax is \$15/ton, a level that causes small increases in energy prices. In the base run of FREE, the tax is \$170/ton, which causes substantial shifts in energy prices and carbon emissions. FREE can also simulate plausible scenarios in which the optimal tax is as high as \$950/ton, which has such strong effects on the energy-economy system that it could be impossible to implement. The difference in conclusions is dramatic. It arises from the interactions of a number of assumptions about discounting, economic growth, energy technology, the flexibility of the economy, depletion, and decision making.

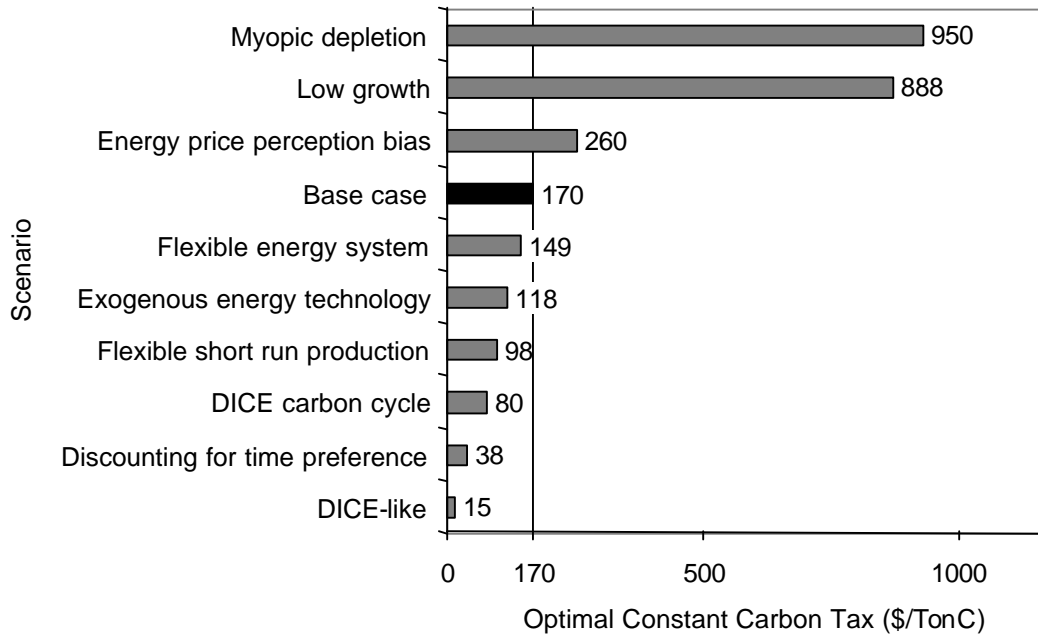
Table 1: Contrasting scenario assumptions

	DICE-like	FREE base case
Factor productivity growth	Asymptotically zero, so that economic growth eventually stops.	Always greater than zero; growth slows but does not stop.
Production structure	Putty-putty, with low to moderate capital-energy and inter-energy substitution elasticities.	Putty-clay, with high long-run elasticities moderated by slow behavioral adjustments.
Behavior	Rapid adjustment to optimal factor balances.	Adjustment to optimal factor balances, but subject to delays in perception and action.
Energy production capacity	Low share of capital in energy production, rapid capacity adjustment and short construction lead times.	Capital-intensive output, with long construction lead times.
Energy production technology	Exogenous.	Endogenous learning curve.
Fossil fuel depletion	None.	Limited fossil resources and renewable energy production rates.
Carbon cycle	Linear, with infinite carbon uptake capacity.	Nonlinear, with limited carbon sinks.
Welfare evaluation	Time discounting of social welfare.	Intergenerational equity.

The DICE-like scenario is deliberately similar to Nordhaus' original DICE model (1994). The FREE base case incorporates a more complex production structure, behavioral dynamics, depletion, endogenous technology, and a more realistic carbon cycle.

Because these assumptions interact in a highly nonlinear fashion, there is no definitive way to attribute the changes between scenarios to any single parameter. Figure 5 compares the relative impacts of the major differences between the two scenarios by testing groups of assumptions individually. Each test applies a subset of the differences in Table 1 to the base case scenario, in which the optimal tax is \$170/ton.

Figure 5: Summary of model tests



Columns indicate the optimal constant carbon tax level for each test. The simulation identified as the base case is used as the starting point for uncertainty simulations in the next section.

Discounting accounts for much of the difference between DICE and FREE. Adding discounting for pure time preference to FREE lowers the optimal tax by a factor of four, from \$170 to \$38/ton carbon. Another important difference is the representation of the carbon cycle. The original DICE carbon cycle is linear and has no sink constraints to carbon uptake. It also introduces a discrete delay between emissions and effects, as the model is simulated with a discrete 10-year time step. Because DICE discounts for time preference, the spurious delay diminishes the present value of emissions reductions. The FREE carbon cycle, by contrast, conserves carbon and has diminishing returns to uptake by the ocean and biosphere. Replacing the FREE carbon cycle with that of DICE lowers the optimal tax by half, from \$170 to \$80/ton.

In the DICE model, emissions reductions can be implemented instantaneously, without adjustment costs. FREE, by contrast, includes capital stocks in the energy system, embodied energy requirements, and delays in perception and action that constrain the ability of the economy to adjust to changing energy costs in the short run. Making the energy system flexible by reducing the role of capital stocks in energy production causes a small change in the optimal carbon tax,

from 170 \$/TonC to 149 \$/TonC. Increasing the short run flexibility of the goods producing economy has a greater effect, reducing the tax from \$170/ton to \$98/ton. In both cases, increasing flexibility results in lower taxes because the effort required to achieve a given level of emissions reduction falls. The true risk of assuming flexibility becomes apparent in simulations including uncertainty; then the instantaneous emissions abatement in DICE creates an incentive to wait until the brink of disaster to act. In FREE, rapid abatement can be extremely expensive and disruptive.

The behavior of the energy system is strongly shaped by the evolution of technology. However, nearly all models treat technology in the energy system as an exogenous factor. In FREE, learning curves are substituted for exogenous technological trends. Endogenous technology creates path-dependence and the opportunity for lock-in of dominant carbon-based energy sources (Moxnes 1992). Ignoring learning lowers the optimal tax from \$170 to \$118/ton. Consideration of other mechanisms that cause path dependency, like scale economies, network effects and complementary infrastructure, could change indicated tax levels significantly. Path dependence has implications for the timing and nature of interventions. Earlier action has a greater impact because small initial changes are amplified by positive feedback. It may be possible to discover market domains where reinforcing effects are particularly strong, and small interventions have large impacts. As non-carbon or energy-efficient technologies become more prevalent, it may be possible to relax carbon taxes and allow lock-in effects to take over.

There is a heated debate over the availability of a “free lunch” from costless or negative-cost emissions reductions. Even in the absence of misperceptions in energy decision making, subsidies on energy use and environmental externalities may offer a free lunch (Hall 1990; Burniaux, Martin et al. 1992). Most models neglect these opportunities. The free lunch is implemented as a bias in energy price perception. Even a modest bias (discounting energy prices by 20%) has substantial tax implications, raising the indicated tax 50% to \$260/ton; the higher tax compensates for the bias.

Exogenous forecasts of factor productivity or GNP growth, which drive most integrated models, have dramatic effects on policy conclusions. In the FREE model, a low-growth scenario leads to a very high optimal tax, as it is more important to protect the welfare of future generations when they are not so wealthy. The importance of growth forecasts is strongly conditioned by the discounting approach chosen, illustrating the necessity of exploring parameter and structural changes together rather than individually. The importance of exogenous factor productivity improvements as a driver of growth suggests that they should be made endogenous in the same way as energy technology. Making aggregate technological progress endogenous is likely to reduce the optimal carbon tax by increasing the importance of economic growth in the near term (Hogan and Jorgenson 1991).

Finally, if the valuation of fossil fuel resources is myopic, i.e. resource managers do not fully recover appropriate depletion rents, climate policy can have unpleasant interactions with exhaustion of oil and gas resources. A low-to-moderate carbon tax accelerates the depletion of oil

and gas by shifting energy consumption from coal to these lower-carbon fuels, without inducing a full transition to non-carbon sources. Rapid depletion of oil and gas makes the transition to alternate energy sources more costly and disruptive and requires it to occur sooner. An extraordinarily high carbon tax (\$950/ton) is required to avoid rapid depletion, largely because it is not an ideal policy instrument for that purpose. This result suggests that the current enthusiasm to for using gas as a low-carbon energy source should be regarded with some caution, and that carbon policy cannot be made without regard for other major issues in the energy system.

Policy under Uncertainty and the Kyoto Agreement

The current framework for greenhouse gas emissions reductions is the Kyoto Agreement, which sets targets for emissions slightly below 1990 levels. Freezing emissions implies substantial reductions in the carbon intensity of the economy as output grows, particularly as the first commitment period begins in 2008. To equalize the cost of meeting emissions goals globally, a permit trading system allows regions that can cheaply reduce emissions to sell their reductions to regions where it is more costly to do so.

Analysis of the agreement can be decomposed into two questions: whether the scale of emissions reductions proposed is optimal, and whether the policy instruments used to achieve it are appropriate. Many other models have already addressed valuation of the Kyoto agreement, particularly with respect to the question of scale. A special issue of *The Energy Journal* reports on the outcome of several (Weyant 1999). Most models conclude that the agreement is too stringent and thus a net welfare loss (compared with doing nothing) or at least very inefficient compared to optimal policies (Nordhaus 2001). Stringency greater than that embedded in Kyoto is usually only warranted in models with features like catastrophic climate effects (Keller, Tan et al. 1999; Roughgarden and Schneider 1999; Keller, Bolker et al. 2001).

There are several attractive features of the permit structure in the agreement (Kopp 1999). If it works, it guarantees that emissions will be capped. Permit trading provides a mechanism for transferring resources from developed to developing nations. It fits with both market and non-market economies (by contrast taxes are difficult to speak of without a price system). If permits are distributed by auction, they raise government revenue. Tradeable permits thereafter transfer wealth among firms, rather than to governments. Permits avoid the term “tax,” a seemingly trivial feature that is critical to acceptance in the US.

At the same time, there are several features that are problematic. Permit trading has high transaction costs. Permits allocated based on past emissions institutionalize a distribution of emissions that is far from equitable. If permits are given away initially, they amount to a windfall for current emitters. Most importantly, both future baseline emissions and the cost of a given reduction are highly uncertain, making it difficult for politicians to make commitments.

It is difficult to think about the Kyoto agreement without considering uncertainty. A major challenge facing policymakers is the need to commit to fixed emissions targets when there is great

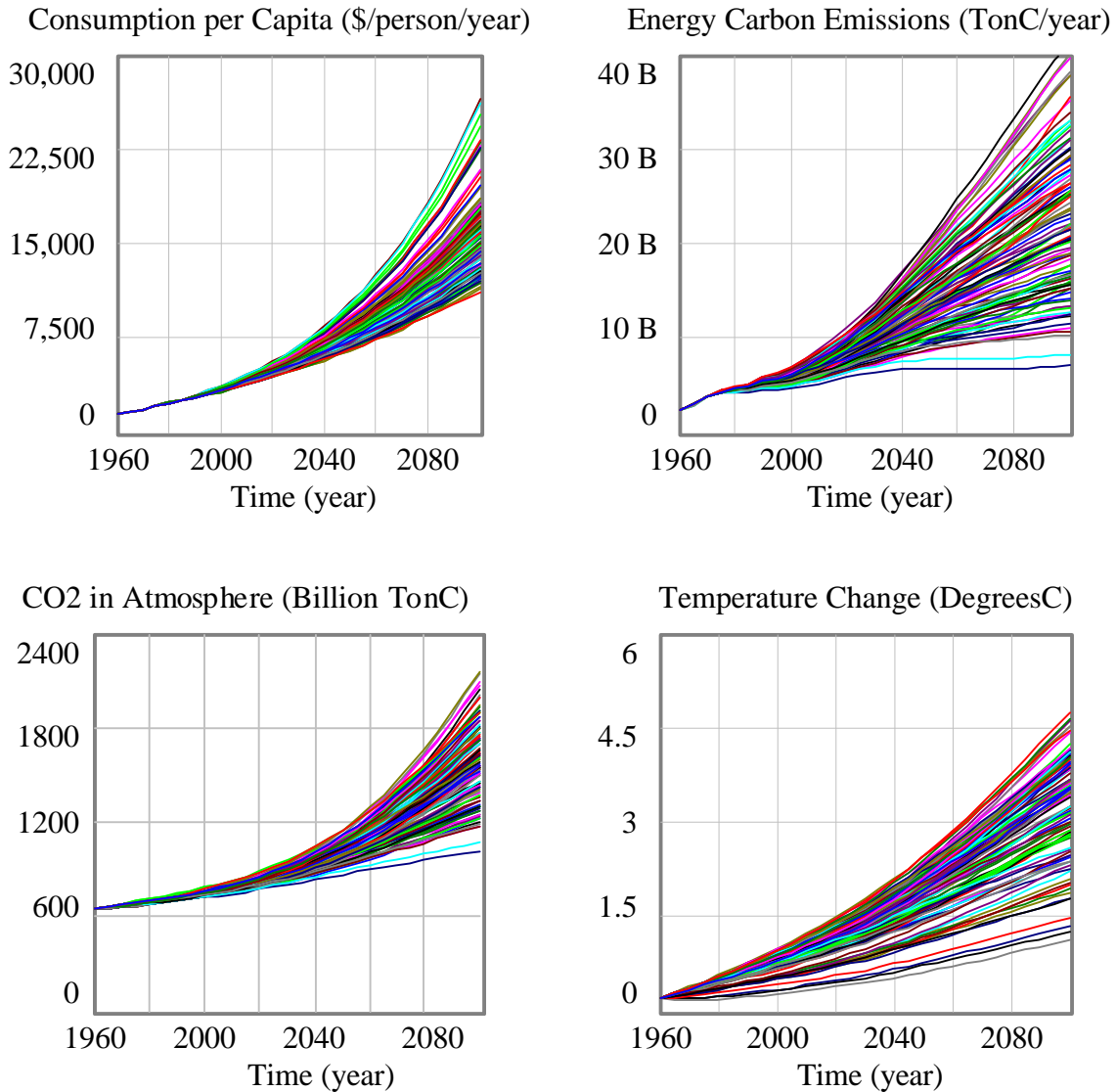
uncertainty about both the cost of those reductions and the likely future trend of emissions. The presence of delays and rigidities in behavior and capital stocks increases the importance of uncertainty by raising the short-run adjustment costs of policy implementation and increasing the urgency of taking near-term action to avoid later damage.

Uncontrolled emissions

Uncertainty is implemented in FREE (as in other models) by Monte Carlo simulation. Values for key parameters are drawn from subjective probability distributions. For example, the sensitivity of climate to a doubling of CO₂ is assumed to be normally distributed with a mean of 2.9 degrees and a standard deviation of 1 degree. Inputs include exogenous population and technology growth rates, energy substitution elasticities, rates of carbon uptake by the ocean and biosphere, sensitivity of the climate to a doubling of CO₂, and the scale of economic damages from climate change (Fiddaman 1997).

In simulations without policy intervention (Figure 6), consumption per capita grows by a factor of five by 2100, with a standard deviation of about 20%. Carbon emissions also rise—sometimes to extraordinary levels. Emissions reach between 7 and 41 billion tons carbon per year by 2100. The range of outcomes is roughly comparable to the range of 1 to 6 times current emissions in the IPCC IS92 and SRES emissions scenarios (IPCC 2000). As a result, the concentration of CO₂ in the atmosphere nearly always doubles (over preindustrial levels) and sometimes triples. Global average temperature rises 1 to 5 degrees Celsius, with a mean of 3.2 degrees and a standard deviation of 0.8 degrees.

Figure 6: Representative uncontrolled trajectories



100 random simulations of consumption, emissions, CO₂ in the atmosphere, and temperature.

Tradeable permits

Emissions can be controlled by introducing a permit system to the model. In most models permit prices instantaneously equilibrate to the level needed to restrict emissions to the permitted level. Permitting is implemented through optimization or solution of simultaneous equations. Both approaches have been tested in FREE but were found to be computationally wasteful. Instead, the market for permits is implemented somewhat abstractly as a proportional controller that rapidly adjusts permit prices to whatever level is necessary to meet the target. The modeler may trade performance (the degree to which constraints are observed) for efficiency (the time step required

for stability) by choosing the gains of the controller. The structure shown exhibits some steady-state error that has an insignificant effect on results; adding integral control makes only a small numerical difference. Additional constraints (not shown) can limit the permit price to lie within predetermined bounds.

$$P_c(t) = \int \frac{DP_c(t) - P_c(t)}{\tau_p} dt \tag{Eq. 3}$$

DP_c = desired permit price

τ_p = permit implementation time

$$DP_c = P_0 + \frac{P_1 E}{E_0} \tag{Eq. 4}$$

P_0 = permit price constant

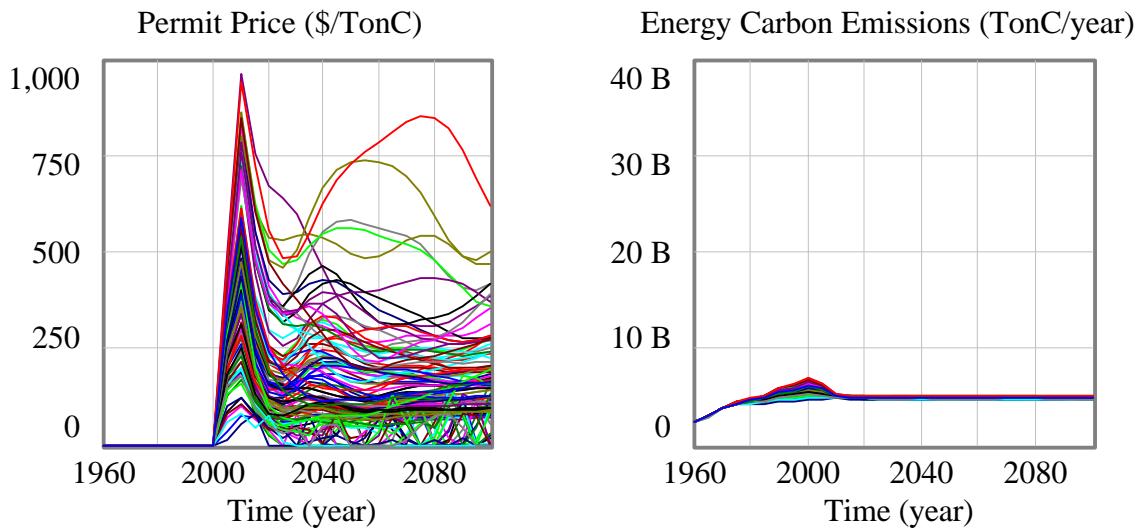
E = perceived CO_2 emissions rate

P_1 = permit price emissions coefficient

E_0 = reference emissions rate

Figure 7 shows the impact of implementing a permanent cap on emissions at 4.75 gigatons carbon per year (92% of 1990 emissions in the model). For purposes of the test, the cap is applied globally, though in fact targets are nonbinding in developing regions in the actual agreement. The permitted emissions rate is a much less aggressive change than would be needed to prevent a doubling of atmospheric CO_2 and stabilize climate near its current state.

Figure 7: Permit impact with Kyoto targets



Permit price and emissions in 100 representative simulations. Compare with Figure 6.

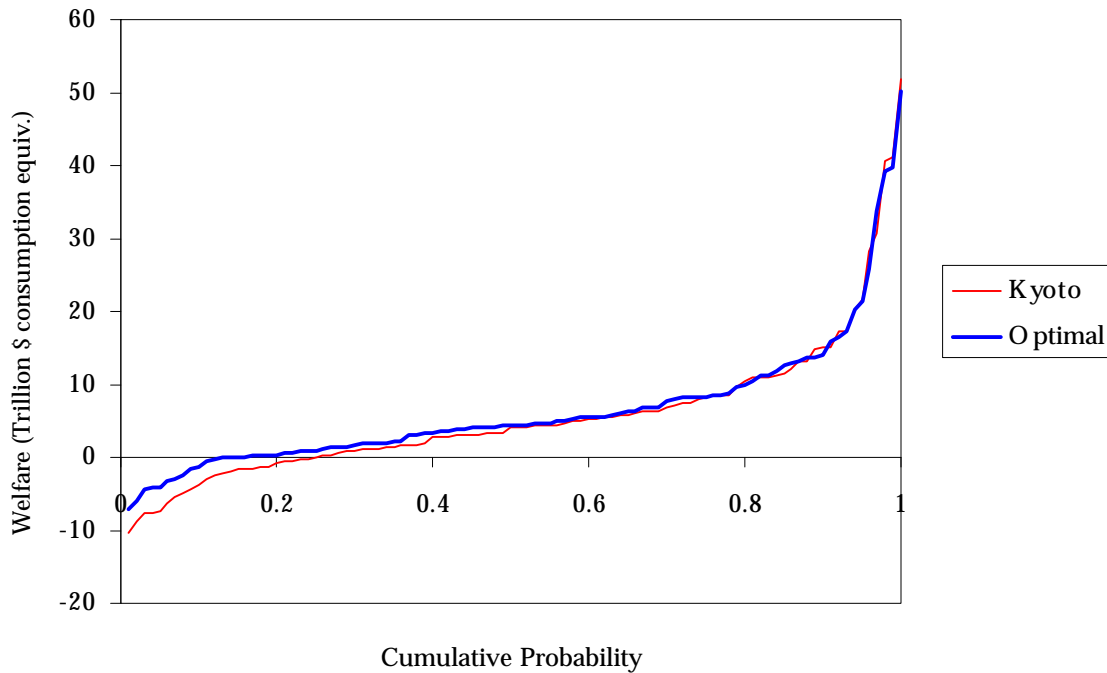
Following activation of the permit scheme, emissions constraints are met (with deviations of a few percent) through the year 2100. The side effect of tightly-controlled emissions is a very wide range of permit prices in different scenarios. Permit prices in some cases approach \$1000 per ton carbon, 50 times the control effort models typically identify as optimal. The high variance in permit prices is due to the fact that permits are forcing futures with differing costs of emissions reduction and growth drivers to meet a common goal. The inflexibility of permits is particularly problematic in the short run, where momentum in capital structure and behavior make it very costly to shift the system more than a little from its baseline trajectory.

Surprisingly, even with sharp disruptions from the aggressive control, the agreement is a net benefit from a welfare perspective, with a present value of over \$5 trillion in current consumption equivalent (see Table 2). The valuation is much higher than in other models is principally due to the fair discounting approach in FREE, which makes the model less myopic. Avoided costs of climate damage in the far future play a much larger role in the assessment of the cost-benefit balance. It should be remembered that FREE is not a full disequilibrium model, and could understate the disruption to the economy caused by the sharp rise in permit prices. More importantly, extreme permit price behavior would certainly lead to political failure of the agreement.

Optimal constant permits

Still, the FREE model concurs that the Kyoto agreement is far from ideal. The optimal constant permit level is more than 25% higher (less stringent)—6.11 vs. 4.75 billion tons carbon per year. The higher permit level is justified mainly by a few bad outcomes in which near-future abatement costs are extremely high. In these worst-case scenarios, raising the permit level drastically reduces abatement costs while only modestly affecting climate damages. In scenarios with better outcomes, the avoided costs of near-term abatement roughly balance the increased costs of long-term climate damage when the permitted emissions level is raised. Thus the main impact of changes to the permit level is a shift in the left tail of the outcome distribution in Figure 8.

Figure 8: Distribution of welfare outcomes

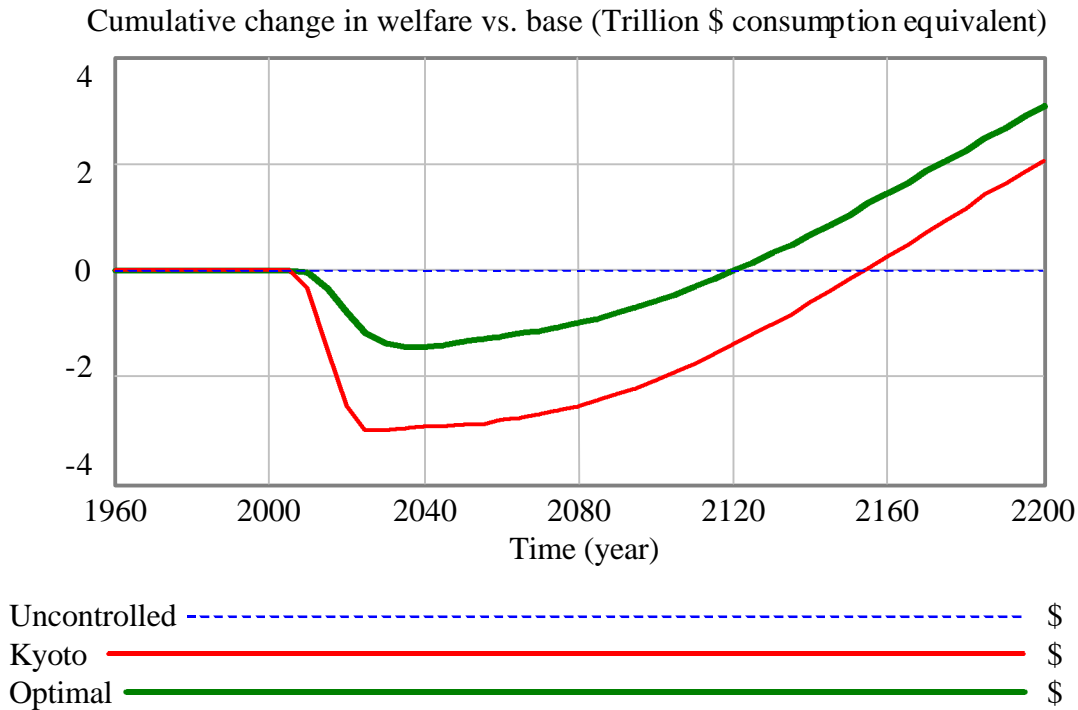


Cumulative distribution of welfare outcomes with constant permitted emissions at Kyoto and optimal levels. Welfare is in current consumption equivalent, with respect to a zero baseline reflecting no abatement effort. Note that welfare here and in subsequent figures and tables refers to cumulative discounted utility, converted to its 1995 consumption equivalent by dividing the flow of utility by the marginal utility of a unit of consumption in 1995.

The outcome is highly sensitive to the permit level. Errors in judgement on the low side are particularly costly—setting a permit level 15% more stringent than optimal reduces welfare by \$280 billion. Setting permit levels too high risks a do-nothing approach in many scenarios; under the optimal constant permit scheme emissions are uncontrolled in 2010 in 15% of the simulations.

It is worth noting the distribution of benefits over time. Almost irrespective of the permit level, the breakeven point at which cumulative benefits of avoided climate damage exceed cumulative abatement costs is more than a century away—an extreme case of worse-before-better behavior. The lack of short-term benefits reflects three features of the model as used here: there is no “free lunch” from low- or negative-cost energy conservation, there are no other negative externalities (like pollution or warfare) associated with carbon energy use, and there is no possibility of climate catastrophe (like disruption of the Atlantic thermohaline circulation). Relaxing any or all of these assumptions could move the breakeven point much closer in time. In any event, the long delay is likely to be problematic: it implies that there will be an extended period of time in which the pain of permit prices subjects the agreement to intense political pressure.

Figure 9: Permit benefits trajectory



Cumulative impact of two permit levels on welfare, relative to the baseline uncontrolled scenario.

Can permits be improved?

Kopp, Morgenstern et al. (2000) propose a “safety valve” price for permits above agreement levels. McKibbin (1998) proposes a similar scheme of national permits allocated with a fixed price above a target emissions level. Both approaches modify to the permit system to behave more like a tax, where the price of emissions is fixed (or at least has an upper bound).

Simulations with the FREE model indicate that safety valves can create modest improvements in welfare as long as they are not set too low. A ceiling price of \$200/ton carbon is near the breakeven point. A ceiling of \$400/ton carbon improves welfare on the order of \$100 billion. Adding the flexibility of a ceiling allows the optimal permit level to be lowered slightly, for an improvement of \$150 billion. These are very large sums but small increments compared with global GDP over the 300 year horizon. One problem that persists with permit price ceilings is the lack of opportunistic control in cases where emissions reductions turn out to be cheap or easy, a circumstance in which common sense suggests doing more but permits are static.

Table 2: Summary of permit policies

Scenario	Policy		Mean Outcomes in year 2100				
	Emissions target	Ceiling price	Consumption per capita	Emissions	CO ₂ in atmosphere	Temperature Change	Welfare Change
	Gigatons carbon/yr	\$/ton carbon	\$/person/yr	Gigatons carbon/yr	Gigatons carbon	Degrees Celsius	Billion \$
Uncontrolled			16,111	22.86	1587	3.3	0
Kyoto	4.75		16,256	4.82	985	2.2	5591
Optimal -15%	5.25		16,248	5.32	1010	2.3	6119
Optimal	6.11		16,233	6.18	1055	2.4	6399
Optimal +15%	6.95		16,220	7.02	1099	2.5	6270
\$200/ton ceiling	6.11	200	16,234	6.40	1062	2.4	6381
\$400/ton ceiling	6.11	400	16,233	6.18	1055	2.4	6505
Optimal ceiling	6.03	829	16,234	6.10	1051	2.4	6549

Note that preindustrial CO₂ in the atmosphere was 590 gigatons carbon, and temperature is the change with respect to the 1960-1990 global average.

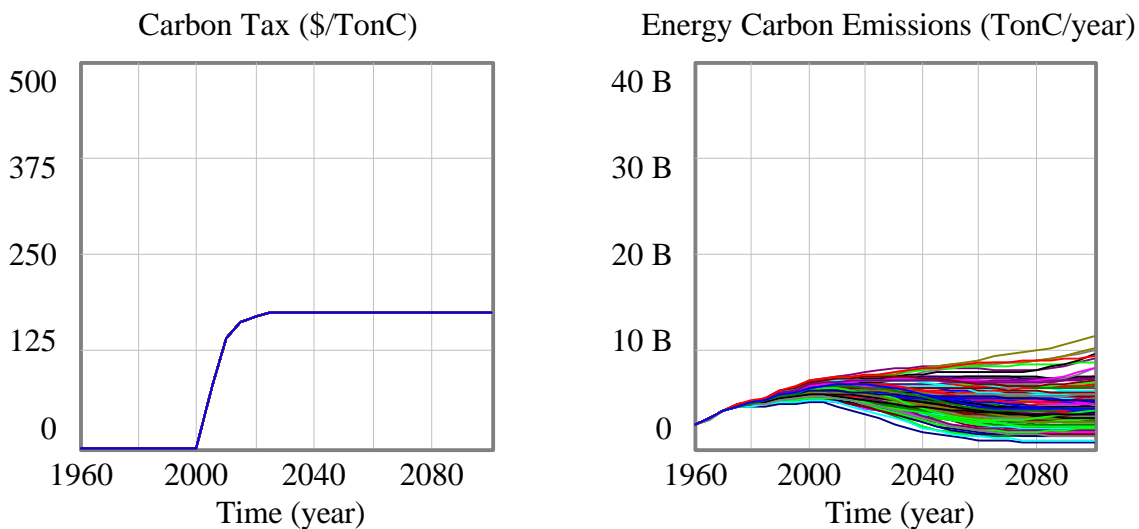
It is easy to imagine other improvements to a constant permit. An obvious starting point is to test schedules of permit levels rather than constant emissions rates. Many other models, including DICE, actually operate in this fashion. However, this is computationally expensive and sensitivity tests suggest that results are qualitatively the same. Permits must still strike a balance between increasing stringency—starting slow to avoid economic shocks—and the reality of upward pressure on emissions from growth. Another possible improvement is to give permits a wide temporal window, recognizing that with delays of at least a century in the carbon cycle and climate, it makes relatively little difference whether a unit of carbon is emitted this year or next. However, this seems likely to create more, rather than less instability, as it introduces new possibilities for mismanagement of the stock of outstanding permits. It would also create opportunities for cynical gaming of the permit system; parties could consume the bulk of available permits early in the period, then use the prospect of catastrophe to relax standards for the remainder.

It is possible that permits could be further improved by more complete revisions of their allocation mechanism. For example, the total quantity of outstanding permits could be regulated by an authority to maintain a set price or price range. This would cap the upper bound to permit costs *and* set an opportunistic minimum so that some effort is always undertaken. However, it is hard to imagine that added complexity can contribute enough performance to justify the practical and political difficulties of implementation.

Constant tax

Pizer (1997; 1999) concludes that taxes substantially outperform permits under uncertainty. The FREE model supports this conclusion. Figure 10 shows the response to the best possible constant carbon tax (phased smoothly with a five-year time constant). By contrast with permits, the price of emissions is fixed, but emissions vary over a wide range. Welfare is increased by \$400 billion over any permit structure, and the mean emissions level in 2100 is actually lower than the most stringent permit tested (see Table 3). The best constant tax is \$175/ton carbon, comparable to the best-guess deterministic tax of \$170/ton, and roughly 4-10 times the level in the DICE model (Nordhaus 1994). Significantly, performance is insensitive to small deviations in the tax. Raising or lowering it by 15% has almost no effect on welfare.

Figure 10: Constant carbon tax



Emissions trajectory subject to an optimal constant carbon tax of \$175/ton carbon. Compare with Figure 6 and Figure 7.

Adaptive Tax

There is no reason to suppose that a constant tax (or permit level for that matter) is optimal. A typical alternative is to explore taxes that change over time, by specifying a vector of taxes at specified times or constructing a tax as a polynomial function of time. However, this is still a ballistic strategy of selecting a tax that must fit all uncertain futures. An alternative approach is to create a feedback control rule, shown below. The tax is a linear function of perceived emissions rates and atmospheric CO₂ concentrations, with an implementation delay (that also provides smoothing).

$$T_c(t) = \int \frac{DT_c(t) - T_c(t)}{\tau_t} dt \quad \text{Eq. 5}$$

DT_c = desired carbon tax

t_t = tax implementation time

$$DT_c = T_0 + \frac{T_E}{E_0} + \frac{T_C}{C_{a,0}} \quad \text{Eq. 6}$$

T_0 = carbon tax constant

E = perceived CO_2 emissions rate

T_1 = carbon tax emissions coefficient

E_0 = reference emissions rate

T_2 = carbon tax concentration coefficient

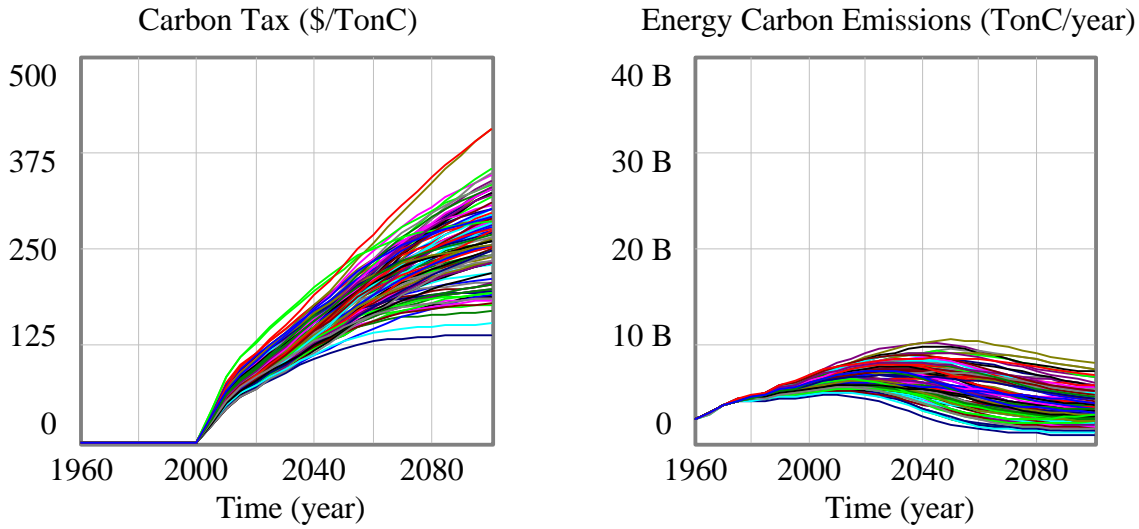
C_a = atmospheric CO_2 content

$C_{a,0}$ = reference atmospheric CO_2 content

Figure 9 illustrates the effect of the tax, with parameters selected optimally. The adaptive tax improves welfare by an additional \$500 billion (see Table 3). Exploration of other tax rules indicates that the main benefit is that the additional degrees of freedom allow the tax to start small, minimizing short-run disruption of the economy, and to continue rising to suppress increasing emissions pressure from economic growth. However, the tax coefficients on emissions and CO_2 in the atmosphere do indicate that the tax is exploiting some information about the state of the world. The tax responds positively to the atmospheric concentration of CO_2 , so that in scenarios with slow natural uptake of carbon, taxes will be higher, as they ought to be. Similarly, the tax responds negatively to perceived emissions, so that abatement effort is restricted in scenarios with high abatement costs (emissions that resist policy), also as one would expect.

The adaptive tax approach could be generalized to the construction of a stochastic control rule using full state information in the model. A logical first step would be to include information about observed temperature and climate damages. In this way the tax heuristic could be made to function much like the act-then-learn decision framework explored in some models (Valverde, Jacoby et al.; Nordhaus 1994). While this would be an informative pursuit, it is somewhat unhelpful from a policy perspective for at least two reasons. First, it appears that the response of welfare is relatively flat around the optimal tax, so added precision may contribute little. Second, it is implausible that key variables (like global average temperature) can be perceived on short enough time scales to be usable now.

Figure 11: Adaptive carbon tax



Emissions and tax trajectories for an optimal tax heuristic with constant, emissions, and concentration components. Compare with Figure 6, Figure 7, and Figure 10.

Table 3: Summary of taxes

Scenario	Tax		Mean Outcomes in year 2100				
	2020	2100	Consumption per capita	Emissions	CO ₂ in atmosphere	Temperature Change	Welfare Change
	\$/ton carbon	\$/ton carbon	\$/person/yr	Gigatons carbon/yr	Gigatons carbon	Degrees Celsius	Billion \$
Uncontrolled			16,111	22.86	1587	3.3	0
Optimal - 15%	146	150	16,252	4.97	1004	2.3	6767
Optimal Constant	171	175	16,254	4.40	983	2.2	6801
Optimal +15%	195	200	16,254	3.98	967	2.2	6780
Optimal Adaptive	90	262	16,229	3.69	1006	2.3	7310

Compare with Table 2.

Flexibility

It is interesting to note what happens to the ranking of taxes and permits when the rigid short-run energy-economy in FREE is relaxed to a flexible production structure as in DICE and other simple models. Flexibility is implemented by shortening delays in perception and energy capital acquisition, diminishing the role of capital in energy production, increasing the rate at which

existing capital can be retrofitted to use new energy sources, and increasing short-run elasticities of substitution among fuels and between capital and energy.

With a flexible short-run economy, constant permits outperform constant taxes by a substantial margin. As emissions approach the cap, the permit price rises smoothly and gradually, so that emissions are suppressed more strongly as the economy grows. Because the economy is flexible in the short run, emissions can be restricted aggressively without creating the disruptive spike in permit prices observed in Figure 7. The adaptive tax still outperforms the constant permit, as it controls emissions even in circumstances where they would fall below the permit threshold anyway.

Table 4: Summary of taxes with unrealistic flexibility of the energy-economy system

Scenario	Tax or Permit Price		Mean Outcomes in year 2100				
	2020	2100	Consumption per capita	Emissions	CO ₂ in atmosphere	Temperature Change	Welfare Change
	\$/ton carbon	\$/ton carbon	\$/person/yr	Gigatons carbon/yr	Gigatons carbon	Degrees Celsius	Billion \$
Uncontrolled			16,155	19.66	1366	2.8	0
Optimal constant permit	31	144	16,215	5.05	944	2.1	5199
Optimal constant tax	89	89	16,257	6.56	917	1.9	4225
Optimal adaptive tax	33	139	16,225	4.77	924	2.0	5615

Note that welfare magnitudes in this table are not directly comparable with other tables due to the different base model structure.

Conclusions

The FREE model identifies a number of feedback structures that have profound effects on climate policy recommendations. It is important that these structures be tested by other integrated modeling efforts. In addition, this work leaves many key features of integrated models unexplored. Making key subsystems like population endogenous, even with the crudest and most flawed models, would yield insights not available from the exogenous forecasts currently in use.

Many structures from earlier system dynamics models were omitted or abstracted in FREE for simplicity. Restoring some of these would provide additional insights. Inclusion of an explicit capital-producing sector, for example, would impose additional constraints on the expansion of capital stocks in energy supply. A behavioral theory of saving and investment behavior would be more robust and realistic than the current structure, and would link naturally to a more disaggregated, endogenous treatment of population. Monetary effects may be necessary if permits induce large financial flows.

To a large extent, the journey is the destination in integrated modeling. Result-oriented optimization or sensitivity analysis ought to be preceded by a thorough exploration of model dynamics, with less attention to single measures of performance like cumulative discounted utility (Gardiner 1980). Models aren't needed to justify doing little or nothing; there are many interests that already support this view. A more worthwhile pursuit would be to seek ways of achieving radical emissions reductions should they become necessary. This objective would require models that include robust representation of behavior far from current circumstances.

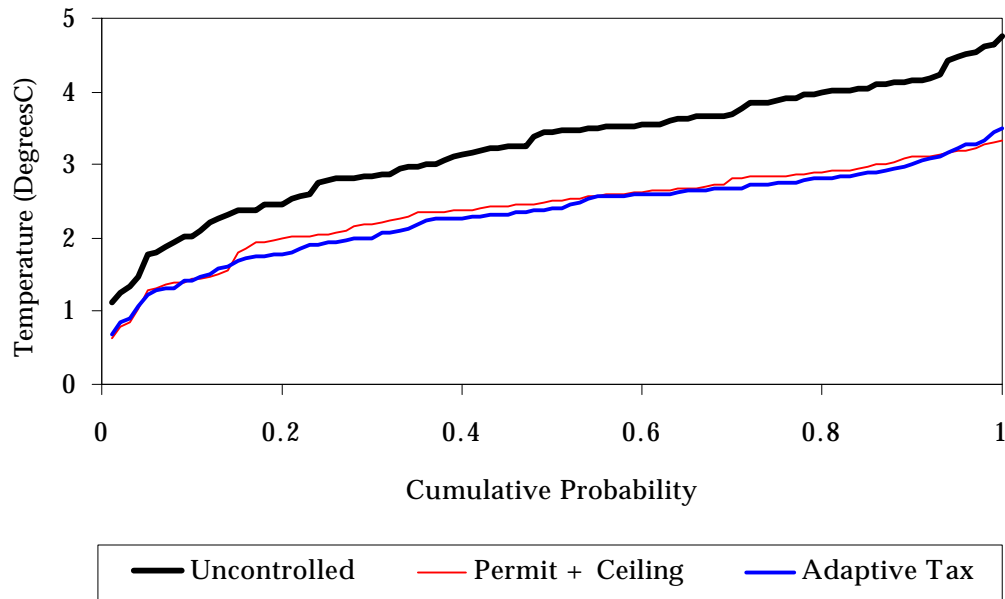
Taxes or permits?

The FREE model supports the conclusion that taxes outperform permits. However, the context of the conclusion is somewhat different. Most models heavily discount future climate damages and thus conclude that emissions reductions offer, at best, modest net benefits that can easily become negative through poor design and implementation. With intergenerationally fair discounting, though, the perceived benefits of emissions reductions are much greater. Thus even policies like Kyoto that are marginal by selfish yardsticks have a high net benefit in FREE.

The high benefits of avoided climate change provide considerably more latitude for judgement, experimentation, and error, which suggests that the emphasis of discussion should shift from fine-tuning of optimal taxes or permits to other questions. One key domain is the political viability of agreements. Here again dynamics and uncertainty favor taxes over permits. The risk that permits will fail because they are set too stringently (producing a backlash against soaring permit prices) or too loosely (where they will do nothing, as with the availability of "hot air" from diminished emissions in former Soviet economies) is high. Capping permit prices helps with the first failure mode; further refinements or the political process could conceivably solve the second but only with an additional layer of complexity.

Another key question is whether current models take the question of climate seriously at all. Nearly all policies proposed by modelers do no more than stabilize emissions at historically high levels; IPCC emissions scenarios contemplate nothing like zero emissions or stabilization of atmospheric CO₂ at current levels (IPCC 2000). Nordhaus' RICE model (a regionalized version of DICE) suggests optimal emissions reductions of less than 10%, so that emissions rise to more than 20 billion tons carbon per year (Nordhaus and Boyer 1999; Nordhaus 2001). As a result, substantial climate change always occurs. The FREE model used here is no exception—permits and taxes fail equally to achieve a stable climate (Figure 12). Permits certainly appear impractical for reaching ambitious targets like zero emissions; taxes may be as well. The search for optimal policies needs to be expanded to other kinds of instruments—technological and social for example.

Figure 12: Distribution of temperature, taxes vs. permits



Distribution of temperatures in year 2100 in 100 representative simulations, comparing an optimal adaptive tax to a permit with a ceiling price. The outcomes are essentially identical (within 0.1 degree).

If even a few of the issues explored in the FREE model prove important, the implications for climate policy are considerable. Together, these explorations suggest an alternative paradigm for climate policy, in which depletion is a serious issue in the near term, policies induce technological change and other path-dependent effects, the economy is far from equilibrium or an optimal state, behavioral and structural factors constrain and delay action, and people are concerned with the welfare of future generations. Even in the face of substantial adjustment costs, aggressive, immediate action is warranted to avoid climate change.

The challenge for policymakers is to take aggressive action without causing extreme short-run economic disruption, triggering a political backlash. For this purpose, taxes appear to be a more suitable mechanism than emissions permits. However, since further delay is in itself expensive, it seems sensible to make modest changes to current agreements and take first steps as soon as possible; permits can always be scrapped for taxes later.

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