A Feedback-Rich Climate-Economy Model

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Abstract

More than 20 energy-economy models have been developed to address different climate policy questions. While these integrated models are quite varied, most draw heavily on the energy-economy models of the 70s and 80s, which were motivated by energy security issues and explored the potential impacts of increasing energy prices on economic growth. They typically employ exogenous rates of technological improvement and backstop energy prices. Factor allocation is optimal. The impact of a carbon tax on the energy system at a given time can often be reduced to an instantaneous tradeoff between abatement costs and emissions.

System dynamics models of energy-economy interactions focus instead on disequilibrium dynamics and feedback complexity, with behavioral decision rules and explicit stocks and flows of capital, labor, and money. This research uses elements of earlier system dynamics work to create a new model, FREE[1], that tests the implications of feedback processes that have not been explored in the climate change context. 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 intertemporally fair criteria.

Experiments with the model indicate that depletion of oil and gas resources has critical interactions with climate policy. The inclusion of learning-by-doing and other path-dependent mechanisms suggests that abatement efforts will be more effective and should be more stringent than models with exogenous technology forecasts indicate. Inclusion of delays and biases from structural and behavioral features of the energy system reveals higher long-run emissions reduction potential but imposes substantial constraints that prevent rapid reductions. Fair discounting and consideration of intangible damages substantially raise the indicated abatement effort.

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[1] The FREE model is fully documented in Fiddaman (1997). A version is available online at http://home.earthlink.net/~tomfid/.

Introduction

This paper explores a new integrated climate-economy model, FREE (Feedback-Rich Energy-Economy model), that 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 across time.

The purpose of this study is not to identify optimal policies under a central scenario assumed to be correct. Instead, it identifies the policy implications of the structures above, so that further research may be better targeted and policy makers may become aware of blind spots in current analyses.

These features were selected on the basis of a detailed inventory of the feedback structure and simulation methods of other integrated models. Collectively, they represent an alternative approach to important aspects of integrated modeling, synthesizing ideas from system dynamics, evolutionary economics, and behavioral decision theory.

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 relatively simple biogeophysical models. With appropriate parameters, the model may be reduced to a form which behaves much like simpler neoclassical models.

Background

The climate change debate has spawned more than 20 integrated climate-economy models (Dowlatabadi 1995; Parson and Fisher-Vanden 1995). The motivation for these models is the need to identify an efficient distribution of the burdens of climate change or efforts to avoid it. The ultimate goal is to allocate effort efficiently:

- over time,
- across regions,

- among greenhouse gas abatement, adaptation, and possibly geoengineering options,
- between energy supply and energy conservation options,
- with the most efficient economic and regulatory instruments, and
- with a healthy appreciation of the uncertainties involved.

A diverse set of models has developed around various subsets of the questions above. 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.

The Standard Paradigm

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. Most of these similarities can be attributed to the roots of integrated models in the economic tradition of energy modeling. Specifically, most integrated models share the following attributes, 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,
- exogenous population,
- exogenous 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 evolution of energy technology,
- consumer and producer optimization with full information and, frequently, perfect foresight,
- rapid equilibration of factor inputs to production, and
- general exclusion of positive feedback mechanisms in the economy (other than capital stock growth).

Obviously, not all integrated models fit the characterization above perfectly. Of the well-known models, the DICE model (Nordhaus 1994) is probably the purest example of the standard paradigm. In the central 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 1996).

Other integrated models depart from the standard paradigm in a variety of ways. Cline (1992), for example, favors lower discount rates. Grubb (1995) explores the possibility that the costs of greenhouse gas abatement are partially impermanent adjustment costs. The ICAM model (Dowlatabadi and Ball 1994) incorporates many distributions of uncertain parameters elicited from experts, thus attempting to represent the diversity of opinion in various disciplines.

Many of the shortcomings of the current treatment of social, economic, and energy interactions are widely recognized. Long-term trends of population growth and technological change in particular are often cited as key areas for future improvement of models (Grubb 1993; Parson 1995). However, important structures appear to be neglected. The consistent exclusion of selected feedback loops may expose integrated models to biases in their conclusions. The FREE model reexamines some of the assumptions embedded in current models in order to assess their impact.

Contributions to Integrated Modeling

This research makes a number of contributions to the practice of integrated modeling. The survey of existing models led to the replication and verification of models and results by several authors. Some of these models are now available in a common simulation language, allowing other researchers to explore them easily. In the course of replicating existing models, a number of weaknesses in simulation methods were discovered. These weaknesses could be easily avoided by adherence to a few basic modeling practices.

The FREE model identifies some of the feedback mechanisms, not yet incorporated in other integrated models, that are most sensitive and deserving of further investigation. It links existing system dynamics work in energy and macroeconomic modeling to climate change policy, and demonstrates the importance of key features of the system dynamics approach to the formation of policy over very long time horizons.

The FREE model is feedback rich, yet computationally tractable. It is easy to perform extensive optimization and uncertainty analysis with the model. FREE will facilitate the reexamination of the conclusions from simple models like DICE or Connecticut/YOHE in a more realistic context (Nordhaus 1994; Yohe and Wallace 1996).

Contributions to Policy

The FREE model informs policy by identifying heuristic control measures (such as a carbon tax rule) which are robust to structural and parameter uncertainties. Perhaps more importantly, experiments with the model suggest several possible biases in current analyses of climate policy, of which policy makers should be aware. In the future, the model can serve as the basis for the creation of a “policy flight simulator”, which will enable decision makers to explore the dynamics and structural uncertainties of the climate change issue experientially.

Model Description

Time Horizon

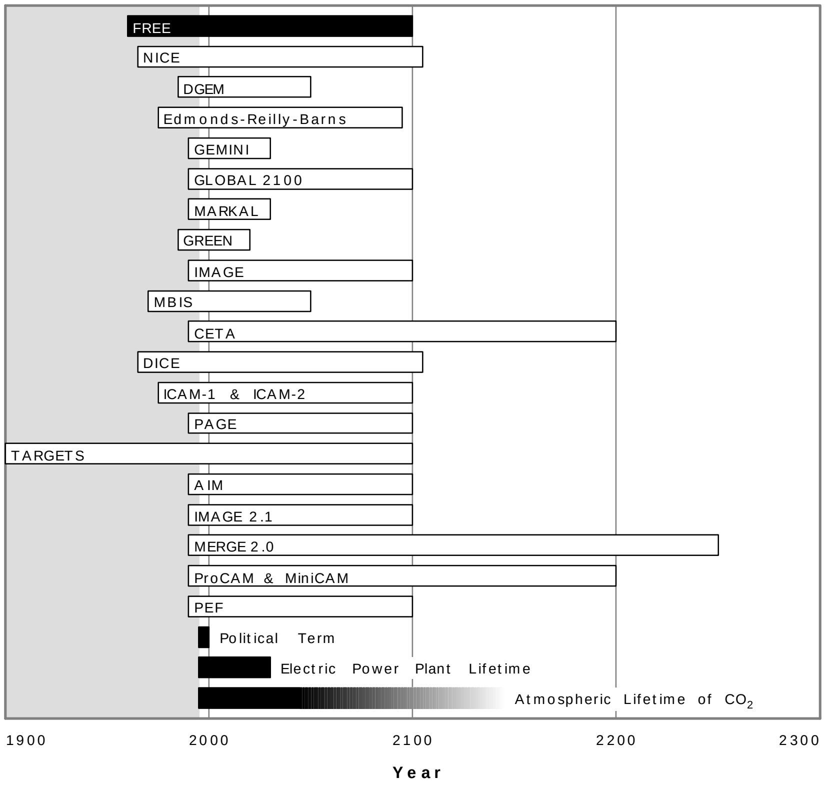
The nominal time horizon of the model is 1960-2100. However, for optimization purposes, runs are typically extended to 2300 in order to reduce horizon effects. The historical period of the model is relatively long compared to most, which typically replicate only a decade of two of history. While it was not the purpose of this study to estimate model parameters from data, the comparatively long historical period provides a useful test of model behavior.

Boundary

The FREE model represents the global energy-economy system and, in a more limited fashion, global biogeophysical processes. The great 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.

Several exogenous variables drive the model behavior. Population, factor productivity growth, and autonomous energy efficiency improvement are all exogenous, as in other models. Cost-reducing energy production technology is normally endogenous, but may also be specified as an autonomous process for testing purposes. Since the model focuses on the energy-economy system, nonenergy emissions of CO_2 and radiative forcing from other greenhouse gases are treated exogenously. Over the historical period (1960-1990), prices for coal, oil, and gas are given exogenously, as replicating the OPEC period endogenously would be difficult, to say the least. Thereafter prices make a five-year transition to their endogenously generated values.

Figure 1: Integrated Model Time Horizons



Adapted from Dowlatabadi (1995). Note that these are reporting time horizons, and some models (including DICE and the FREE model) are simulated for longer periods when optimizing.

The use of exogenous variables severs feedback loops which may have important policy implications. This occurs in several areas in the model. If population growth and factor productivity improvement are dependent on increasing wealth, the model understates the importance of favoring current economic output over future welfare. On the other hand, to the extent that emissions of nonenergy CO_2 and other greenhouse gases are coordinated with energy production and economic activity, the model understates the need for current abatement.

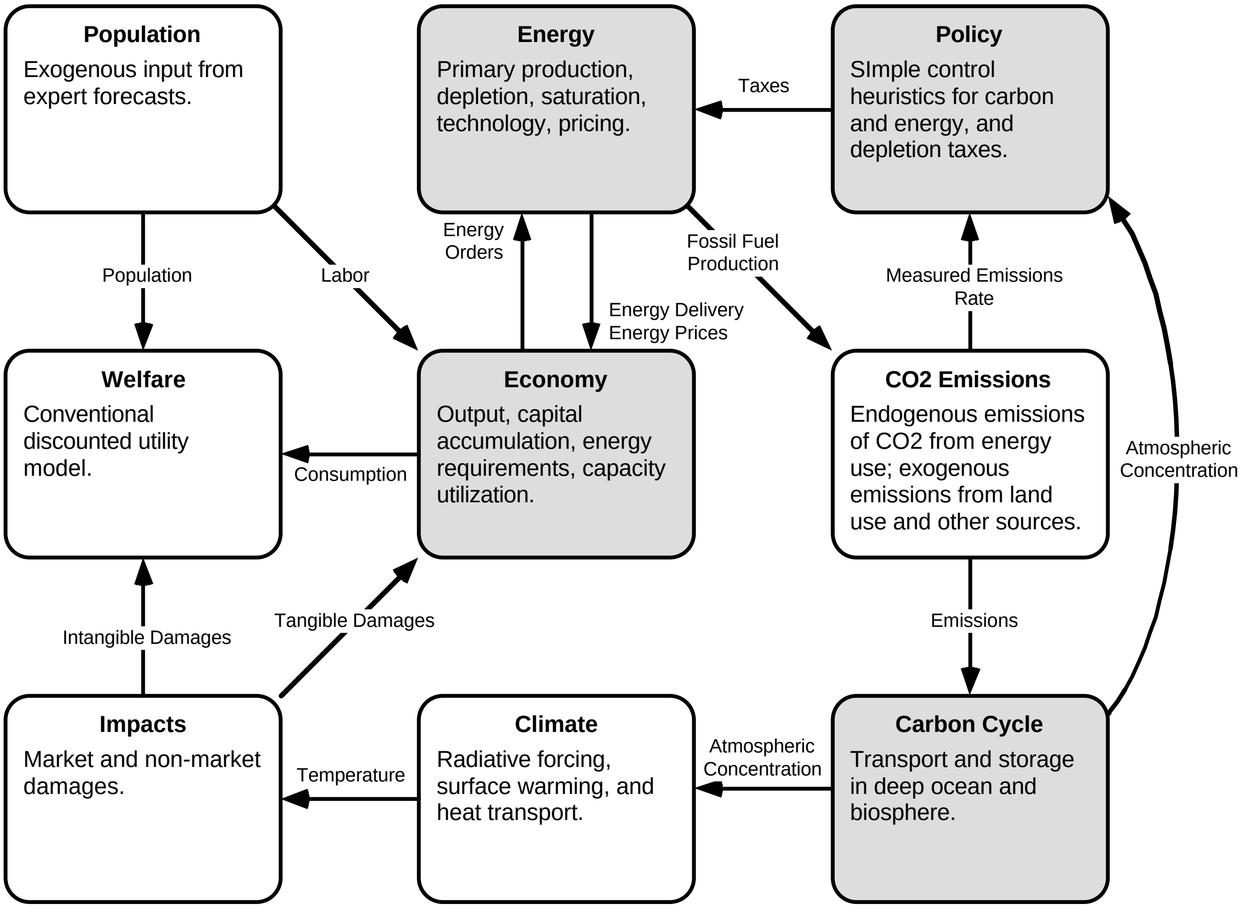
For simplicity, many features have been omitted from the model. There is no regional or sectoral disaggregation (except in the energy sector). Non-energy natural resources are ignored. While the energy sector includes several distinct energy sources, energy conversion activities (such as the generation 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 (except for a brief energy delivery delay), as they equilibrate very quickly relative to the model horizon.

Table 1: Model Boundary

Endogenous	**Exogenous**	**Excluded**
Economic output	Population	Labor mobility and participation
Consumption	Factor productivity	Money stocks and monetary effects
Interest rates	Autonomous energy efficiency improvement	Non-energy resources
Investment	Oil/gas and coal prices (1960-1990)	Regional disaggregation
Embodiment of energy requirements in capital	Nonenergy CO_2 emissions	Sectoral disaggregation (other than energy)
Energy prices	Greenhouse gases other than CO_2	Fossil-fired electric power generation
Energy production		Inventories and backlogs
Energy technology		
Depletion		
CO_2 Emissions		
Carbon Cycle		
Atmosphere and ocean temperature		
Climate damages		

The model can be divided into a number of subsystems that have relatively sparse interactions with the remainder of the model. Figure 2 illustrates the sector boundaries, internal activities, and external relationships.

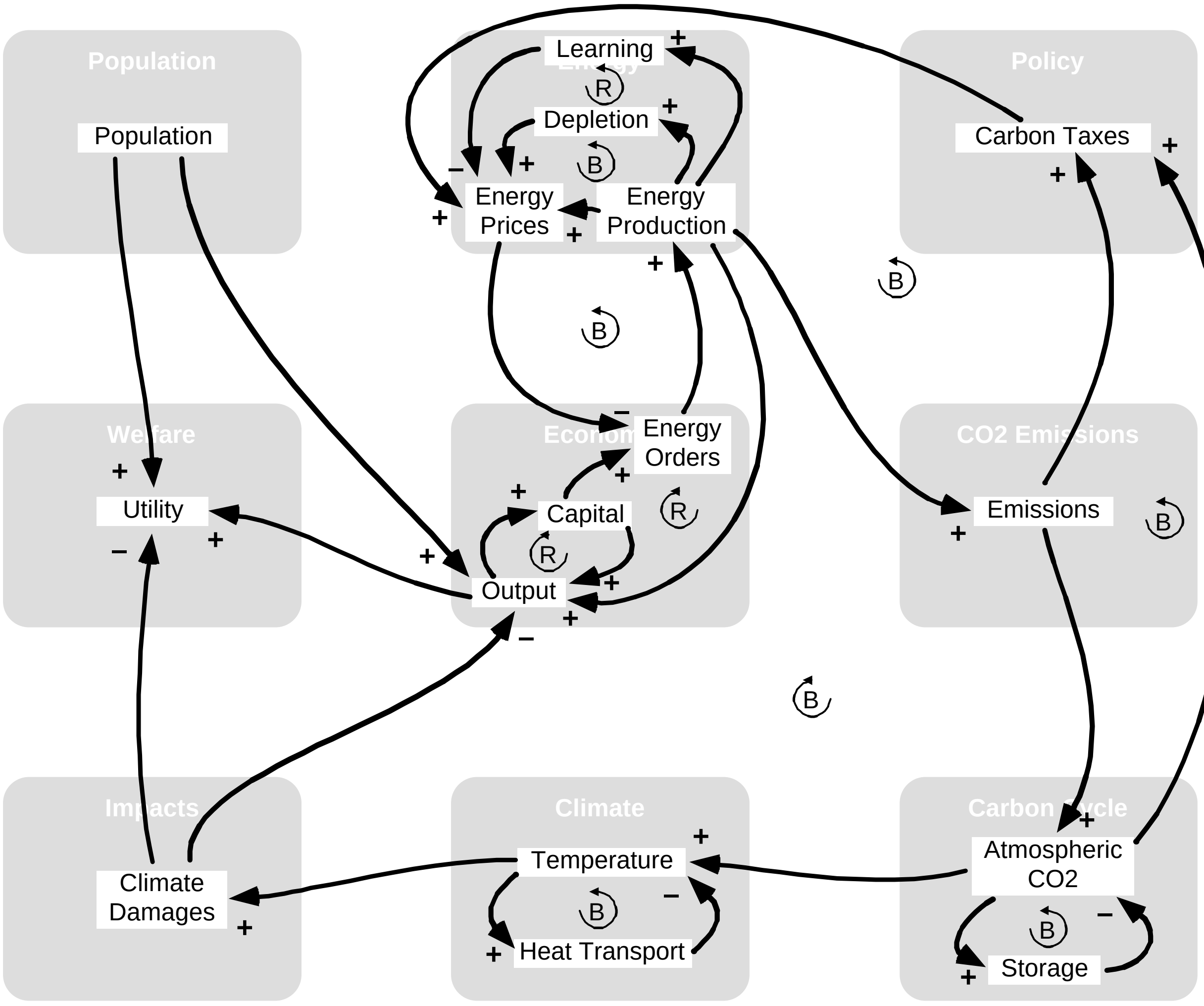
Figure 2: Sector Boundary Diagram



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

Much of the macrobehavior of the model arises from the feedback structures shown in Figure 3. The reinforcing process of capital accumulation drives economic growth (augmented by exogenous population and factor productivity growth). Economic activity requires energy input; which leads to carbon emissions. Emissions increase the concentration of CO_2 in the atmosphere, causing temperature to rise. As the global temperature rises, climate change damages reduce economic output and divert it from other purposes. The energy and economy sectors interact through the exchange of goods for energy. Within the energy sector, learning and depletion drive energy production costs. Carbon taxes raise energy prices in response to increasing CO_2 emissions and atmospheric concentrations.

Figure 3: Major Feedback Processes



Sources of Structure

The FREE model draws on a number of preceding models for elements of its structure. Since the principal purpose of this study is to explore the energy-economy system, the DICE model was a convenient source of structure in other areas, such as the climate system (Nordhaus 1994). Nordhaus' subsystems are simple, well-documented, and widely understood. Using them allows implications of the energy-economy model to be compared with Nordhaus' results in a common biogeophysical context.

The energy-economy systems in the model draw heavily on Sterman's energy-economy model and the System Dynamics National Model (Senge 1978; Sterman 1980; Sterman 1981). In general, the structures for capital investment and embodiment of energy requirements in capital have been closely copied, while most other disequilibrium features of these models have been omitted. The energy sector also draws heavily on my prior construction of an energy system for the DICE model (Fiddaman 1995; Fiddaman 1996).

While the DICE carbon cycle model is preserved for comparison purposes, an alternate carbon cycle model is also provided. This subsystem incorporates the carbon uptake mechanisms of the IMAGE-1.0 and Goudriaan & Kettner models coupled to a simpler eddy-diffusion ocean and two-level biosphere (Oeschger, Siegenthaler et al. 1975; Goudriaan and Ketner 1984; Rotmans 1990).

Policy Analysis

The purpose of the FREE model is to explore the impact of climate policies, focusing on a carbon tax. Optimization is used to identify effective tax policies in a variety of model scenarios. It is possible to test a variety of other policies in the model, but a carbon tax alone is sufficient to reveal many interesting consequences of changing assumptions. Particular attention is paid here to the implications of depletion and endogenous energy technology.

Impact of a Carbon Tax

The impact of a carbon tax can be very complex in the FREE model. Figure 4 illustrates the impact of a 100 $/TonC tax. The tax is imposed in 1995 and maintained indefinitely at a constant level thereafter. In response to the tax, consumption, and thus utility, rises and falls several times. Surprisingly, the first impact of the tax is a slight increase in consumption, which persists for about 10 years. This occurs because energy system costs decrease significantly over that period. Costs fall because the carbon tax suppresses energy demand, reducing the need for new investment and depressing capacity utilization, so that only the most efficient capital is used.

After about 2005, consumption falls, because productivity losses begin to exceed the modest savings in the energy system. Productivity losses occur 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. This reduces the marginal product of capital, diminishing investment. As a result of reduced capacity utilization and investment, output grows more slowly than it does with no tax.

After about 2020, consumption losses increase sharply, because energy system costs rise well above their baseline levels. With the exhaustion of oil and gas, the economy must make a transition to more costly renewables, rather than to coal. Mainly as a result of increased energy costs, consumption losses peak around 2045. Thereafter, consumption rises above its baseline level, as the benefits of reduced climate change finally begin to be felt. Reduced climate damages also improve returns in the goods producing sector, leading to greater investment and higher productivity. The net benefit of the carbon tax policy—a small improvement in welfare in this case—is thus a complex interplay of short and long term factors, which may behave in a very counter-intuitive fashion.

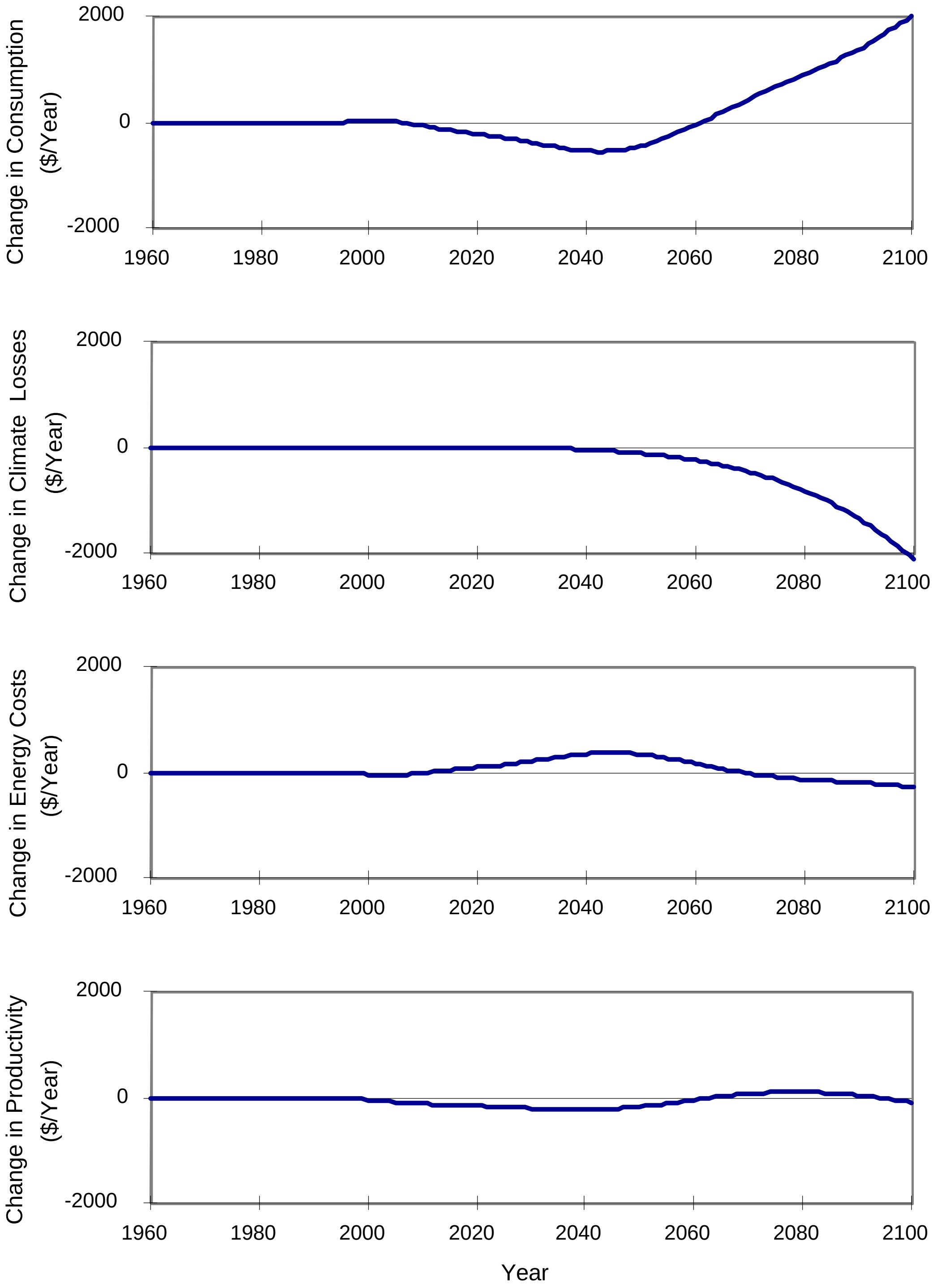
Optimal Carbon Tax

A useful starting point is to identify an effective carbon tax policy in the base run of the model. In general, this is done by searching for the optimal parameters of a simple rule that responds to the CO_2 emissions rate and atmospheric concentration. For simplicity, a constant tax (implemented gradually) is used in most tests presented here. The criteria for policy evaluation is maximization of cumulative discounted utility over the simulation period. The search is performed by a gradient-free hill-climbing algorithm (Powell 1981; Ventana Systems 1994).

If there is no climate change, one would expect a carbon tax to reduce welfare. The surprising outcome is that a large carbon tax may be less damaging than a small tax, and that the optimal carbon tax is actually slightly negative (see Figure 5). This occurs because of the assumption that the opportunity cost of depletion of oil and gas is not correctly reflected in prices. A carbon tax of 200-400 $/TonC shifts energy demand from coal onto oil and gas more than it reduces aggregate energy demand, because the interfuel substitution potential is greater than the capital-energy substitution potential. Thus the carbon tax increases demand for oil and gas, even though they are carbon-based fuels. Accelerating the depletion of these (undervalued) fuels adds to the losses from the allocative inefficiency caused by the tax.

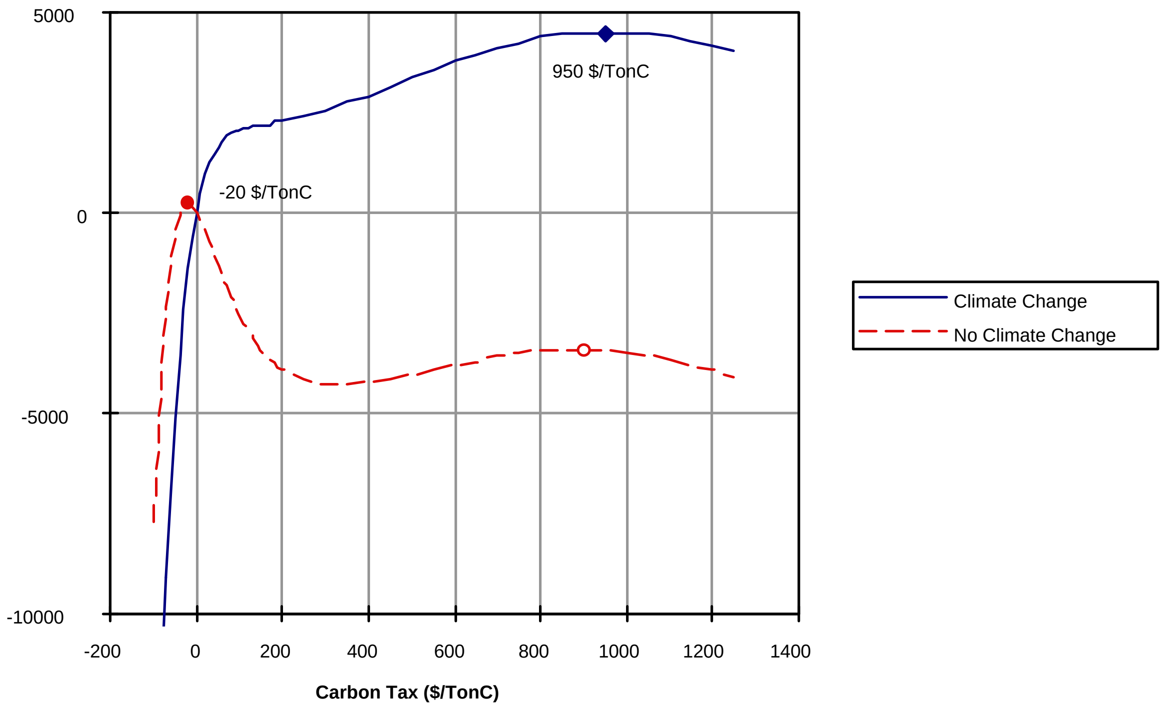
A large carbon tax suppresses aggregate energy demand enough to slow depletion, creating a local optimum at a tax of 900 $/TonC. However, at this high tax, welfare is still significantly lower than with the globally optimal tax of -20 $/TonC. The negative tax—in effect a subsidy on carbon-based fuels—is beneficial because it shifts demand to coal, slowing the depletion of oil and gas.

Figure 4: Impact of a Constant Carbon Tax



Each plot shows the change (compared to the base scenario with no carbon tax) in the indicated variable when a tax of 100 $/TonC is imposed in 1995. The change of productivity is defined as the change in output that would occur from changes in investment and capacity utilization if there were no effects of climate change.

Figure 5: Welfare Implications of a Constant Carbon Tax



The taxes shown are target tax levels, held constant over the simulation period. The initial tax in effect is zero until 1995; it then adjusts gradually (with a time constant of 20 years) to the target tax level. The slow adjustment to target tax levels is used in order to prevent the effects of short-run adjustment costs in response to sudden tax changes from dominating the results. Utility is converted to its consumption equivalent at the marginal utility of consumption in 1990, and is shown net of the base case (zero tax).

When climate change is taken into account, a negative carbon tax is no longer optimal, as it greatly increases CO_2 emissions and climate damages. Instead, the optimal policy is a very high carbon tax. In this case, though there is some fuel switching from coal to oil and gas, aggregate energy demand is suppressed enough so that oil and gas consumption falls, delaying exhaustion of the resource. The high tax indicated—950 $/TonC—is far higher than that recommended by other studies, and would likely be impossible to implement. The tax must be extremely high because a carbon tax is a very poor instrument for controlling depletion of oil and gas.

Depletion

Because depletion of fossil fuels is so closely coupled with climate policy, and may have greater welfare implications over the next few decades than climate change, it is important to explore in more detail. Depletion has a limited effect on policy in most other models, because perfect foresight precludes undervaluation of resources, the production structure has considerable short-run flexibility, there are highly-substitutable infinite backstops, or depletion is simply omitted or exogenous. For example, the DICE model has no explicit energy system or fossil fuel resource limits (Nordhaus 1994). Therefore, the issue of depletion simply does not arise. In some sense, the accumulation of carbon in the atmosphere is similar to depletion. However, Nordhaus' carbon cycle is an infinite sink, so it behaves more like a renewable resource than a depletable one.

Some models employ full intertemporal optimization. Thus oil and gas depletion and capital investment decisions are made with perfect foresight. Manne and Richels cite Solow in defense of this assumption:

> *"If a market-guided system is to perform well over the long haul, it must be more than myopic. Someone—it could be the Department of the Interior, or the mining companies, or their major customers, or speculators—must always be taking the long view. They must somehow notice in advance that the resource economy is moving along a path that is bound to end in disequilibrium of some extreme kind."*
>
> *(Manne and Richels 1992)*

To say that someone *must* be attending to the long view does not mean that someone actually *is*. While reserves may be well managed—property rights are established, extraction costs are reasonably certain, and the time horizon is limited, the same cannot be said for ultimate resources.

While governments clearly do capture some revenue from resource extraction, through severance taxes and the sale of exploration rights, for example, there are a number of problems involved in achieving the optimal depletion trajectory. First, their is great uncertainty about the extent and extraction cost profile of the resource. Different assumptions about resource abundance suggest substantially different depletion trajectories (de Vries 1989). Geological and price uncertainty may lead firms to use simple adaptive heuristics rather than optimization (Mueller 1994). The resource base is generally in the hands of governments, which may attempt only to maximize revenue over a short (politically inspired) time horizon, or even to intentionally accelerate depletion (Porter 1992).

Even if resource managers have the proper incentives, realistic models are not available for solving the intertemporal problem. Optimal depletion models typically employ unrealistic assumptions, like infinitely substitutable backstops, zero or constant extraction costs, and exogenous or static technology. The central conclusion of most Hotelling-type models, that the resource price should increase at the prevailing interest rate, certainly is not observed for oil and gas. In the absence of definitive model results, decision makers are likely to use simple heuristics which miss very long term, disequilibrium, and nonlinear effects. There is evidence for adaptive expectations and misperceptions of feedback in energy forecasting and resource estimation (Sterman 1988; Sterman 1988).

In the standard scenario, the FREE model assumes that the opportunity cost of current use (the loss of future use and contribution to increased extraction costs) is unrecovered, because resource managers do not have a correct and complete model for valuation. Oil and gas are priced on the basis of costs of discovery, development, and production of the resource. Much of the harm from depletion actually arises from the difficult period of transition away from oil and gas, rather than from the long-run effects of losing the services of those fuels.

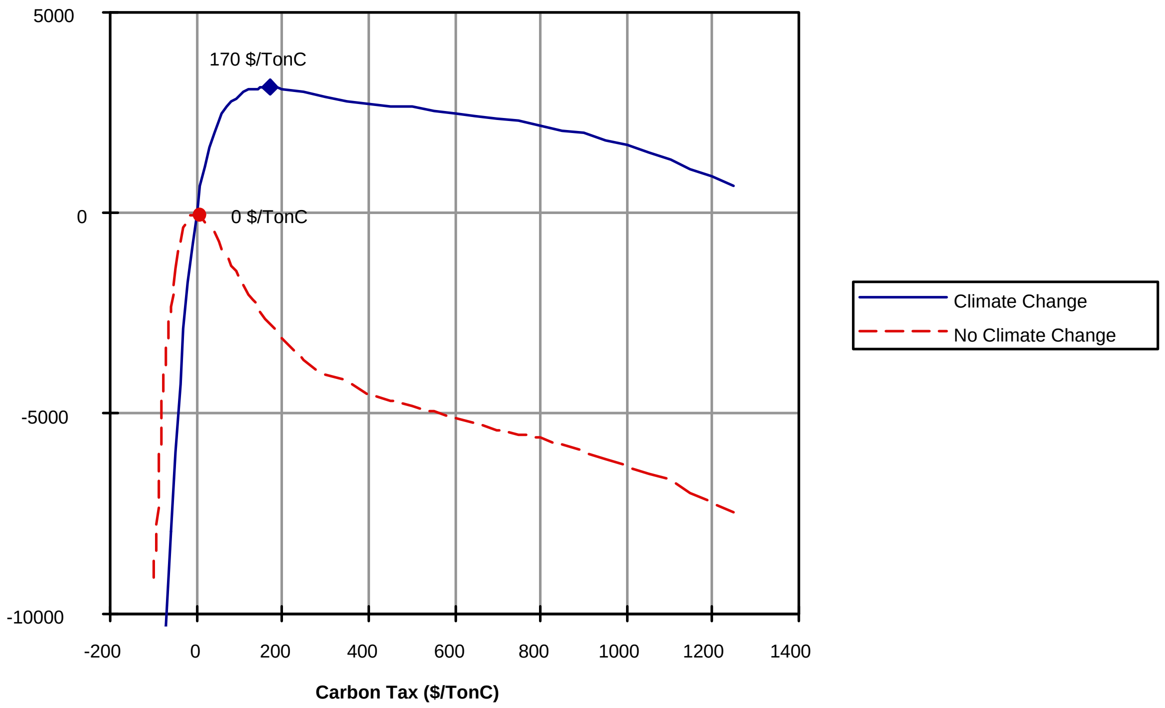
Depletion leads to subobtimal capacity utilization in the goods producing sector, because energy prices are far from the levels for which the capital stock was designed. In extreme scenarios, when depletion suddenly becomes severe, a near-shutdown of the economy is possible. With greater foresight, this can be avoided, as new capital can be installed with embodied energy requirements that anticipate higher future energy prices. Some foresight is already present in the model, as decision makers extrapolate current energy prices when making capital investment decisions.

Adding a depletion tax on oil and gas further improves economic performance. The depletion tax increases oil and gas prices earlier in the simulation, slowing depletion and leading to prices that are ultimately lower. This eases the shock of the transition from oil and gas to coal and renewables, and preserves a greater portion of the oil and gas resource for critical applications later in the simulation period.

With the depletion tax in place, the optimal carbon tax now reflects mainly climate change considerations, and is much lower. With no climate change, the optimal tax is zero, as one would expect if energy were already properly utilized in the economy (see Figure 6). With climate change, the optimal tax is about 170 $/TonC, still substantially larger than the tax suggested by most other studies.

One other feature to notice in Figure 6 is that the payoff to different carbon taxes is quite asymmetric around the optimum. Negative carbon taxes cause energy prices to approach zero, leading to extremely high energy consumption. This causes direct welfare losses from inefficient resource allocation and greatly increases CO_2 emissions, eventually leading to high climate damages as well. Above the optimal carbon tax, welfare diminishes much more slowly than below it, because the benefits of reduced climate change partially offset the losses from excessive abatement efforts. This suggests that it may not be too costly to err on the side of caution.

Figure 6: Welfare Implications of a Constant Tax, with Depletion Tax



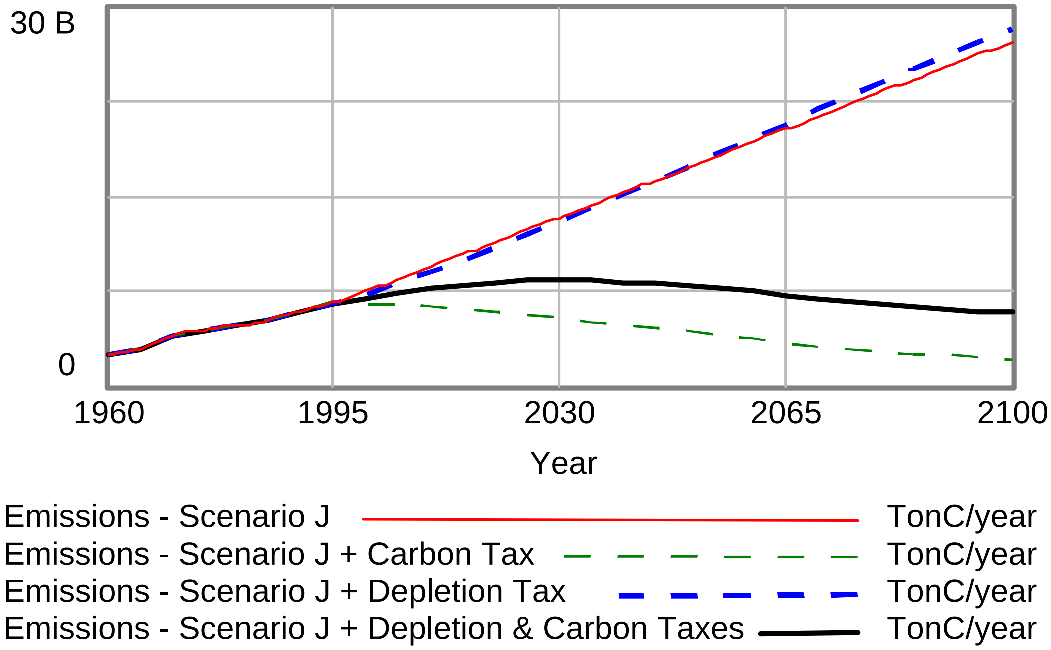
Compare with Figure 5. Note that there are no longer multiple optima for the no-climate-change case. The best tax with no climate change is zero, indicating that energy use is optimal with respect to factor allocation and depletion considerations. Taking climate change into account, the optimal tax is now much lower, as depletion is addressed separately.

Table 2: Effect of Optimal Carbon Tax, with and without Depletion Tax

	Price ($/GJ)			
	2000		2050	
	Coal	Oil/Gas	Coal	Oil/Gas
No Depletion Tax				
Producer Price	0.74	2.72	0.68	5.51
Depletion Tax	0.00	0.00	0.00	0.00
Carbon Tax (950 $/TonC)	5.20	3.60	21.98	15.22
Total Price	5.94	6.32	22.66	20.73
With Depletion Tax				
Producer Price	1.08	2.93	0.88	8.45
Depletion Tax	0.00	1.69	0.00	10.27
Carbon Tax (170 $/TonC)	.93	.64	3.93	2.72
Total Price	2.01	5.26	4.82	21.44

With a depletion tax in place, carbon taxes may be much lower. As a result, the price of coal is much lower than in the scenario with no recovery of depletion rents.

Figure 7: Effect of Carbon and Depletion Taxes on Emissions



Emissions shown are from energy only; nonenergy emissions, which are exogenous in the model, are omitted.

The depletion tax has an ambiguous effect on emissions (see Figure 7). In the uncontrolled cases (no carbon tax), emissions are nearly identical with and without the depletion tax. Substitution between oil / gas and coal compensates for the depletion tax. Improving the valuation of fossil fuel resources alone will not solve the climate problem. When a carbon tax is introduced, emissions are significantly higher with the depletion tax in place than without it. This is because the carbon tax must be excessively high in order to suppress depletion. In spite of the higher emissions (and therefore greater climate damages), the depletion tax improves welfare because the losses from abatement costs induced by the carbon tax are lower.

Lock-in

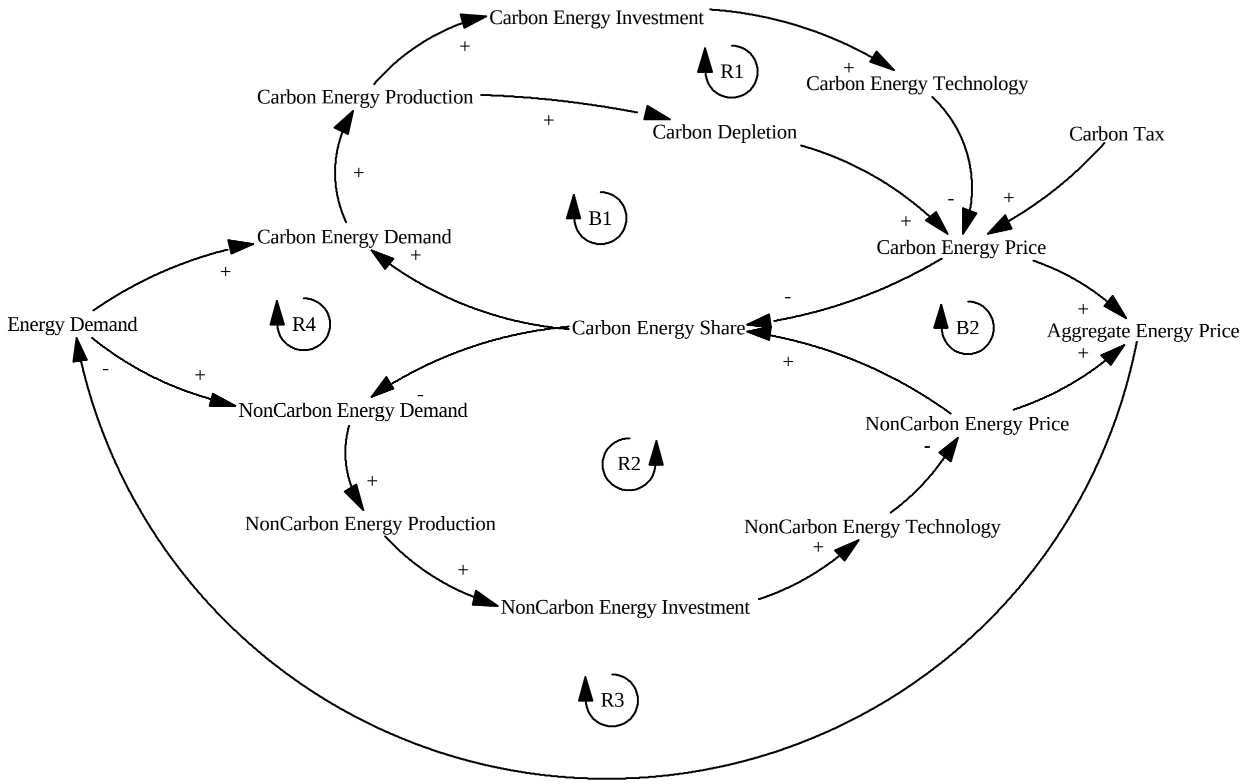
There are other interesting dynamic issues that affect the cost of abatement as well. One such issue is lock-in of dominant energy supply and end-use technologies. Lock-in arises when positive feedback reinforces the position of a dominant technology or firm (Arthur 1989). Principal among these positive loops are learning-by-doing, economies of scale, network or bandwagon effects, and the development of complementary infrastructure. In the energy system, this means that dominant technologies may have a self-sustaining advantage by virtue of size alone, even though they may be suboptimal in terms of their energy or carbon intensity. Fossil fuels appear cheaper than renewables in part because they are the dominant source, not because they are inherently superior.

In most models, technology in energy production and energy efficiency evolves autonomously, either as a constant exponential reduction in costs or by exogenous dates of penetration of new technologies. One implication of exogenous technology is that one should wait to reduce emissions until new technologies make it cheaper to do so. Another is that the required new technologies will materialize, whether or not any deliberate effort is undertaken to acquire them.

Some progress in energy technology is attributable to causes outside the energy sector; electric power plants benefit from advances in materials science and computing, for example. But even this type of externally forced progress is not fully realized until it is embodied in particular products, requiring research and development and accumulation of experience in production and use. It is clear that technology for a non-carbon energy system will not become available without deliberate action.

Learning curves are one established way of representing technical progress endogenously, at both the firm and aggregate level (Arrow 1962; Argote and Epple 1990). Learning curves have been estimated for many industries, including some parts of the energy sector. The learning rate used in FREE, 20% per doubling of experience, is identical for all energy sources. This rate is typical of those reported for the thermal efficiency of coal electricity generation, nuclear electricity construction costs, and some renewables (Cantor and Hewlett 1988; Sharp and Price 1990; Christiansson 1995; Messner 1996).

Figure 8: Reinforcing Loops Introduced by Learning Curve



The key loops added to the model are R1 and R2, which represent the learning curve effect. Associated with these are R3 and R4, which represent increasing energy demand with falling prices, but these loops are dominated by the impact of efficiency technology. Loops B1 and B2 represent the effects of rising prices from depletion of fossil fuels on the market share of carbon energy sources and on overall energy demand. Two energy sources are shown here for simplicity, though the model includes four. In conventional models, only loops B1 and B2 are present.

Learning is one of several mechanisms that make the energy system path dependent and subject to lock-in. There is no guarantee that the locked-in path of the energy system is globally optimal. To test the importance of lock-in effects for climate policy, it is useful to compare the learning-curve technology in the standard run of the model with autonomous technological progress.

For this test, the technological trajectory from the uncontrolled case (zero carbon tax) in the learning curve version of the model is used as an exogenous driver in the autonomous technology case. If there is no tax intervention, the two simulations will have identical technological histories. In the autonomous case, loops R1, R2, R3, and R4 in Figure 8 are effectively switched off and replaced by the exogenous technology forecast. The omission of these feedback loops has serious implications for model behavior.

Figure 9: Energy Technology—Learning Curve vs. Autonomous

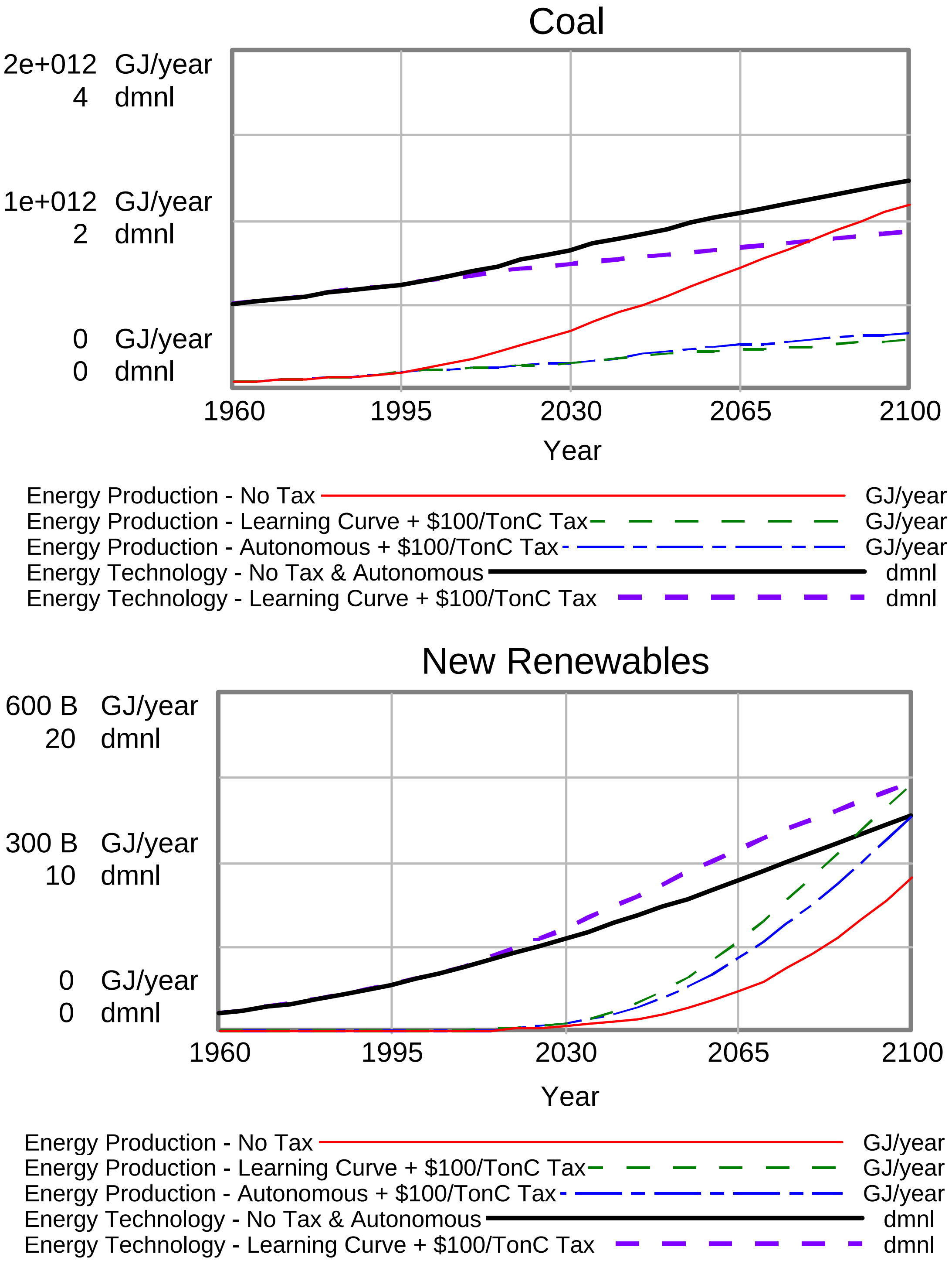


Figure 9 compares the response of learning curve and autonomous technology to a 100 $/TonC carbon tax implemented in 1995. With endogenous (learning curve) technology, the response to the tax is greater. The carbon tax raises coal prices significantly, which directly contributes to reduced coal production and increased use of new renewables. Because production rates change, investment shifts from carbon fuels to noncarbon fuels. When technology is endogenous, the change in investment patterns leads to reduced technological improvement for coal (compared to the no-tax and autonomous cases) and more rapid technological improvement for renewables. The change in technology has a small impact on coal production, as the carbon tax overwhelms any reduction in coal production costs from technological improvement. Production of new renewables is significantly accelerated over the no-tax and autonomous cases.

Because the energy system is more resistant to intervention with autonomous technology, the optimal tax is lower than when a learning curve is active. The energy system is less responsive to the carbon tax when technology is autonomous, so that the short-run losses from abating emissions weigh more heavily in the balance of costs and benefits.

Table 3: Impact of Technology Specification

	Optimal Carbon Tax $/TonC	Emissions in 2100 TonC/year	Emissions Reduction %
Uncontrolled	-	28.3	0
Learning Curve - Controlled	170	5.8	79
Autonomous - Controlled	118	9.2	67

Optimal taxes listed are constant (see notes to Figure 5). The depletion tax from the previous section is applied prior to the carbon tax, so the taxes here reflect the effects of climate change and technology specification, and not depletion.

The differences shown in Figure 9 and Table 3 are important, and could be even greater in reality. The strength of the reinforcing feedback loops introduced by an endogenous specification of technology is the key determinant of the importance of lock-in. In the FREE model, the strength of these loops depends on two factors: the slope of the learning curve and the elasticity of substitution among energy sources. The slope of the learning curve effect (i.e. the reduction in costs for an additional increment of experience) could be stronger, though not by a large margin.

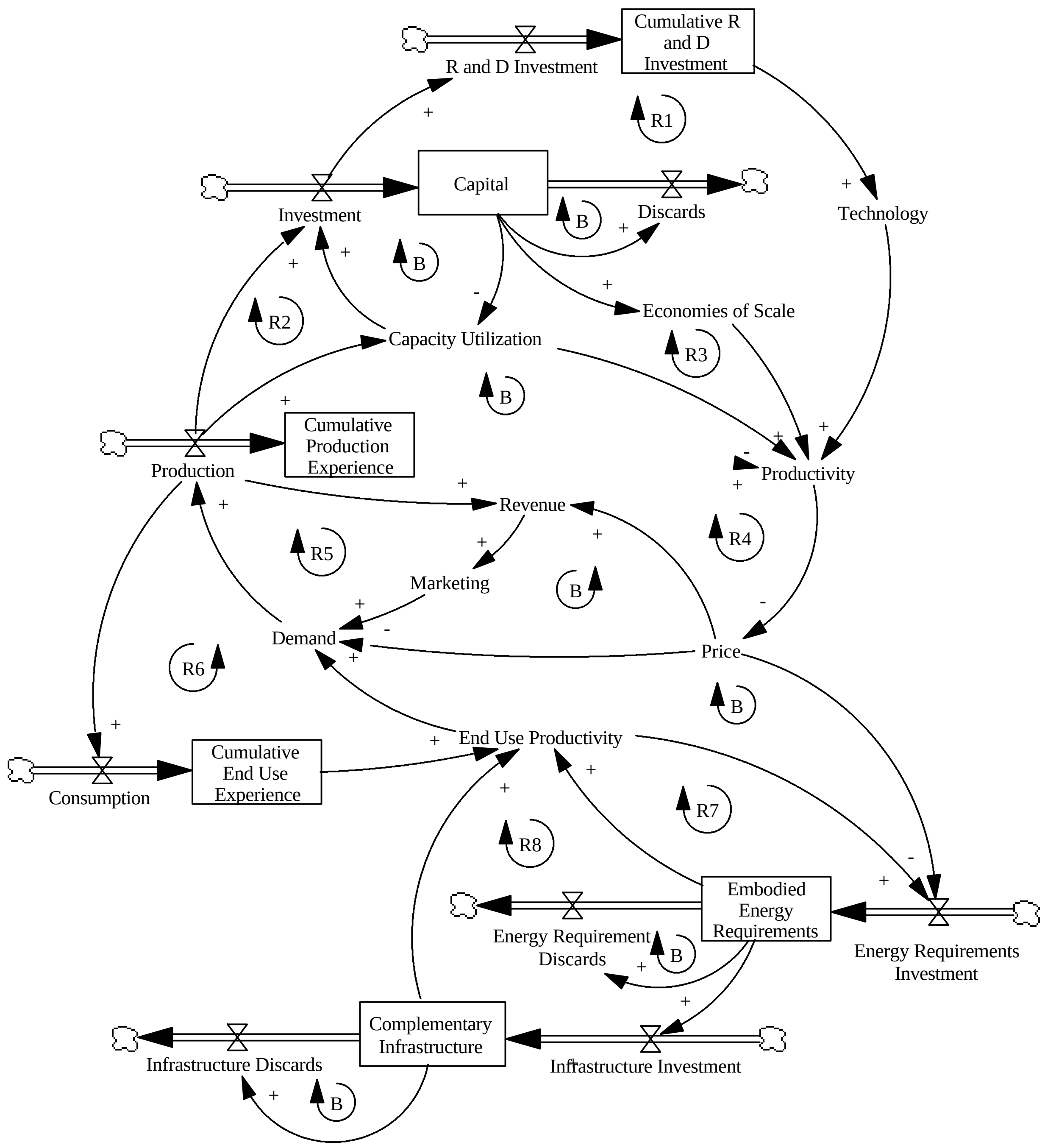
However, learning is not the only effect leading to reinforcing feedback in the energy system; a variety of positive feedback effects may contribute to lock-in. Figure 10 shows several mechanisms for a single representative energy source. Research and development investment improves technology, increasing demand, and generating further R&D investment (R1). Investment in energy producing capital improves productivity by lowering pressure from capacity utilization (R2, largely offset by other loops not shown) and by promoting economies of scale (R3). Accumulation of production experience also contributes to learning, reducing costs and creating further demand for production (R4). Revenue from energy sales may be reinvested in marketing (or similarly, in political influence), generating further sales (R5).

Positive feedback effects are not confined to the production side. Accumulation of end-use experience with a particular source increases its utility (R6). Increasing embodied energy requirements generate economies of scale and network effects, which further augment end-use productivity, increasing the energy intensity of new investment (R7). Complementary infrastructure in distribution and end-use builds up around the existing energy requirements, further reinforcing the current energy mix (R8).

The strength of many of the reinforcing loops in Figure 10 depends on the relationship between energy prices and demand. While the long-run elasticity of substitution among energy sources is relatively high (2) in the FREE model, the effective short-run elasticity is low. A 10% reduction in cost from improved technology implies a 20% increase in demand in the long run, a powerful reinforcing effect. But in the short run, only 2-5% of this increase is realized, dramatically reducing the gains from learning. While this is realistic for the competition among energy sources at the global aggregate level, it is unrealistic for narrower markets. If the model were more disaggregated, learning effects would play a more important role in competition among highly substitutable energy products.

This suggests that a micro-level perspective is necessary to really understand the impact of lock-in effects. To date, there are no evolutionary models for climate policy analysis, but they may be needed. The search for effective climate change or energy efficiency policies may do better to focus at a low level of aggregation, identifying areas in which a small initial push is reinforced by positive feedback. In the long run, it may be possible to relax emissions controls in a path-dependent energy system, as new technologies establish sustained advantages. In addition, it would be useful to identify ways in which technological progress could be decoupled from the slow accumulation of experience, in order to increase the flexibility of the energy system.

Figure 10: Reinforcing Loops Contributing to Lock-in



The diagram above is somewhat stylized; the details of investment decisions are omitted to more clearly portray the reinforcing loops (labeled R#), for example.

Conclusions

The conventional wisdom from simple integrated models like DICE or Connecticut/YOHE is that abatement efforts in the near term should be limited, with modest carbon taxes on the order of 10-50 $/TonC (Nordhaus 1994; Yohe and Wallace 1996). This conclusion rests on an assessment of the tradeoffs between near-term abatement costs and long-term benefits from reduced climate damages. The FREE model facilitates exploration of a number of assumptions that influence the recommendation of limited abatement effort.

The FREE model can be parameterized to behave much like the DICE model (Scenario A, Table 4). In this case, the optimal carbon tax is 15 $/TonC, a level that causes small increases in energy prices. Yet in the standard model run, Scenario J, the optimal tax is 950 $/TonC, a very high tax with strong effects on the energy-economy system. 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 4: Contrasting Scenario Assumptions

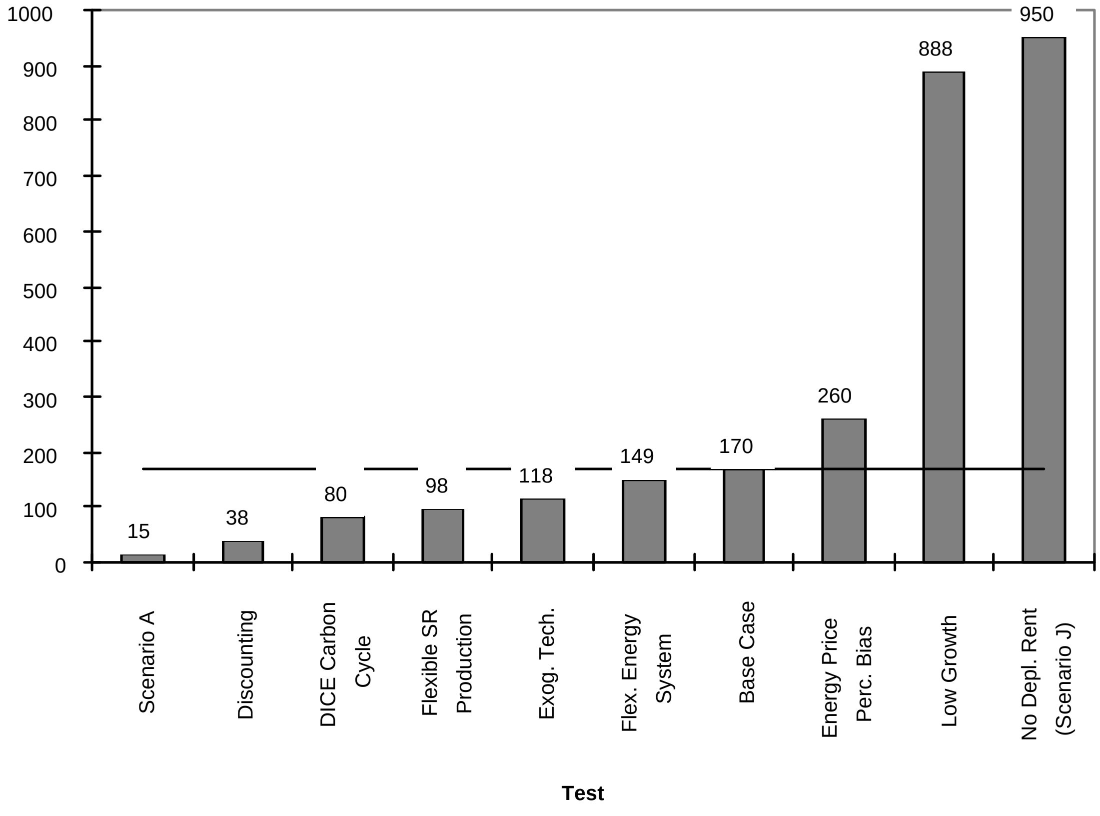
	Scenario A (DICE-like)	**Scenario J (Standard Run)**
Factor productivity growth	Asymptotically zero, so that economic growth eventually stops.	Always greater than zero; growth slows but does not stop.
Production structure	Putty-putty, with low to moderate capital-energy and inter-energy substitution 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 technology	Static.	Learning curve.
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.

Scenario A is much like the DICE model. Scenario J incorporates a more complex production structure, behavioral dynamics, depletion, endogenous technology, and a realistic carbon cycle.

Because these assumptions interact in a highly nonlinear fashion, there is no definitive way to attribute the changes between Scenario A and Scenario J to any particular parameter change. Figure 11 compares the relative impacts of the major differences between the two scenarios by applying them singly to a base run. The base case, in which the optimal tax is 170 $/TonC, is Scenario J with a depletion tax added to prevent depletion dynamics from obscuring other effects. In this scenario, the carbon tax more than quadruples the price of coal, and the depletion tax more than doubles the price of oil and gas.

One major difference between the two scenarios is the discounting method used to evaluate social welfare. In Scenario A (and in most integrated models), the welfare of future generations is discounted simply because they are remote from us in time. In Scenario J, the welfare of future generations may be discounted because they grow wealthier, but not for pure time preference. Discounting for time preference, as in Scenario A, leads to diminished concern for the future implications of climate change, and causes the optimal tax to differ by more than a factor of four.

Figure 11: Summary of Model Tests



Columns indicate the optimal constant carbon tax level for each test. Taxes are implemented gradually (with a 20 year time constant) beginning in 1995.

The choice of discounting method is essentially ethical, and most models can support a variety of perspectives through simple parameter changes. Other differences between models are structural, and thus more resistant to experimentation. The carbon cycle is one such subsystem. Carbon cycles in integrated models tend to make unwarranted assumptions of linearity, which are particularly important when scenarios generate high emissions trajectories. The optimal tax using the FREE carbon cycle, which includes nonlinearities and sink constraints in the uptake of carbon, is more than twice that found using the DICE carbon cycle.

Another important dynamic issue is the flexibility of adjustment in the economy. In Scenario A, and most integrated models, a variety of structures that lead to disequilibrium of the economy are omitted. As a consequence, the response to carbon taxes is rapid. The FREE model, 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 $/TonC to 98 $/TonC. In both cases, increasing flexibility results in lower taxes because the effort required to achieve a given level of emissions reduction falls while the benefits of emissions reductions remain relatively constant.

The major implication of constraints to adjustment is not really apparent from the search for optimal deterministic carbon taxes. It arises instead under uncertainty about future climate conditions. To prepare for worst-case scenarios, it may be necessary to begin acting now, because adjustment constraints reduce the ability to respond rapidly to new information.

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. This creates path-dependence and the opportunity for lock-in of dominant carbon-based energy sources. Ignoring learning by using exogenous technology biases the optimal carbon tax downward by roughly 30% (see also Table 3). Consideration of other mechanisms that cause path dependency, like network effects and complementary infrastructure, could raise 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. Most models neglect these opportunities. One kind of free lunch, from the correction of energy price perception biases, can be tested in the FREE model. Even a modest bias (discounting energy prices by 20%) has substantial tax implications, raising the indicated tax 50% to 260 $/TonC. This suggests the importance of continued investigation of this avenue at a micro level, and of including the possibility of biases in the sensitivity analysis of aggregate models.

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 becomes more important to protect the welfare of future generations because they are not so wealthy. This conclusion interacts strongly with 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; Sala-i-Martin and Barro 1995).

Finally, if the intertemporal valuation of energy resources is flawed, as in the standard run of FREE, climate policy can have unpleasant interactions with resource depletion. A carbon tax can actually accelerate the negative consequences of depletion brought on by undervaluation of oil and gas resources. This suggests that the current enthusiasm to use gas as a low-carbon energy source should be regarded with some caution. A carbon tax (and probably most other instruments suggested for addressing climate issues) may perform very poorly if they are also required to compensate for depletion.

Recommendations for Future Research

The FREE model identifies a number of feedback structures that have profound effects on climate policy recommendations. It is important that these structures be further investigated by other integrated modeling efforts in order to ensure that their importance is not formulation-specific. 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.

Before expanding the scope of integrated modeling, a number of simple improvements to modeling practices should be made. There are several common errors in the representation of dynamics that could easily be avoided by more widespread adoption of continuous time simulation, use of dimensional consistency as a formal check on model structure, verification of model robustness, and abandonment of discrete logic in many formulations. To a great 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, without particular attention to a single measure of performance like cumulative discounted utility.

The FREE model occupies an important niche among integrated models. It has a feedback structure that is rich enough to provide a realistic picture of the economy and to generate surprising behavior, yet it is computationally tractable enough to allow replication of the extensive optimization and uncertainty analyses that have been performed mainly on very simple models to date. The sensitivity and uncertainty analyses presented in this work are particularly deserving of extension.

Several model structures would benefit from extension as well. It would be useful to distinguish primary energy sources from end-use energy carriers and to explicitly represent capital stocks in energy conversion. This would allow a more realistic representation of substitution potentials, complementary infrastructure, learning, and network effects.

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.

At the time of model conceptualization, the depletion issue was not expected to be as dramatic as it later proved to be. The depletion issue needs to be reexamined. A central part of this effort should be the development of a resource valuation process founded on observations of real behavior rather than on principles of optimal control.

If even one or two 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 policy makers are concerned with the welfare of future generations. In this case, aggressive, immediate action is warranted to avoid climate change.

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