Feedback Complexity in Integrated Climate-Economy Models

by

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Abstract

Assessing the economic and ecological impacts of climate change induced by human activity has become a major activity with a substantial modeling community. More than 20 climate-economy models have been developed to address different policy questions. While these integrated models are quite varied, most share some common assumptions and features. They typically employ a nested structure of neoclassical production functions to represent the energy-economy system. Technological potential is represented by elasticities of substitution, exogenous rates of technological improvement, and backstop energy prices. Factor allocation is myopically or intertemporally optimal. The impact of a carbon tax on the energy system at a given time can often be reduced to a simple tradeoff between abatement costs and emissions (though capital stock rigidities complicate the short-run picture in some models). The major endogenous dynamics of these models involve capital accumulation, atmospheric concentrations of greenhouse gases, and the temperature of the atmosphere and ocean system.

These models 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. System dynamics models of that period shared the same motivation, but sought alternatives to the assumptions of optimization and equilibrium. They focused instead on disequilibrium dynamics and feedback complexity, with behavioral decision rules and explicit stocks and flows of capital, labor, and money.

This research builds on earlier system dynamics models of energy economy interactions, creating a model that tests the implications of a number of feedback processes that have not been explored in the climate change context. Among these are endogenous technological change and boundedly rational decision making, with perception delays and biases. 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. To enhance the link between this research and other studies, the model is constructed so that an appropriate parameterization will recover the neoclassical case found in models like Nordhaus' DICE (1994).

The principal purpose of the model is to identify the structural features that have the greatest implications for policy, and thus are worthy of further pursuit. 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 creates 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. In both deterministic and uncertain cases, near-term inaction is a poor policy.

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The climate change issue would not have caught my attention if not for the many pleasant months I spent working with Bert de Vries. In the course of our efforts to blend neoclassical economics and the World3 model, Bert introduced me to most of what I now know about energy and resource policy. We spent many hours struggling over formulations together, and more importantly wondering about the meaning of it all.

John Sterman provided the seed for this research four years ago by handing me a metaphorical hatchet and a copy of Nordhaus' first publication on the DICE model. I am grateful for his continued interest in and support of my work, even when it was completely orthogonal to his normal research activities. John deeply cares about the issues addressed in this thesis, and his enthusiasm for doing the job right helped to keep me energized.

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My family and friends helped to maintain my sanity as well. They believed in me in whatever I chose to pursue, set great examples of integrity, curiosity, and hard work, and always knew when it was time to have fun. I hope this work in some small way helps to make a better world for their grandchildren.

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Introduction

> *"If the building blocks are so shabby, is it worthwhile building integrated models at all? The answer is clearly yes, despite the present weaknesses of the models. The reason is that modeling forces us to reveal our assumptions and changing those assumptions shows how important they are with respect to the outcome."*
>
> *(Toth, 1995)*

This dissertation documents and 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.

Technological Change

One effect that is consistently excluded from integrated models is the endogenous evolution of energy technology through deliberate research and development and the accumulation of production experience. This creates a positive feedback loop. Production of a new energy source generates experience, which contributes to cost reducing technical improvements. As costs fall, demand for the new energy source rises, leading to greater production and accumulation of experience.

Several common objections to the inclusion of endogenous technology are technical. Growth theory and energy system modeling have a strong orientation toward optimization. Endogenous technology introduces the possibility of multiple optima, making models analytically intractable and making identification of optimal decisions more difficult. Models with endogenous technological change appeal to an additional, unobservable state variable and thus obtain greater realism at the expense of statistical tractability as well. However, it is misleading to describe technology as an unobservable; it might better be termed an "unobserved" variable. Many indicators of technology, like R&D expenditures or thermal power station efficiencies, are directly observed, but, with a few exceptions (Watanabe 1995; Messner 1996), have yet to be integrated into a macro-level framework.

Because the evolution of technology is not well integrated into economic theory, existing models instead treat technology as an autonomous trend influencing energy efficiency or production costs, omitting the positive feedback loop from learning. To compensate for this omission, modelers perform sensitivity simulations across a range of technology forecasts. This leads to an understatement of the response of the model to policy interventions like a carbon tax. A more productive approach is to implement and test alternative causal theories of the evolution of technology. One such theory—learning curves—is explored in this work.

Adjustment Constraints

Just as the focus on optimization has excluded endogenous technological progress, it also excludes the need for and possibility of incorporating other forms of dynamic complexity, such as delays in the perception of market conditions or the construction of new capital, which are often regarded as "bells and whistles" (Nordhaus 1992). For the most part, integrated models have flexible short run production structures, and the costs of reducing greenhouse gas emissions represented neglect adjustment constraints (Nordhaus 1994; Grubb, Chapuis et al. 1995).

A few integrated models already incorporate some key structures, such as a putty-clay production structure with capital vintaging (Yang, Eckaus et al. 1996). However, these models still assume instantaneous equilibration of the economy. This implies that delays in capital construction, labor mobility, acquisition of financing, and changing the energy intensity of new capital have zero duration. By contrast, system dynamics models of energy economy interactions typically incorporate the structures that create these delays (Sterman 1981). The FREE model, while it neglects labor and money flows, does incorporate delays in capital construction and adjusting the energy intensity of new capital.

Behavioral Decision Making

Adjustment constraints and endogenous technology increase the complexity of the problems markets and agents would have to surmount to achieve optimality, reducing the plausibility of optimization as a behavioral assumption. One way out of this dilemma is to assume that agents have high discount rates or limited horizons, so that their ability to solve intertemporal problems is not so implausible. However, this approach in turn introduces new problems with ethics and equity.

According to Silverberg & Verspagen,

> *"the rejection of fully optimizing behavior as an explanation of economic activity does not single out any precise alternative as a theory of boundedly rational behavior. It is probably for this reason—the absence of an operationalizable alternative based on 'first principles'—that economists continue to cling so tenaciously to the standard paradigm." (Silverberg and Verspagen 1994)*

Of course, this becomes in part a self-fulfilling prophesy. The assumption of optimization appears more attractive than competing alternatives in part because its dominance ensures that it is better articulated and accumulates a larger body of work (Sterman 1985).

In fact there are well-tested alternatives to the assumption of optimization. Decisions in the FREE model adhere to a set of principles advanced in the system dynamics literature:

- *Stocks and flows must be explicitly represented.*
- *Desired states (goals) and actual states must be distinguished.*
- *Only information actually available to decisionmakers should be used.*
- *The policy structure for achieving the desired states in the system should correspond to managerial practice.*
- *The model should be robust under extreme conditions.*

(Senge 1978)

Decisions makers in the model behave in an intendedly rational fashion, using heuristics of anchoring and adjustment, adaptive expectations, trend extrapolation, and gradient search or hill-climbing in order to improve economic performance (Forrester 1961; Simon 1979; Sterman 1980).

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. 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, described in the conclusions to the Feedback Structure in Integrated Models chapter.

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. These are explored in the Policy Analysis chapter of this document. 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.

Feedback Structure in Integrated Models

This chapter reviews six climate-economy and energy-economy models, with particular attention to simulation methods and feedback structure. These models address a disparate set of questions about climate change, but share many common features. All represent the economic driving forces of emissions and the tradeoffs between emissions and abatement costs. Most also include climate change impacts. While the models on the whole are very different, there are many similarities in the representation of individual subsystems. The FREE model is included in a portion of the comparison, and is described in detail in the following chapters of this document. For a detailed overview of many integrated models, see Parson and Fisher-Vanden (1995).

Prior model comparisons have focused on regional and sectoral aggregation and conspicuous parametric assumptions like energy conservation or substitution potential and rates of autonomous energy efficiency improvement (Beaver 1993; Dowlatabadi 1995). In models of similar structure, information about parameter choices provides a very economical way to interpret variations in model conclusions. However, the structural differences among the models are more important than the parametric differences. Since feedback structure determines the sensitivity of a model to particular parameters, this review instead attempts to inventory some of the underlying feedback structures in order to assess their similarity across models.

Table 1: Model Purposes

Model	Purpose	References
DICE	Identification of optimal emissions reduction trajectories, valuation of information, and policy evaluation under uncertainty.	(Nordhaus 1992; Nordhaus 1992; Nordhaus 1994)
Connecticut/ YOHE	"... to investigate the relative merits of hedging over the near term against the chance that atmospheric concentrations of carbon dioxide will be limited as a matter of global policy." (Yohe and Wallace 1996)	(Nordhaus and Yohe 1983; Yohe and Wallace 1996)
TIME	Generation and evaluation of energy sector scenarios.	(de Vries 1995; de Vries and van den Wijngaart 1995; de Vries and Janssen 1996)
Hatlebakk/ Moxnes	Basis for a simulation game investigating misperceptions of feedback in climate change policy.	(Hatlebakk and Moxnes 1992)
ICAM 2.1R	Assessment of uncertainty, including implications for different regions and interest groups .	(Dowlatabadi 1993; Dowlatabadi and Ball 1994)
NICE	Critique and extension of DICE.	(Fiddaman 1995; Fiddaman 1996)
FREE	Investigation of implications of bounded rationality, embodied energy requirements, depletion, and endogenous energy technology.	(this document)

For purposes of this comparison, it was useful to represent each of the models in a common simulation language. Vensim was chosen for its flexibility in representation of continuous or discrete time, graphical interface, and ability to perform causal tracing, optimization, and sensitivity analysis (Ventana Systems 1994). Three of the models (DICE, Connecticut/YOHE, and Hatlebakk/Moxnes) were replicated manually in Vensim from published differential equations, with some assistance from the authors in the case of Connecticut/YOHE and Hatlebakk/Moxnes. The TIME model was obtained in STELLA/ithink format (High Performance Systems 1996) and translated by software to Vensim. ICAM was obtained in DEMOS (Maxwell 1996) and partially translated to Vensim by a mix of software and manual labor. The NICE and FREE models were created by the author in Vensim.

Table 2: Implementation Notes

Model	Language	Sources	Replication of Output
DICE	Vensim	Published equations and GAMS code (Brooke, Kendrick et al. 1988)	Exact
Connecticut/ YOHE	Vensim	Published equations and correspondence with author	Imperfect (revisions pending)
TIME	Vensim (translated by software)	Draft model provided by H.J.M. de Vries	Exact
Hatlebakk/ Moxnes	Vensim	Published equations and correspondence with authors	Exact in deterministic case (omits stochastic elements)
ICAM 2.1R	Vensim (translated by software)	ICAM 2.1r code in DEMOS	Suitable for causal tracing only
NICE	Vensim	Original model	Exact
FREE	Vensim	Original model	Exact

Simulation Method

All of the models considered are treated with numerical methods. While it is possible to gain some insight from analytical models similar to DICE (see for example Chao 1995), in general integrated models are too complex to yield closed-form solutions. Simulation attributes for each of the models are summarized in Table 3.

Each of the models has a nominal time horizon from the present to roughly 2100, though Hatlebakk/Moxnes, DICE, NICE, and FREE are simulated for longer periods (typically 400 years) for optimization purposes. The TIME model stands out for its exceptionally long historical period, 1900 to the present, over which it endogenously generates many observed behaviors of the energy system.

The DICE, Connecticut/YOHE, and ICAM models are simulated in discrete time, while TIME, Hatlebakk/Moxnes, NICE, and FREE run in continuous time. In principle, there is no difference between a discrete time simulation and a continuous simulation using the same solution interval and Euler integration. However, the choice of discrete time has potentially troublesome practical implications. Stock and flow relationships are obscured. One-period delays are implicitly infinite-order, which may lead to unrealistic oscillation and instability. Parameter values have embedded time units, so it is difficult to change the time interval after the model has been implemented. Continuous time models are also subject to several implementation problems. These difficulties may lead to errors with serious policy implications, so the implementation of both types of models is closely scrutinized.

Table 3: Simulation Characteristics

Model	Type	Time	Horizon	Interval	Original Language
DICE	intertemporal optimization	discrete	1965-2100*	10 years	GAMS
Connecticut/ YOHE	myopic optimization	discrete	1975-2100*	5-10 years	SuperCalc
TIME	deterministic simulation	continuous	1900-2100	< 1 year (Euler integration)	STELLA/ithink
Hatlebakk/ Moxnes	stochastic simulation	continuous	100+ years	< 1 year (Euler integration)	STELLA/ithink
ICAM 2.1R	stochastic simulation	discrete	1975-2100	5 years	DEMOS
NICE	deterministic simulation	continuous	1965-2100*	< 5 years (Euler integration)	Vensim
FREE	deterministic simulation	continuous	1960-2100*	.125 year (Euler integration)	Vensim

*Simulated over a longer period for optimization purposes.

Discrete Time Models

In the DICE model, discrete time is apparently chosen mainly because the simulation language, GAMS, is rooted in discrete time. Since most time constants in the model (roughly 50 years for population growth, 120 years for CO_2 storage, and 50 years for ocean/atmosphere heat transfer) are long with respect to the 10-year time period, the discrete representation is a good approximation of the continuous case. However, for the capital stock, with a lifetime of 10 years, this is not so. Because the model is simulated with a time step of 10 years, Nordhaus corrects the capital life to account for compounding, using instead a fractional depreciation rate of 65% per decade. This is what one would expect if depreciation were the only factor influencing capital, in which case Eq. 1 may be compounded to yield Eq. 2:

$$K(t+1) = K(t) - \delta * K(t) = (1-\delta) * K(t) \qquad \text{Eq. 1}$$

$$K(t+n) = (1-\delta)^n * K(t) \qquad \text{Eq. 2}$$

K = capital *δ = depreciation rate*

If δ = 10% per year and n = 10 years, K(t+10) = .35*K(t). However, in the model capital has an inflow of investment as well as an outflow of depreciation, and the two may not be compounded in isolation from one another. Accounting for investment,

$$K(t+1) = I(t) + (1-\delta)*K(t) \qquad \text{Eq. 3}$$

I = *investment*

Nordhaus assumes that Eq. 3 may be translated to Eq. 4—a false assumption unless I(t) = 0, which is not the case:

$$K(t+n) = nI(t) + (1-\delta)^n *K(t) \qquad \text{Eq. 4}$$

The appropriate way to correct for compounding in this case would be to use a shorter time interval. Nordhaus' correction yields an effective lifetime of capital of 15.38 years, not 10 years. Fortunately in this case, this is still a reasonable value, and their are no negative implications for policy judgments made with the model.

Another thing to notice about Eq. 3 is that, for consistency, K and I must have the same units ($) and δ must be dimensionless. Investment thus represents the accumulation of investment over the 10-year time interval. Similarly, δ represents the product of the fractional depreciation rate (1/year) and the time interval (years). This obscures the fact that capital is a stock with units of $ that accumulates the flows of investment and depreciation, which have units of $/year, and requires the parameter δ to be changed if the time interval changes. This makes it difficult to verify the numerical accuracy of the simulation by varying the time period.

Nordhaus' equation can be restated in continuous time using either differential or integral notation:

$$dK/_{dt} = I(t) - \delta*K(t) \qquad \text{Eq. 5}$$

$$K(t) = \int(I(t) - \delta*K(t))dt \qquad \text{Eq. 6}$$

In Eq. 5 and Eq. 6, K has units of $, I has units of $/year, and δ has units of 1/year. This makes the stock-flow distinction explicit and allows the solution interval to be changed without adjusting δ.

The Connecticut/YOHE model is similar to DICE, in that it is essentially a continuous time model expressed in discrete terms. Connecticut/YOHE shares the stock-flow and dimensional consistency issues of DICE (compare Eq. 9 and Eq. 3). In addition, a discrete delay in factor allocation introduces an additional problem.

Output in a given period is a function of technology, climate damages, capital, labor, and energy (Eq. 7). The capital input adjusts so that the marginal product of capital and the capital cost ($r + \delta$) are equal (Eq. 8). Investment occurs at the rate necessary to replace depreciation and augment the previous period's capital stock to the currently indicated level (Eq. 9).

$$Y(t) = A\,\Omega(t)\,K(t)^{\gamma}\left(L(t)^{d(t)}\,E(t)^{(1-d(t))}\right)^{(1-\gamma)} \qquad \text{Eq. 7}$$

$$K(t) = \frac{\gamma\, Y(t-1)}{r+\delta} \qquad \text{Eq. 8}$$

$$I(t) = K(t) - K(t-1) + \delta\, K(t-1) \qquad \text{Eq. 9}$$

Y = output
A = technology
Ω = climate effects
K = capital
I = investment

L = labor
E = energy
d = labor share
γ = capital share
δ = depreciation rate
r = interest rate

Notice in Eq. 8 that the optimal capital level depends on Y(t-1), not Y(t). This means that the capital input lags its true optimal value by one period. With a time period of 5 years and 3%/year growth in output, capital inputs will be about 15% below their optimal value. This is more obvious if one reformulates Eq. 8 and Eq. 9 in continuous terms:

$$K(t) = \frac{\gamma\, Y_p(t)}{r+\delta} \qquad \text{Eq. 10}$$

$$\frac{dY_p(t)}{dt} = \frac{Y(t) - Y_p(t)}{\tau} \qquad \text{Eq. 11}$$

$$\frac{dK_p(t)}{dt} = \frac{K(t) - K_p(t)}{\tau} \qquad \text{Eq. 12}$$

$$I(t) = \delta\, K(t) + \frac{K(t) - K_p(t)}{\tau} \qquad \text{Eq. 13}$$

Y = current output
Yp = previous output
K = current capital
Kp = previous capital

δ = depreciation rate
τ = time constant

In Eq. 10, the current indicated capital level is a function of a previous value of output, Y_p. Y_p adjusts to the current output with a time constant of τ, equal to the discrete time interval (Eq. 11). The previous value of capital, K_p, adjusts in a similar fashion (Eq. 12). Investment is now clearly a flow with units of $/year (Eq. 13). Note that in Eq. 11 and Eq. 12, the adjustment processes are first-order, while a truer representation of the discrete delay in Eq. 7-Eq. 9 would be provided by an infinite-order delay structure. High-order delays are generally unrealistic in highly aggregate models (Forrester 1961). Perhaps more importantly, the delay τ, which is concealed in the discrete time representation, has no clear behavioral or structural basis.

The lag in capital formation imposed by the discrete time formulation implies that an investment subsidy is necessary to restore efficiency. More importantly, the same treatment is applied to carbon and noncarbon energy inputs. Because carbon energy inputs lag their true optimal value by one time period, in the absence of depletion and climate damages, a *negative* carbon tax would help to restore efficiency by boosting carbon energy inputs closer to their true optimal level. Ceteris paribus, this biases the optimal tax level downward unrealistically. This is a very serious problem if the model is used to identify optimal carbon taxes. In Yohe's investigation of the cost of meeting carbon constraints under uncertainty, this biases the results in favor of preparing for higher carbon constraints by taking less action at present.

There are three ways to resolve this problem. One is to shorten the discrete time interval (equivalent to reducing τ in the continuous case) until the error is negligible. This is simple but slows simulations considerably. A more attractive solution would be to solve directly for the optimal capital level in Eq. 7, without using lagged output. If the production function were more complex, this might be impossible. In that case, extrapolation could be added to the continuous version of the system (Eq. 10-Eq. 13) in order to eliminate the steady state error involved in following the growth trend.

DEMOS, the language in which the ICAM model is implemented, is also fundamentally rooted in discrete time. Time is treated like an array subscript, so that it is possible to refer to values of variables at previous time periods. The lack of an explicit state variable construct requires additional caution on the part of the model builder in order to preserve stock-flow distinctions and ensure dimensional consistency. This is particularly important for the ICAM model, as it is much larger and more complex than DICE or Connecticut/YOHE. Identifying state variables for a translation of the ICAM model to continuous time is an arduous task.

The ICAM model provides an example of a correct but confusing treatment of a compounding problem. In ICAM, latitudinal mean temperature T(t) adjusts in response to radiative forcing R(t) according to:

$$T(t) = \alpha\, T(t-1) + \beta\, R(t) \qquad \text{Eq. 14}$$

T = *temperature*
R = *radiative forcing*

a = *fractional temperature adjustment rate*
b = *radiative forcing coefficient*

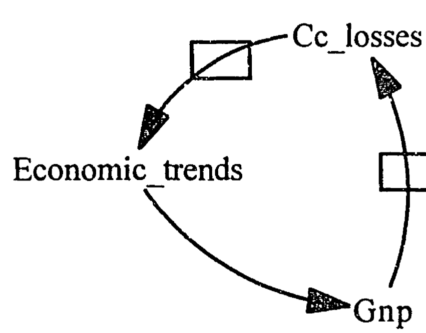
Because Eq. 14 is written for a 1-year time step, while ICAM uses a 5 year time step, Eq. 14 is adjusted for compounding and variation in R(t) over the interval to yield:

$$T(t) = \alpha^5\, T(t-5) + \beta\, R(t)\left(\frac{1-\alpha^5}{1-\alpha} - \frac{1}{5}\frac{\alpha\left(1-6\alpha^5+5\alpha^6\right)}{1-\alpha^2}\right) + \frac{1}{5}\frac{\beta\, R(t-5)\,\alpha\left(1-6\alpha^5+5\alpha^6\right)}{1-\alpha^2} \quad \text{Eq. 15}$$

While this equation is apparently correct, it is not at all transparent to model consumers. It would be far clearer to represent the model in continuous terms and use an appropriately short integration interval. This approach would also avoid the inconsistency of correcting for integration errors in some equations but not others.

Since the compounding correction is applied in only a few places in the model, all other time constants in the model are constrained to be longer than the 5-year time interval. While this is not a problem in principle, it appears that there are some feedback loops in the ICAM model which unrealistically cascade several discrete delays of identical length. An example is the climate damages feedback loop (Figure 1). This is a negative feedback loop, by which climate damages restrict output (GNP). It is unclear why there must be two discrete delays around this feedback loop, or why the delays would have identical five-year periods and infinite-order distributions.

Figure 1: ICAM Climate Damages and GNP

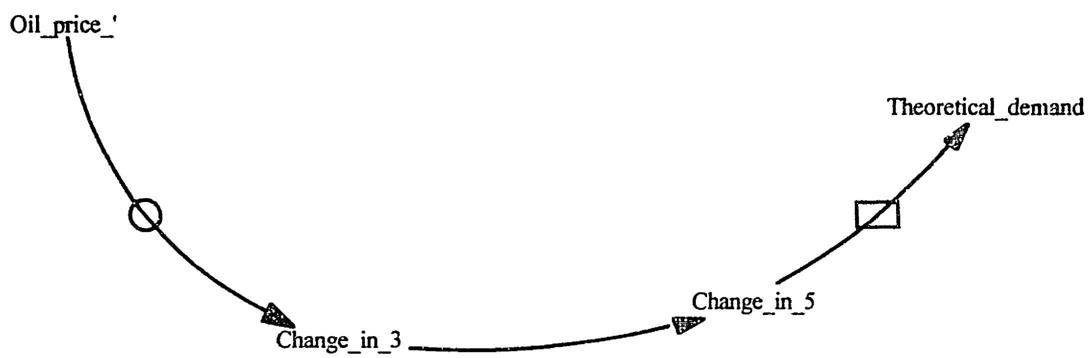



```
Gnp = ... IF_THEN_ELSE( Economic_trends/Un_region_pop<200, 200*Un_region_pop,
   Economic_trends))
   GNP; same as Economic Trends but with a lower limit.

Cc_losses = ...  Gnp[Time-1] * Bounded_ma
   Market Impacts of Climate Change

Economic_trends = ...  (Economic_trends[Time-1] - (Dead_weight_tax[Time-1] +
   Dead_weight_energy[Time-1] + Cc_losses[Time-1])) * Econ_pop_gr
   Indicated GNP
```

Inessential parts of the formulation have been omitted for clarity. See Notation section, page 35.

Another structure used several times in ICAM is a combination of a discrete derivative and integration (Figure 2). The first thing to notice about this structure is that there is no obvious way to map the variables onto state variables, because each employs a mix of current and delayed inputs.

Figure 2: ICAM Oil Demand Price Response




```
Change_in_3 = ... (oil_price-oil_price[Time-1])/oil_price[Time-1]
```

Fractional Change in Oil Price

```
Change_in_5 = ... Table(F_fuels1)(
   Change_in_1,Change_in_3,Change_in_4,Change_in_2)
```

Change in Fuel Prices

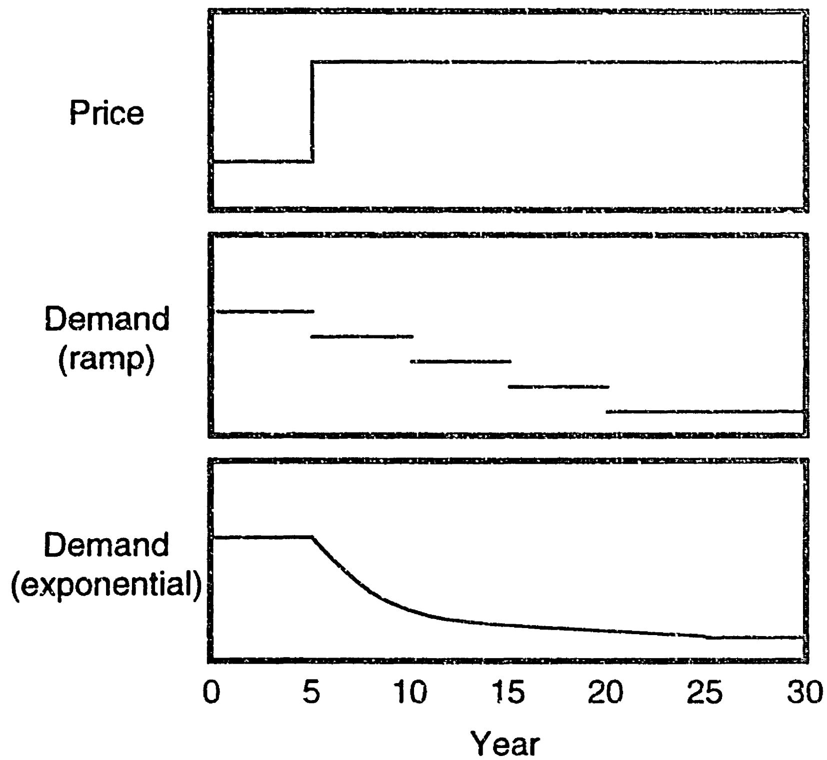
```
Theoretical_demand = ... Sum((F_lr_fuel_su*(((Change_in_5[Time-
   3]+Change_in_5[Time-2])+Change_in_5[Time-1])+Change_in_5)),F_fuels1)/4
```

Theoretical Demand Response

Inessential parts of the formulation have been omitted for clarity. See Notation section, page 35.

Change_in_3 computes the fractional rate of change of the oil price. Change_in_5 aggregates the oil and other fuel price changes to create a vector. Theoretical_demand then calculates the demand response to the price changes. Theoretical_demand responds to the price change with lags of 0, 1, 2, and 3 periods. This is essentially a partial adjustment process, in which the response to a price change is spread over time, rather than occurring instantaneously. The distribution of the response—a linear transition—is somewhat odd, though.

Figure 3: Adjustment to Price Changes



In ICAM, the demand response to a price increase (top) occurs in four equal-sized steps (middle). In continuous time, a more conventional and realistic distribution would be a first order exponential adjustment (bottom).

In the absence of information with which to estimate the delay order (Hamilton 1980), a more conventional and less cumbersome way to represent this effect, even in discrete time, would be a simple first-order adjustment process:

$$D^* = f(P) \qquad \text{Eq. 16}$$

$$dD/_{dt} = (D^*\text{-}D)/_{\tau} \qquad \text{Eq. 17}$$

D^* = *equilibrium demand*	P = *oil price*
D = *actual demand*	τ = *demand adjustment time*

In this case, demand decays exponentially to its new equilibrium level. This formulation of the price response has a more realistic distribution and is easier to understand.

Continuous Time

Continuous time models are also subject to several common problems and limitations. In general, the behavior of a continuous time model should be independent of the time interval and integration method used to simulate it. For accurate integration, the time interval of the simulation must be significantly shorter than the shortest time constant in the model. In models with oscillatory behavior, higher-order integration methods are necessary to prevent integration error from amplifying the oscillation. This precludes the use of discontinuous relationships (e.g. IF ... THEN logic) in the model. Fortunately, it is easy to verify the sensitivity of model results to the integration method by experimentation with reduced time steps and alternate integration algorithms. None of the continuous time models reviewed displays such sensitivity.

If a continuous time model contains dimensionally inconsistent equations, there may be hidden time constants. A typical example is found in the thermal electric generation capacity ordering process of the TIME model:

```
DesElCapOrd = MAX(0,(ExpReqElCap-ActPlusUCElCap)+ElCapDepr)
```
Eq. 18

DesElCapOrd = desired electric capacity order rate
ExpReqElCap = expected required electric capacity
ActPlusUCElCap = existing electric capacity
ElCapDepr = electric capacity depreciation rate

In Eq. 18, DesElCapOrd is the desired rate of capacity ordering (MW/year). Orders replace depreciation (ElCapDepr, MW/year) and adjust the capital stock (ActPlusUCElCap, MW) to the expected required level (ExpReqElCap, MW). To make this equation dimensionally consistent, one must recognize that the stock adjustment component of orders involves an implicit time constant, the time to correct capacity (TCC), with a value of 1 year:

```
DesElCapOrd = MAX(0,(ExpReqElCap-ActPlusUCElCap)/TCC+ElCapDepr)
```
Eq. 19

TCC = time to correct capacity

All time constants or delays in a model ought to have an operational basis and be subject to sensitivity testing, but implicit time constants like this escape scrutiny. There could be policy implications if electric capacity were far from its required level, in which case there would be a large and potentially disruptive pulse of investment due to the short time (1 year) over which the capacity discrepancy is corrected.

Another difficulty with continuous models involves the representation of feedback loops with short time constants. One may include the feedback loop, and accept the degradation of speed that occurs because of the short simulation time step required. Alternately, one may solve for equilibrium in the subsystem with short time constants, and use only the equilibrium relationship in the model.

General equilibrium models like EPPA (Yang, Eckaus et al. 1996) take the latter approach. Within each solution interval, the model converges to an equilibrium in which production and consumption flows balance and prices and marginal products are equal. The processes that bring the economy into equilibrium are effectively instantaneous. This implies that all constraints to market adjustment are short with respect to the 5-year solution interval. The FREE model, which has distinct long- and short-run production structures similar to EPPA's, instead includes the equilibration processes explicitly, with time constants of as little as 1/4 year, necessitating a simulation time step of at most 1/8 year.

Complexity Metrics

The complexity of the models reviewed varies enormously. While there are many dimensions along which complexity may be evaluated, this study looks particularly at feedback complexity. Feedback complexity refers to the richness of the endogenous feedback structure of the model. Models with a high degree of feedback complexity are more likely to generate surprising behavior. They are also more difficult to work with because it is hard to interpret changes in behavior. Simple models are easier to understand, but if there are many omitted feedback loops, policy conclusions may be biased.

There are three major determinants of feedback complexity: the system order, the richness of the structure connecting the state variables, and the nonlinearity of the model relationships. By these measures, a decision tree with thousands of branches would be considered simple, since it contains no state variables or feedback.

For this comparison, each model was replicated in Vensim. The use of a common language eliminates one possible source of spurious variation in the measurement of complexity. The DICE and Connecticut/YOHE models were converted to equivalent continuous representations with first-order stock adjustment processes replacing the discrete delays. For ICAM, this full translation was excessively arduous, so the model structure was translated as a directed graph, allowing exploration of the model structure but not simulation.

The system order was measured by counting the state variables (stocks) in the system. The richness of the feedback structure can be measured by counting the feedback loops in the model. While it would be simplest to do an exhaustive count, this proved impractical because of software limitations and the very large number of loops possible in some models (Kampmann 1996). Instead, the number of feedback loops influencing a few key variables is reported in Table 4. While the degree of nonlinearity of model relationships is important (determining the potential for shifting dominance of feedback loops), no practical measure for this system attribute was found.

Table 4: Complexity Metrics

Model	Equations[1]	State Variables[2]	Search Space[3]	Feedback loops involving... GDP	Oil or Fossil Fuel Price	Total Energy Prod'n	CO_2 in Atmosphere
DICE	170	4	80	2	-	-	2
Connecticut / YOHE	180	6	2	7	8	10	2
TIME	1420	~ 100	-	-	thousands[4]	thousands[4]	-
Hatlebakk / Moxnes	100[5]	9	-	5	-	-	4
ICAM 2.1R	700	high		1100	409	711	25
NICE	300	9-21[6]	4-22	153	136	108	83
FREE	650	94	1-4	2922	12246	5449	291

1. From this author's implementation in Vensim, which may differ substantially from the original model specification. The count includes minor parameters and exogenous variables. Variables with multiple array subscripts count as a single equation in some cases, so the complexity of ICAM, NICE, and FREE is understated.
2. Cumulative discounted utility and state variables with completely exogenous behavior, like population and technology in DICE, are excluded.
3. Dimension of search space for policy optimization runs.
4. Exceeds capacity of loop-finding software.
5. Omits several stochastic processes in the original model.
6. Order depends on carbon cycle implementation; lower figure is with first-order DICE carbon cycle.

There are several interesting features in Table 4. First is the extreme feedback complexity of TIME, ICAM, NICE, and FREE, which each have hundreds to thousands of feedback loops influencing key variables. This is particularly striking for the NICE model, which is conceptually very similar to Connecticut/YOHE, but has an order of magnitude more loops due to a richer representation of behavior in factor allocation and a more complex carbon cycle. In general, the coupling among variables in greenhouse gas cycles and climate systems appears to be much looser than the coupling among variables in the energy-economy systems.

One thing to note about the DICE model (and other intertemporal optimization models) is that, while the system description is 4th order, the system of equations for the optimization problem is 8th order, because each state variable has a co-state variable in the Lagrangian. These co-state variables, representing the shadow prices of the state variables, create additional feedback links that effectively carry information from the future back to the present.

Table 5: Aggregation

Model	Regions	Economic Sectors	Energy Sources	Energy Carriers	Greenhouse Gases
DICE	1	1	-	-	1
Connecticut/ YOHE	1	1	2	1	1
TIME	1	4	6	5	-
Hatlebakk/ Moxnes	1	1	-	-	1
ICAM 2.1R	7	1	4	1	4
NICE	1	1	3	1	1
FREE	1	1	4	4	1

Table 6: Representative State Variables

Model	Economy	Energy	GHG Cycles	Climate
DICE	capital	–	atmospheric carbon	surface ocean temperature deep ocean temperature
Connecticut/ YOHE	capital output	cumulative carbon fuel production	atmospheric carbon	surface ocean temperature deep ocean temperature
TIME	capital (4 sectors) embodied energy requirements irreversible price-induced energy efficiency adjustments	energy resources energy reserves energy producing capital capital under construction transmission and distribution capital energy technology	–	–
Hatlebakk/ Moxnes	capital natural resources	adapted tax level reversible emissions irreversible emissions	atmospheric carbon	temperature adapted temperature
ICAM 2.1R	*	cumulative energy production partial price adjustment	atmospheric carbon (5th order) methane NOx sulfate aerosols	multiple temperature models (typically 1st to 3rd order) adaptation
NICE	capital	cumulative energy production energy intensity of capital	atmospheric carbon surface ocean carbon deep ocean carbon (10th order) biomass carbon	surface ocean temperature deep ocean temperature adapted temperature
FREE	capital embodied energy requirements embodied AEEI energy price perceptions relative return perception	energy producing capital capital under construction relative return perceptions cumulative energy production energy technology energy prices	atmospheric carbon surface ocean carbon deep ocean carbon (10th order) biomass carbon	surface ocean temperature deep ocean temperature adapted temperature

Notes to Table 6. The stock of cumulative discounted utility, implicit in the objective function of most models, is omitted here. Similarly, state variables with completely exogenous behavior, like population and technology in DICE and other models, are excluded. * The ICAM economy is driven by exogenous growth forecasts, but does contain significant feedback. However, it is difficult to map the model structure onto state variables.

Nonlinearity

While it is often convenient to work with linear models, the world is fundamentally nonlinear. Nonlinearities in model relationships allow shifting dominance of feedback loops (Richardson 1995). Shifting dominance can carry a system into new behavior modes which are unexpected on the basis of past behavior. It is important to represent these nonlinearities, as the long time scale and complexity of the climate problem may take the global system into behavior modes which are far from today's world. All of the models reviewed here employ many nonlinear relationships. Typical examples include Cobb-Douglas and CES production functions, the logarithmic effect of CO_2 on radiative forcing, and quadratic or cubic climate damage functions.

One area in which several models make questionable assumptions of linearity is the carbon cycle. Physical models of the carbon cycle incorporate many nonlinearities in the uptake of carbon from the atmosphere that cause the uptake of carbon to increase less than proportionally to the atmospheric carbon concentration. Yet the carbon cycles in DICE, Connecticut/YOHE, and ICAM are linear structures, in which the uptake of carbon is strictly proportional to the atmospheric concentration, regardless of how high it becomes. See the sections on the carbon cycle below (page 55) and in the FREE model description (page 114).

From a methodological perspective, problematic nonlinearities can arise from discrete changes or discontinuities in model relationships. These discontinuities typically arise in several ways. Logical statements (i.e. IF...THEN...ELSE) can generate output that is a discontinuous function of the input. MIN and MAX statements produce discontinuities in the slope of a relationship, as can lookup tables. There are two major effects of these nonlinearities. First, discontinuous changes in variable values introduce high frequencies which may trigger unrealistic oscillations or other behaviors. More importantly, discontinuities can produce rapid and strong shifts in loop dominance and model behavior, which are difficult to understand and are likely to be unrealistic in models at the high level of aggregation required by the climate change problem. The ICAM depletion sector (page 51) provides an example of unrealistic nonlinear behavior from discontinuous functional forms.

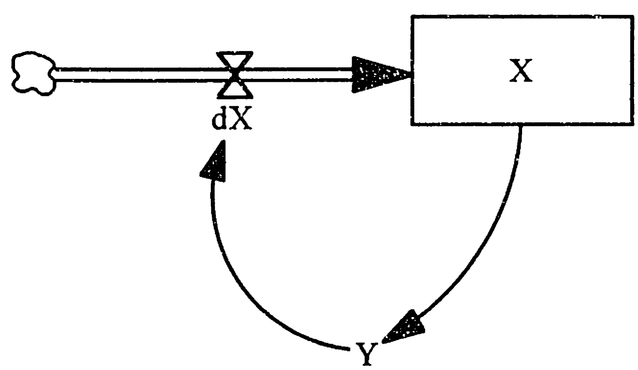
Feedback Structure

The following section presents selected feedback structures from the models reviewed, with particular attention their treatment of key processes like capital accumulation, resource depletion, emissions adjustment, the carbon cycle, and climate dynamics. Since the DICE model is simple, well-known, and easy to understand, it is used as a point of reference for the comparison.

Notation

Where possible, the system dynamics stock-flow diagram conventions are used to present system structure (Morecroft 1982). Stocks (X) are system state variables, indicated by boxes. Stocks integrate flows (rates of change or derivatives), represented by pipes (dX). Auxiliary variables (Y) are used to break the flow equations into manageable segments with a clear meaning. All feedback loops must contain at least one stock.

Figure 4: Stock-flow Diagramming Convention



$$X(t) = \int dX^{*}dt + X(0)$$

$$dX = f(Y(t))$$

$$Y(t) = g(X(t))$$

Stocks (state variables) are indicated by boxes. Flows (rates of change of state variables) are indicated by pipes. Clouds indicate that the source or sink of a flow infinite and therefore has no impact on the model system.

In the ICAM and Connecticut/YOHE models, it was not always possible to adhere to this convention, so an alternate notation is used. For normal causal links, the notation is conventional:

$X \rightarrow Y$ $\quad\quad\quad\quad\quad\quad$ $Y(t) = f(X(t))$

For links in which the output variable is a function of the input with a discrete delay, a box is placed on the arrow, indicating the implicit integration:

$X \text{—}\square\rightarrow Y$ $\quad\quad\quad\quad\quad\quad$ $Y(t) = f(X(t-1))$

All feedback loops must contain at least one discrete delay.

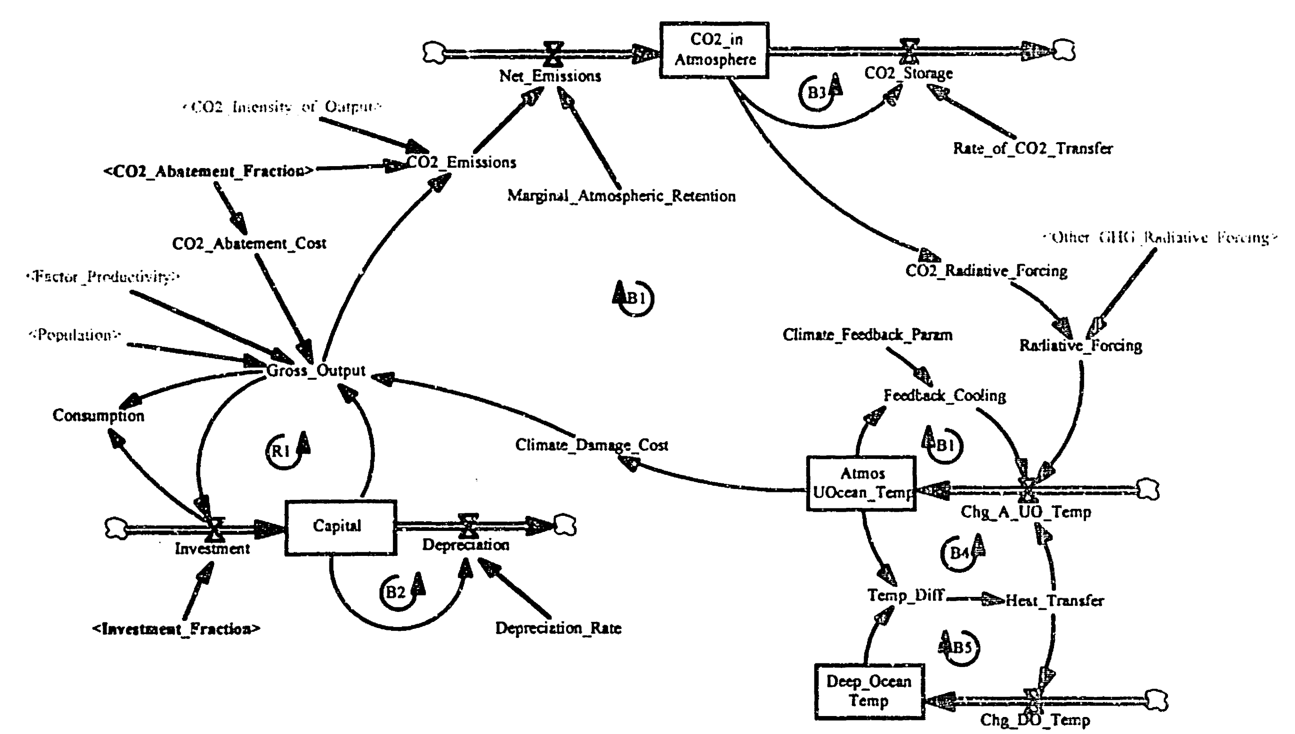
A circle on a causal link indicates a discrete derivative, in which the output is a function of the difference between the current input and the input from the previous period:

$X \!-\!\!\bigcirc\!\!\rightarrow Y$ $\qquad\qquad$ $Y(t) = f(X(t)-X(t-1))$

DICE

The DICE model's causal structure is simple enough to be represented on a single diagram: thus it serves as a useful starting point (for a more detailed critique of the DICE model than is presented here, see Chapman, Suri et al. 1995; Fiddaman 1995; Costanza 1996; Fiddaman 1996). The model can be subdivided into three major subsystems: the economy, the carbon cycle, and climate.

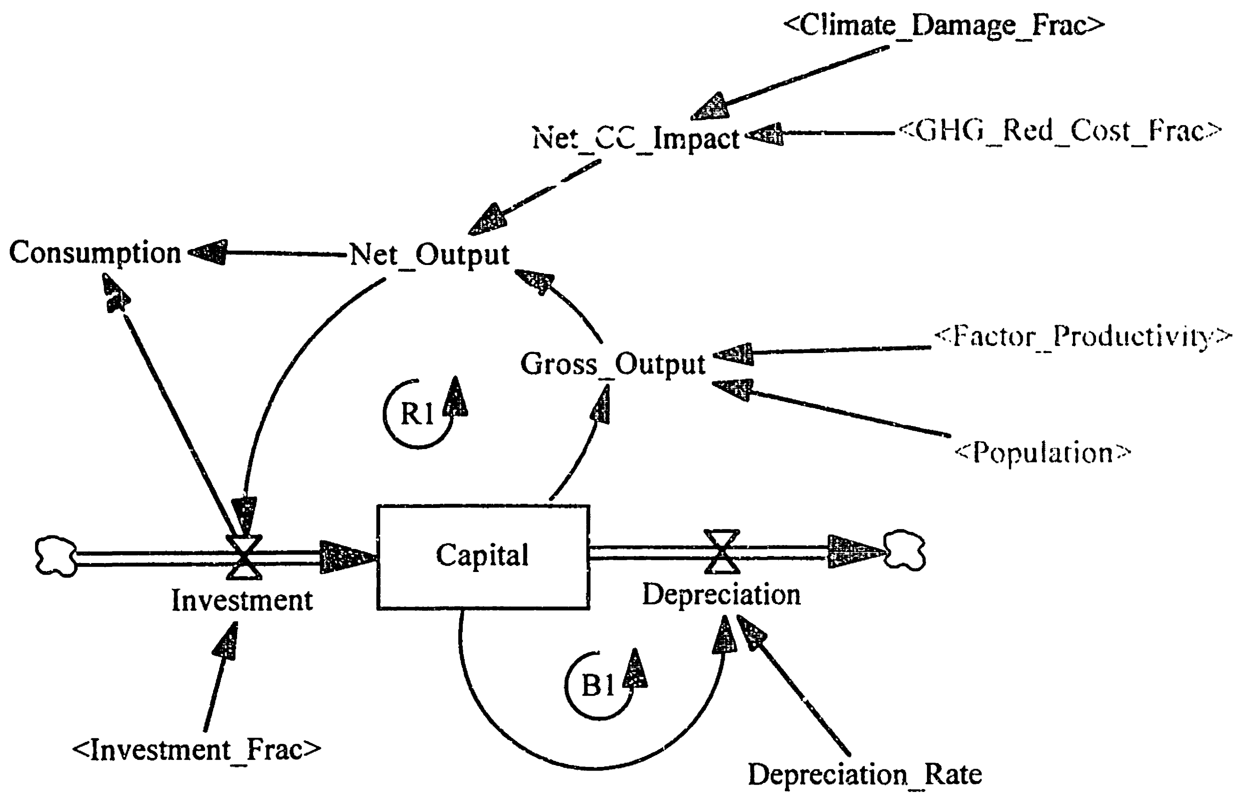
Figure 5: Structure of the DICE Model



Positive feedback or Reinforcing loops are labeled R#, while negative feedback or Balancing loops are labeled B#.

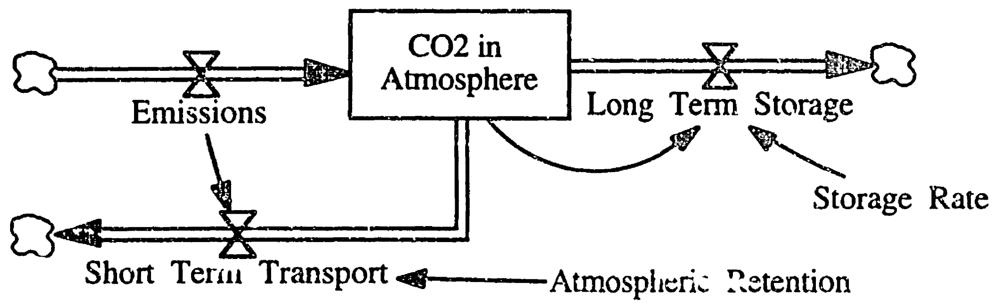
The DICE model uses a simple first-order capital accumulation structure, with two feedback loops: capital accumulation through reinvestment (R1) and depreciation (B1). Output is influenced by capital and exogenous inputs of population and factor productivity, emissions abatement costs, and climate damages (which creates another negative loop, B1).

Figure 6: DICE Capital Accumulation and Depreciation



The DICE carbon cycle is a linear first-order structure. Emissions accumulate in the stock of carbon in the atmosphere and mixed layer of the ocean. With a delay, long term storage processes restore the atmospheric carbon concentration to its preindustrial level. Three features of this system are worth noting. First, there is an implicit flow of carbon, parallel to the anthropogenic emissions flow, which represents short-term storage processes. The capacity of this short-term storage process for emissions uptake is infinite. Second, the long-term CO_2 storage flow is also unconstrained by carbon sink limitations. Third, the uptake of carbon is linear with respect to emissions (in the short run) and atmospheric concentrations (in the long run), so the response of the system to an instantaneous pulse of carbon emissions is the same whether the pulse contains 1 or 100 gigatons of carbon.

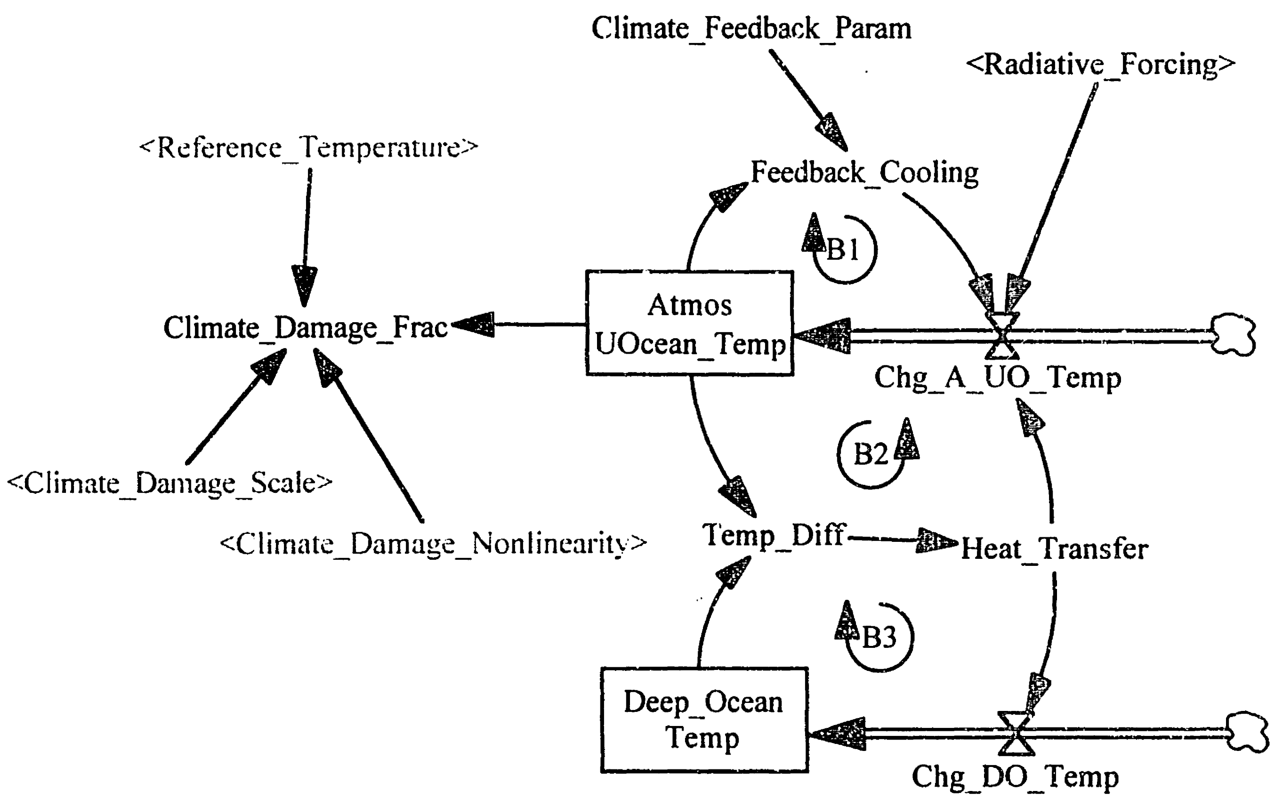
Figure 7: DICE Carbon Cycle



Implicit structure of the DICE carbon cycle. Emissions flow into the atmosphere. A fixed portion (36%) is immediately stored in the surface ocean or biosphere. Over the longer term (with a 120 year time constant), carbon is stored in the deep ocean.

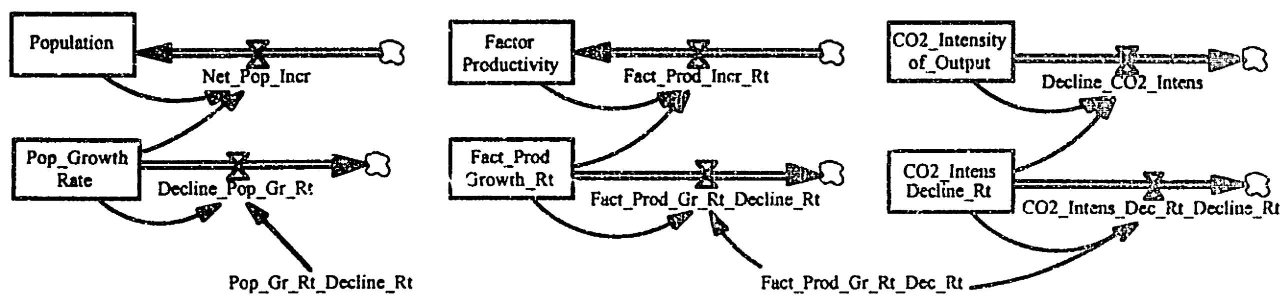
The climate model in DICE is a linear second-order system (Nordhaus also tests a first-order model). Radiative forcing warms the atmosphere and surface ocean. Some heat is rerediated (loop B1) and heat is slowly transferred to the deep ocean (loops B2 and B3). Climate damages are a quadratic function of atmospheric temperature.

Figure 8: DICE Climate System



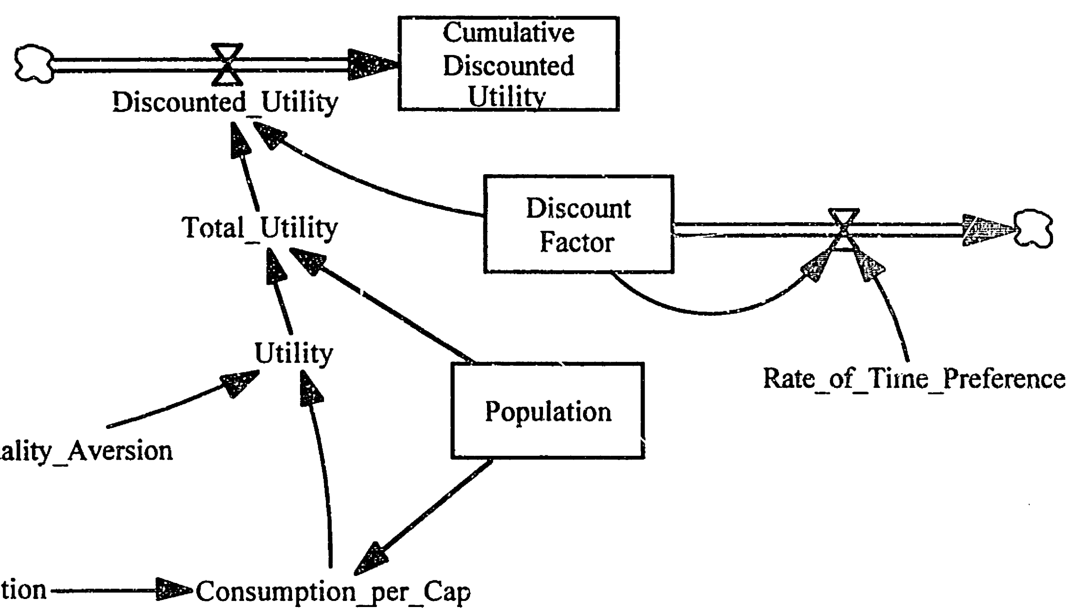
In addition, the DICE model uses an identical second order structure to represent exogenous exponential growth (at diminishing rates) for population, factor productivity, and carbon intensity of output:

Figure 9: DICE Exogenous Drivers



The objective function of the DICE model (also used by many other models) also involves some implicit stock-flow structure (Figure 10). Discounting is a first-order exponential decay process. The accumulation of discounted utility is a pure integration.

Figure 10: DICE Discounting and Utility

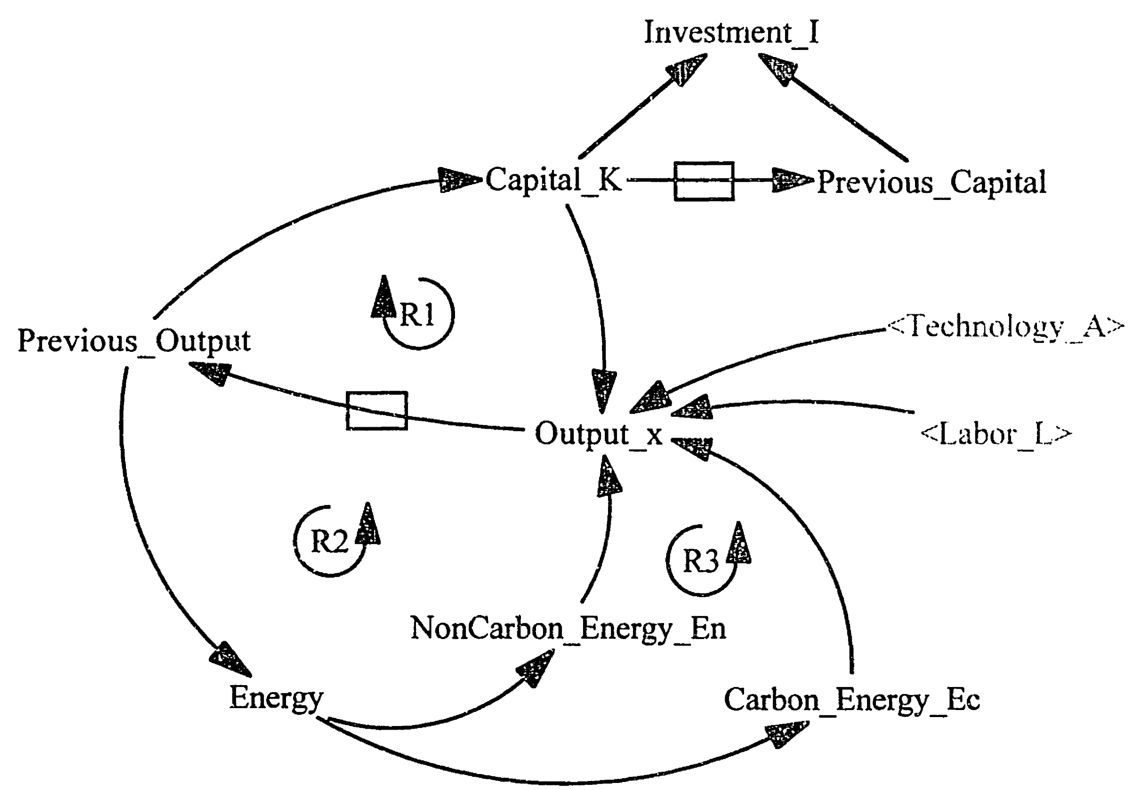


Production and Capital Accumulation

Connecticut/ YOHE

The production function of Connecticut/YOHE is similar to that of DICE, with the addition of an explicit energy factor. However, the feedback structure governing factor allocation is somewhat different. The capital input to production is a function of the previous period's output, creating a positive loop of capital accumulation with a discrete delay (R1). Similarly, inputs of carbon and non-carbon energy depend on the previous period's output, creating two more positive loops (R2 and R3). Investment replaces depreciation on the previous period's capital, and adjusts the previous period's capital to the current period's indicated level. Since investment is decoupled from output, it is possible in extreme conditions for the indicated rate of investment to exceed output, leading to negative consumption. The same can be said of energy inputs. Fortunately, this does not occur under normal conditions.

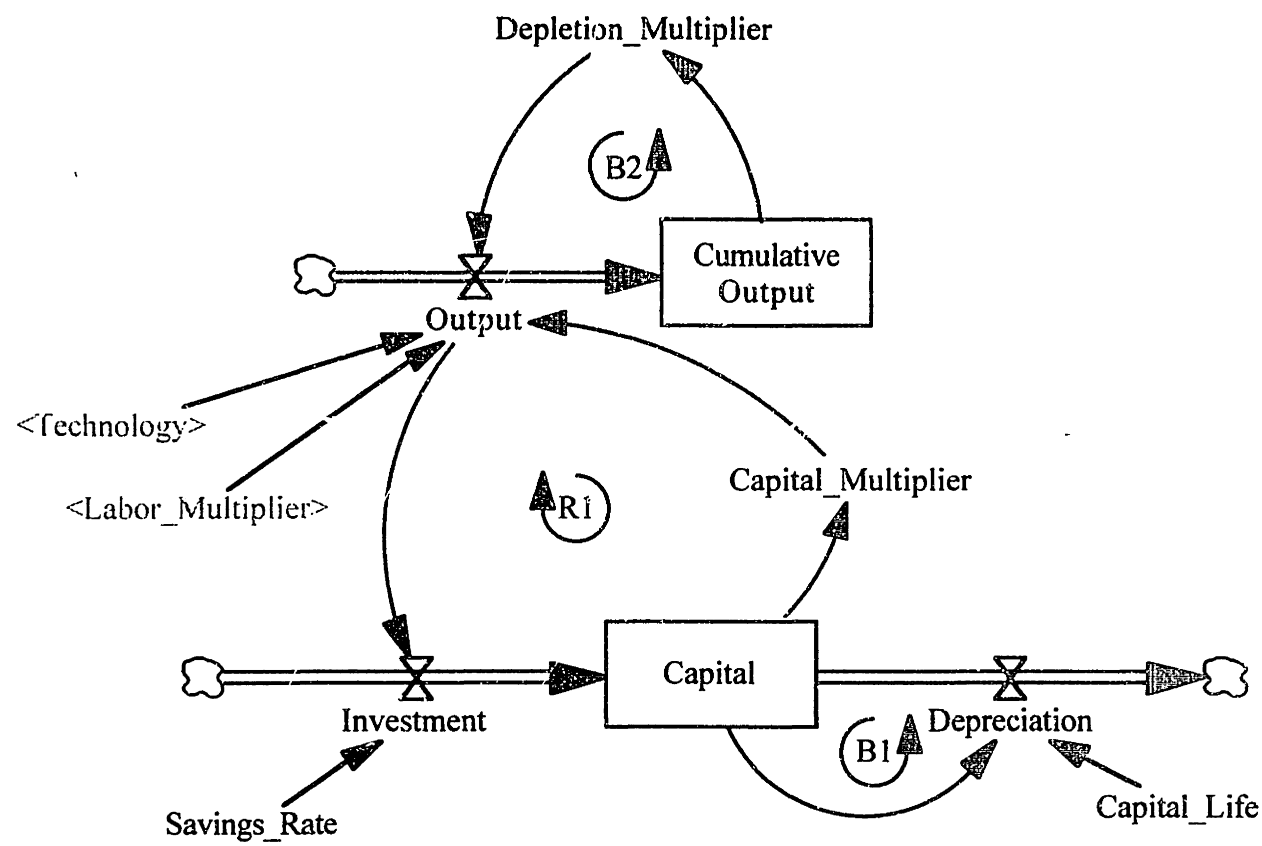
Figure 11: Connecticut/YOHE Capital and Output



Hatlebakk/ Moxnes

In the Hatlebakk/Moxnes model, capital accumulates and depreciates as in DICE. In addition, there is a negative loop of natural resource depletion (B2). This introduces diminishing economic growth, much as the exogenously diminishing factor productivity input in DICE does. This reduces pressure on the climate system from economic growth.

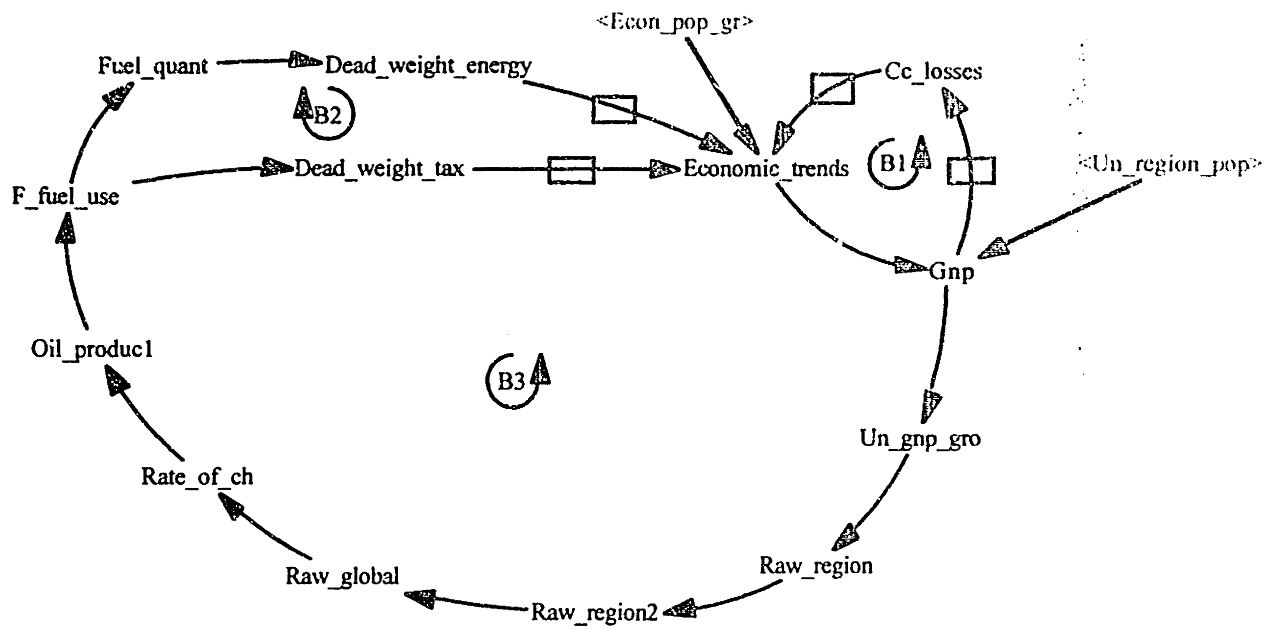
Figure 12: Hatlebakk/Moxnes Capital Accumulation and Depletion



ICAM 2.1R

In ICAM, output (GNP) is driven by exogenous population and per capita income forecasts, with adjustments for climate change losses and deadweight losses from energy expenditures and taxes. These losses create negative feedback loops (B2 and B3); increasing GNP requires increasing production of energy, causing greater losses due to energy and tax expenditures, reducing GNP. Similarly, increasing GNP leads to increasing climate losses, reducing GNP (loop B1).

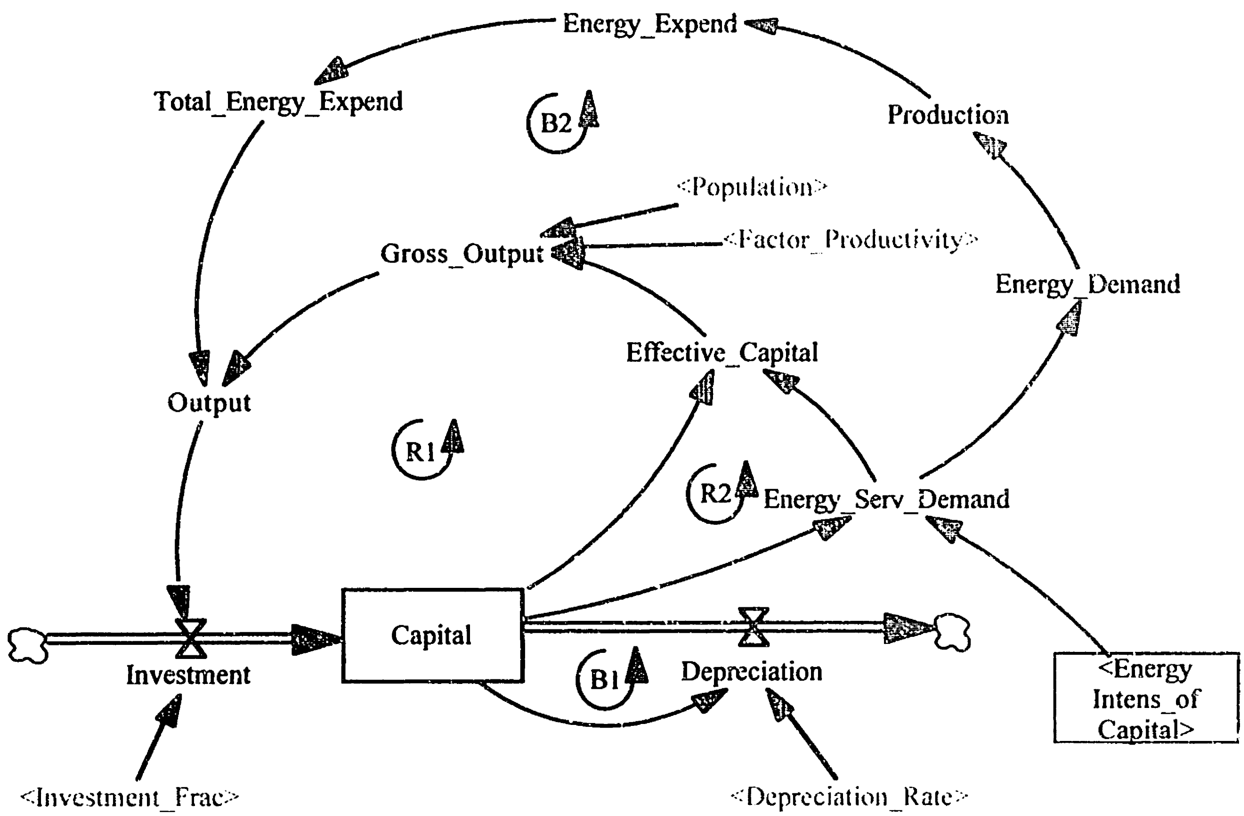
Figure 13: ICAM Output



NICE

In the NICE model, capital accumulates and depreciates as in DICE. In addition, the growth of capital requires additional inputs of energy services, creating a negative loop (as energy expenditures reduce net output available for investment) and a weak positive loop (as increased energy inputs contribute to production).

Figure 14: NICE Capital Accumulation and Output

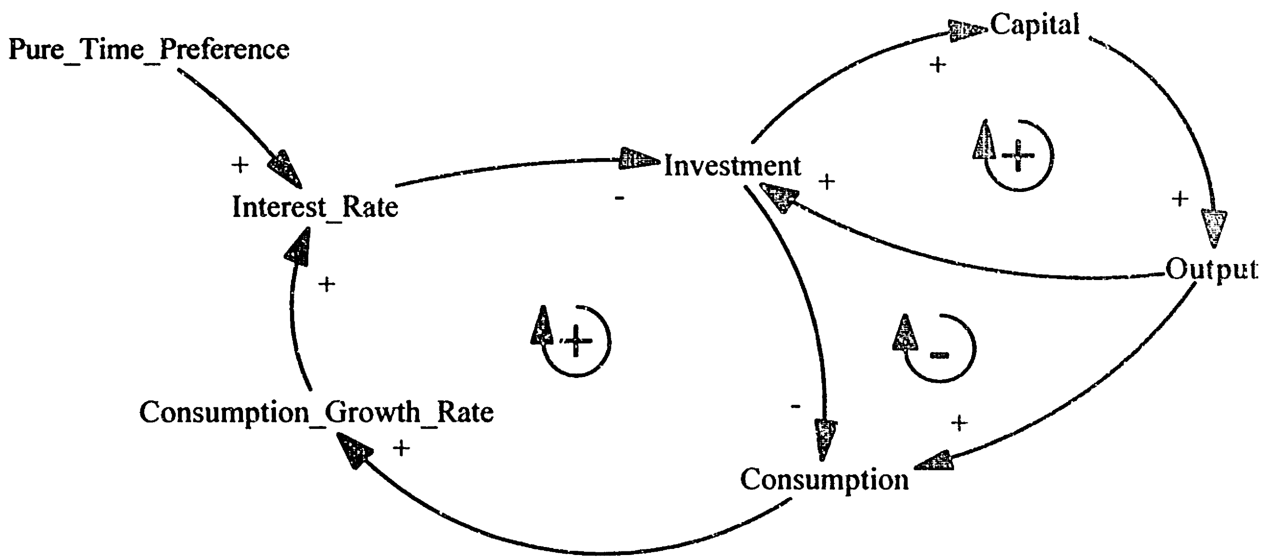


Investment

Connecticut/YOHE

In Connecticut/YOHE, investment adjusts in order to equate the marginal product of capital, net of depreciation, with the interest rate (see page 23 and Figure 11). In addition, the interest rate adjusts according to the optimal growth path criterion of the Ramsey model (see page 76). This creates an additional pair of loops (one positive, one negative) which govern capital accumulation.

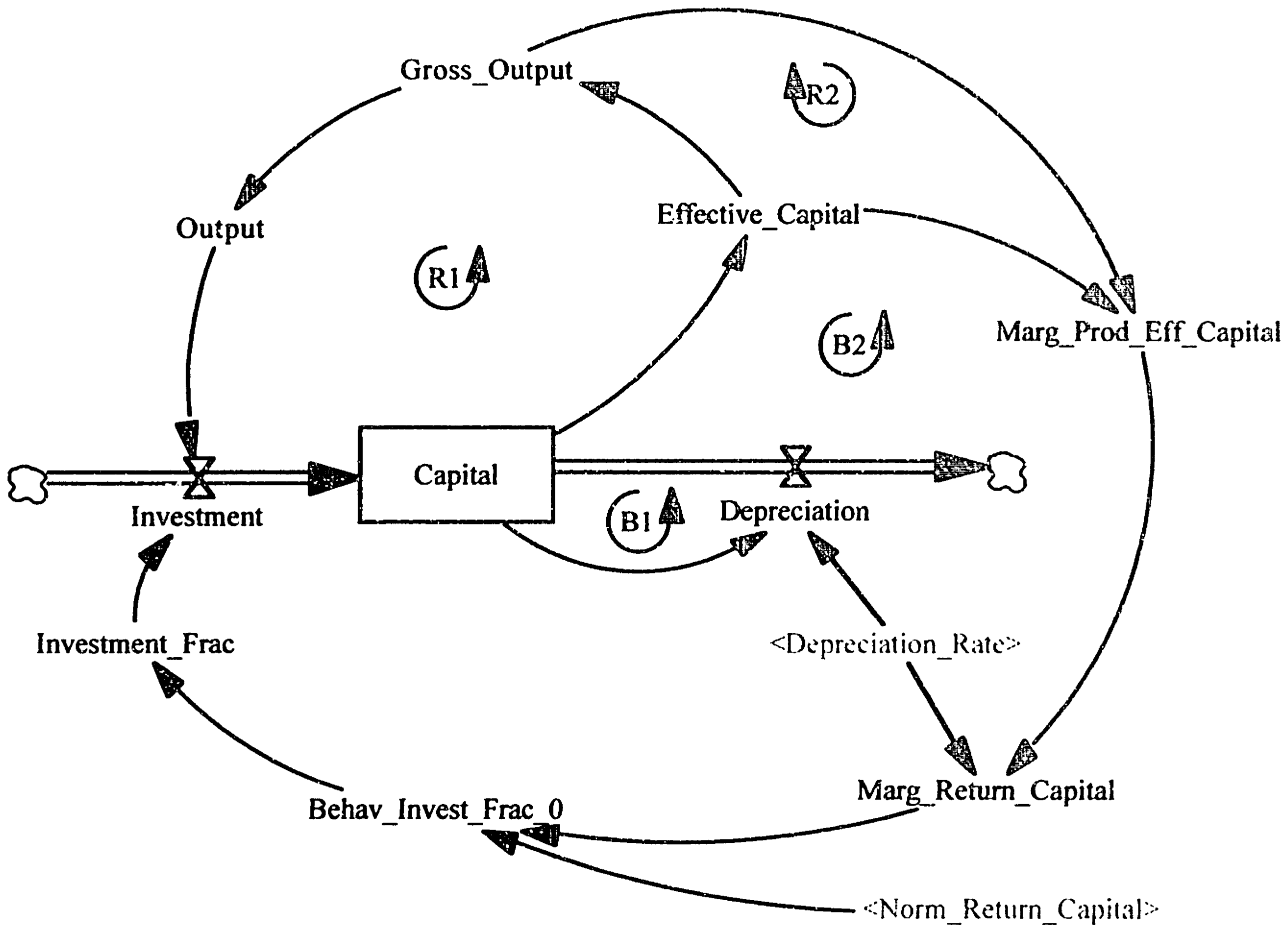
Figure 15: Consumption-based Interest Rates



NICE

The NICE model includes a simple behavioral savings rule, which may be substituted for the optimal investment allocation of the DICE model. The fraction of investment devoted to output is an increasing function of the ratio of the marginal product of capital, net of depreciation, to a normal return or interest rate. This creates two additional feedback loops governing the capital stock (R2 and B2). Because output grows less than proportionately to the capital input, the negative loop dominates; increasing capital lowers the marginal product of capital, reducing investment, and slowing the increase of capital. While this rule can be parameterized to match the optimal investment behavior of the DICE model almost exactly, it does not in general allocate investment optimally over time. Also, this rule is subject to steady-state error; it does not guarantee that the marginal return to capital eventually reaches the normal return in equilibrium.

Figure 16: NICE Investment Rule

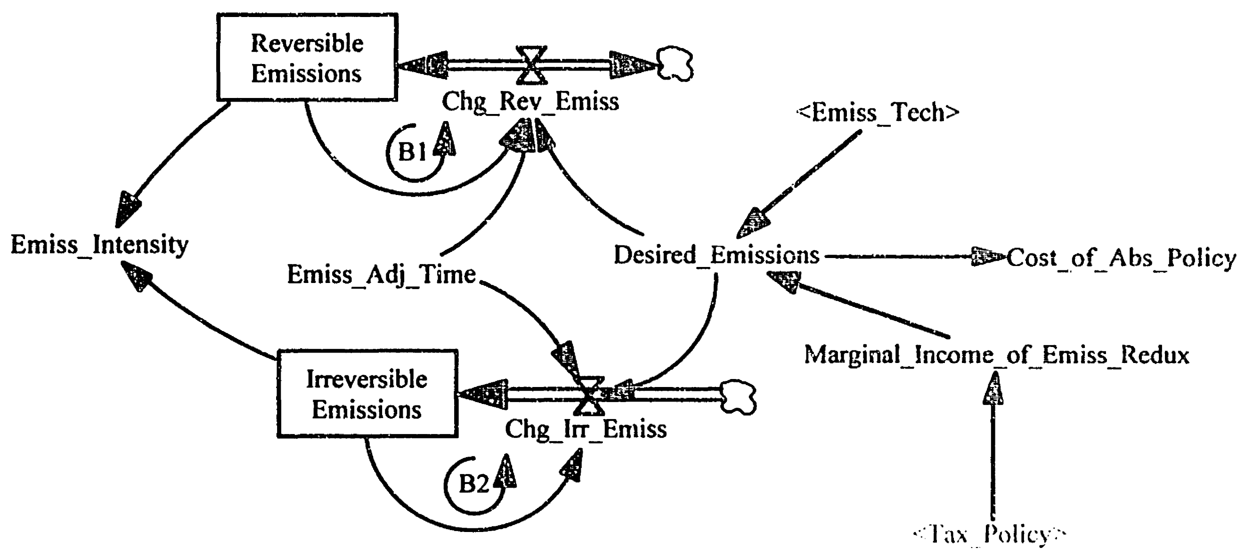


Emissions

Hatlebakk/Moxnes

The Hatlebakk/Moxnes model does not contain an energy sector per se. Instead, emissions are driven by economic output and the level of emissions intensity, as in DICE. Emissions intensity is separated into two components, which adjust with a delay (loops B1 and B2) to the desired emissions intensity (influenced by tax policy). One component, reversible emissions, adjusts down or up as the tax is increased or decreased, respectively. Irreversible emissions, on the other hand, adjust downward only. Thus emissions are "sticky" downward—some improvements induced by a tax are sustained even if the tax is removed.

Figure 17: Hatlebakk/Moxnes Emissions

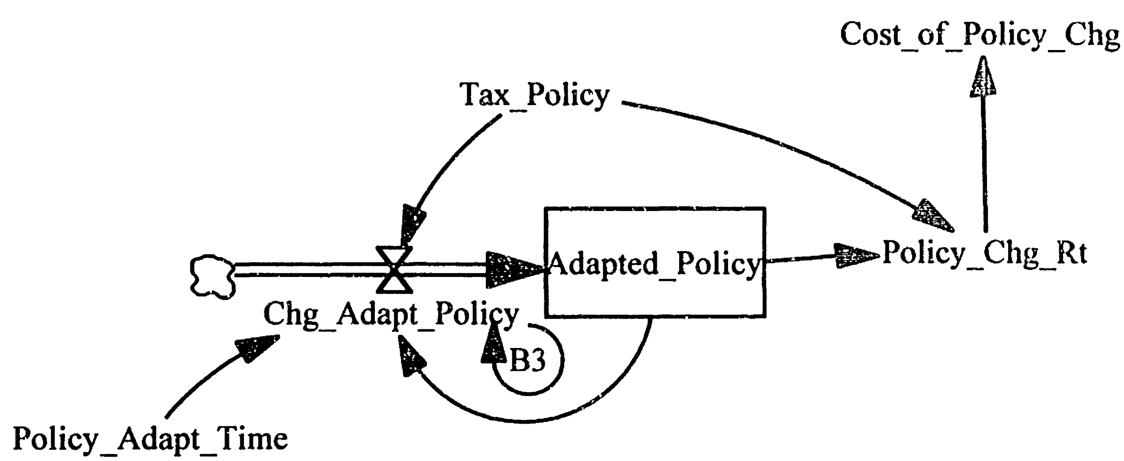


Abatement Policy

Hatlebakk/Moxnes

Greenhouse gas emissions abatement induces costs in the Hatlebakk/Moxnes model, as in DICE. Unlike DICE, a portion of the costs are related to the adjustment to a new tax level, rather than the absolute level of the tax. Adaptation occurs by first-order stock adjustment (loop B3).

Figure 18: Hatlebakk/Moxnes Adaptive Policy Response

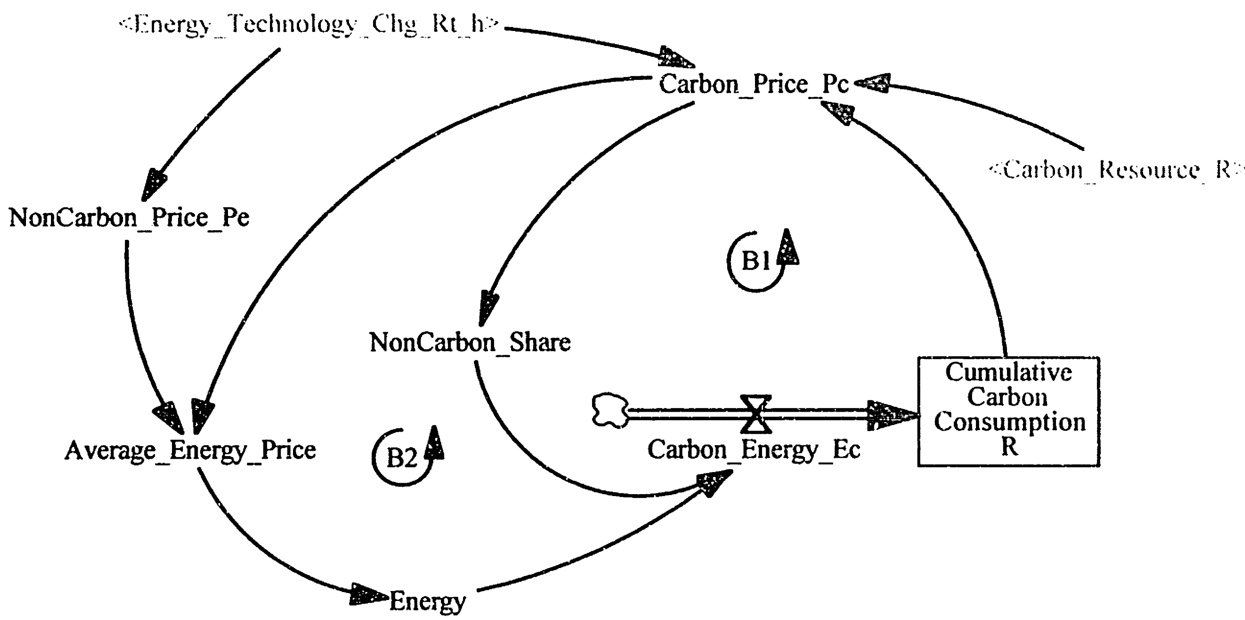


Energy

Connecticut/YOHE

In the Connecticut/YOHE model, energy prices are a function of exogenous technological change and, for carbon-based fuels, depletion and taxes. The depletion effect creates two negative feedback loops. As cumulative carbon fuel consumption increases, the price of carbon energy increases, increasing the market share of noncarbon energy, and reducing the rate of carbon fuel consumption. Similarly, as the price of the carbon fuel increases, the average energy price increases, diminishing total energy consumption, which also reduces the rate of carbon fuel consumption.

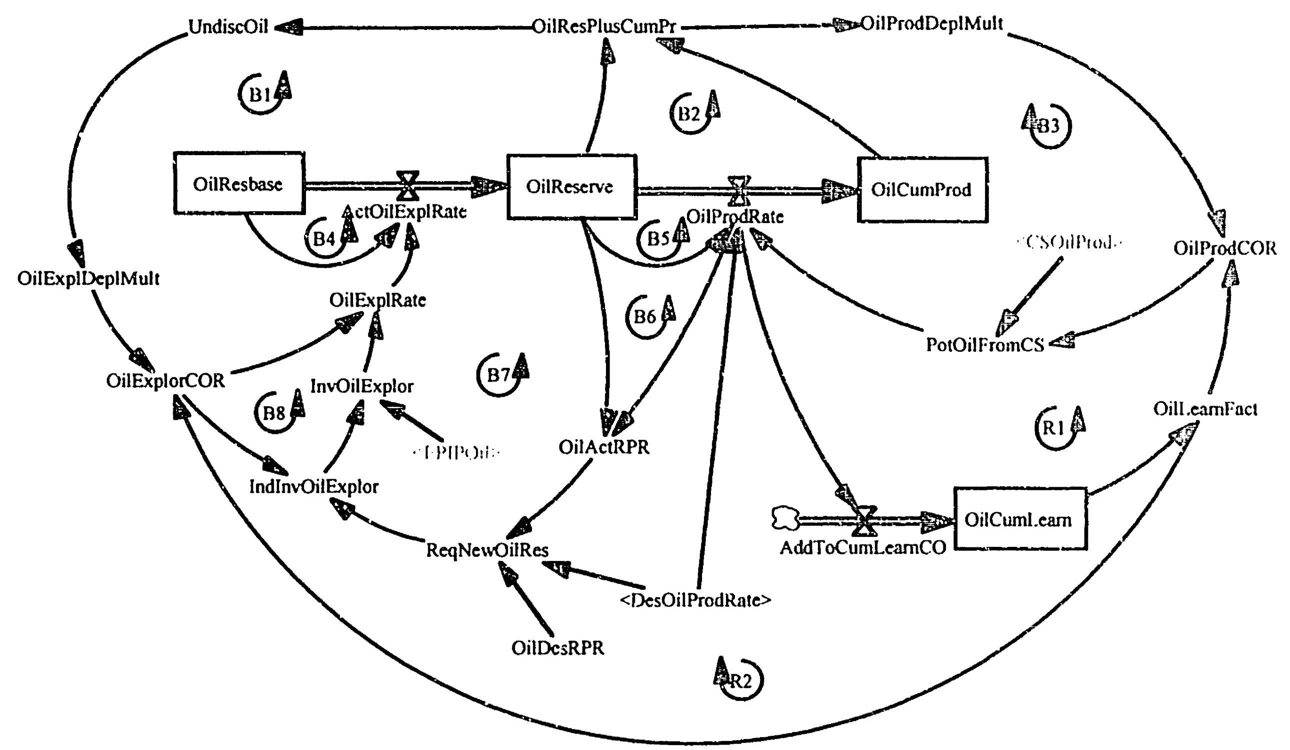
Figure 19: Connecticut/YOHE Energy



TIME

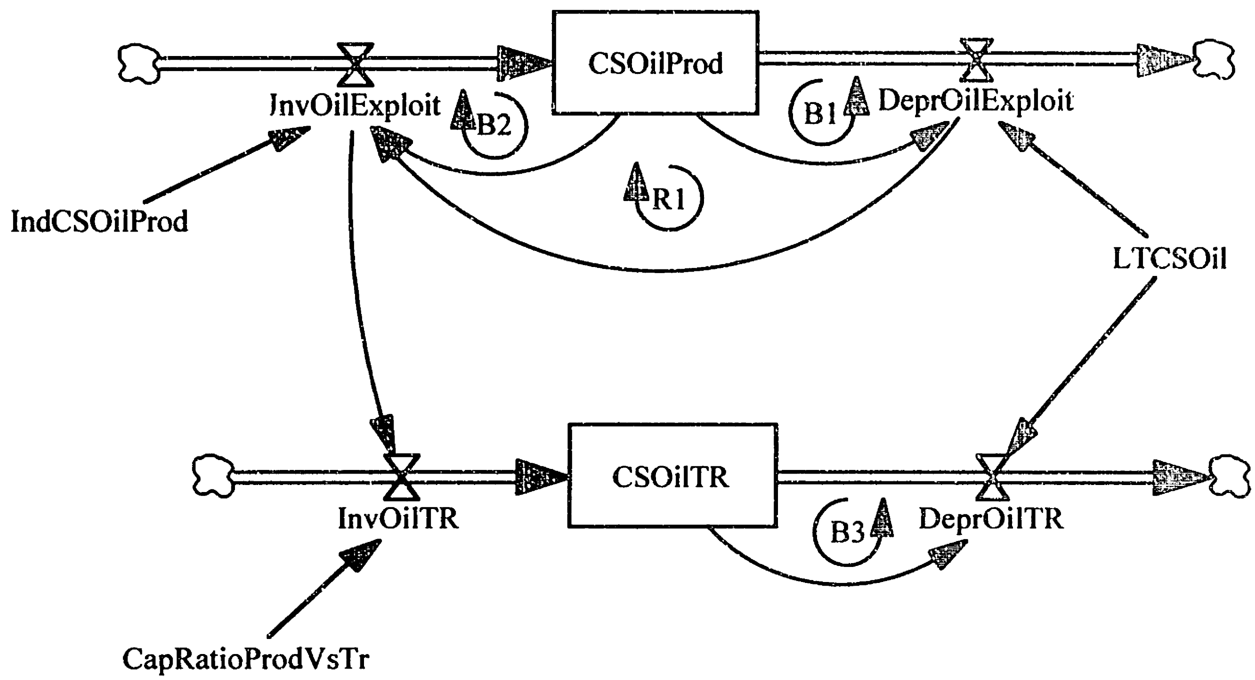
The energy sector of the TIME model employs a more detailed model of resources for fossil fuels, distinguishing discovered reserves from the undiscovered resource. The structure for oil is shown here. Oil is produced to meet demand, but production is constrained by the available resource (B5) and producing capital. Exploration is undertaken in order to maintain a desired reserve/production ratio (B6 and B7). As cumulative production rises, the productivity of production and exploration falls, reducing production and discoveries (B1, B3, and B8). Accumulated production experience leads to learning, which raises the productivity of exploration and production (R1 and R2).

Figure 20: TIME Oil Production, Depletion, and Learning



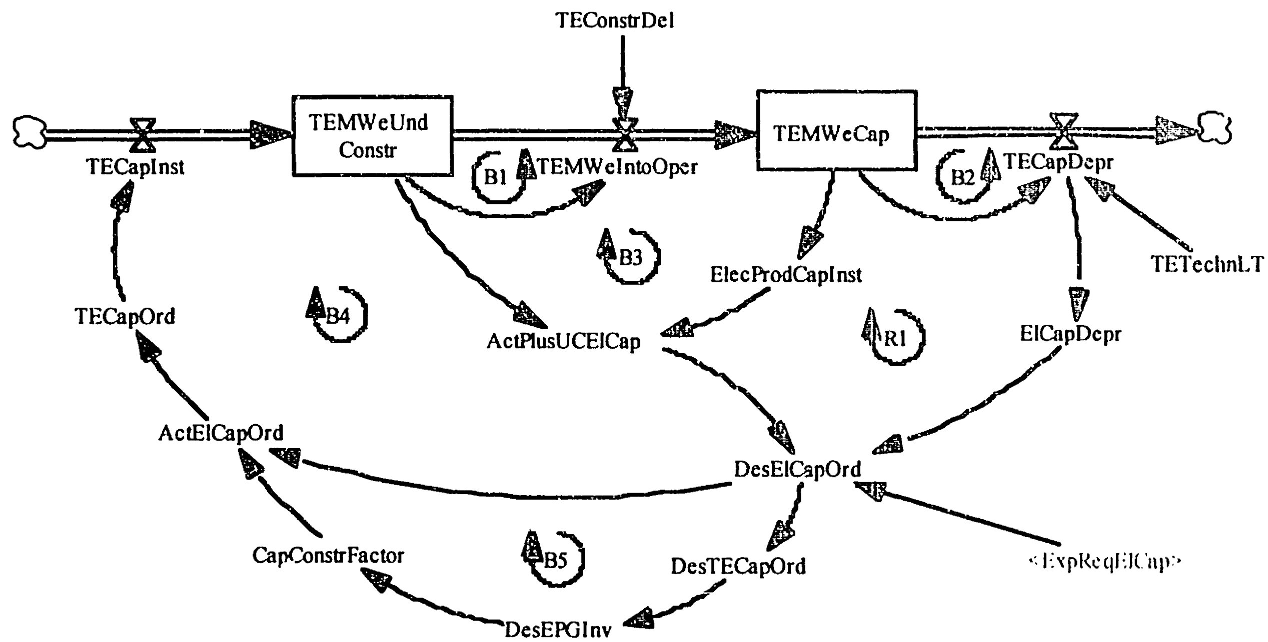
Energy production is constrained by the availability of capital, which is disaggregated into separate stocks for production and transmission/distribution. Investment replaces depreciation (loop R1, exactly offset by B1) and adjusts the capital stock to a target level (B2). Transmission and distribution capital is maintained in a fixed ratio to producing capital, so the two stocks have the same lifetime and investment in transmission and distribution capital occurs at a fixed ratio to investment in producing capital.

Figure 21: TIME Oil Production and Distribution Capital



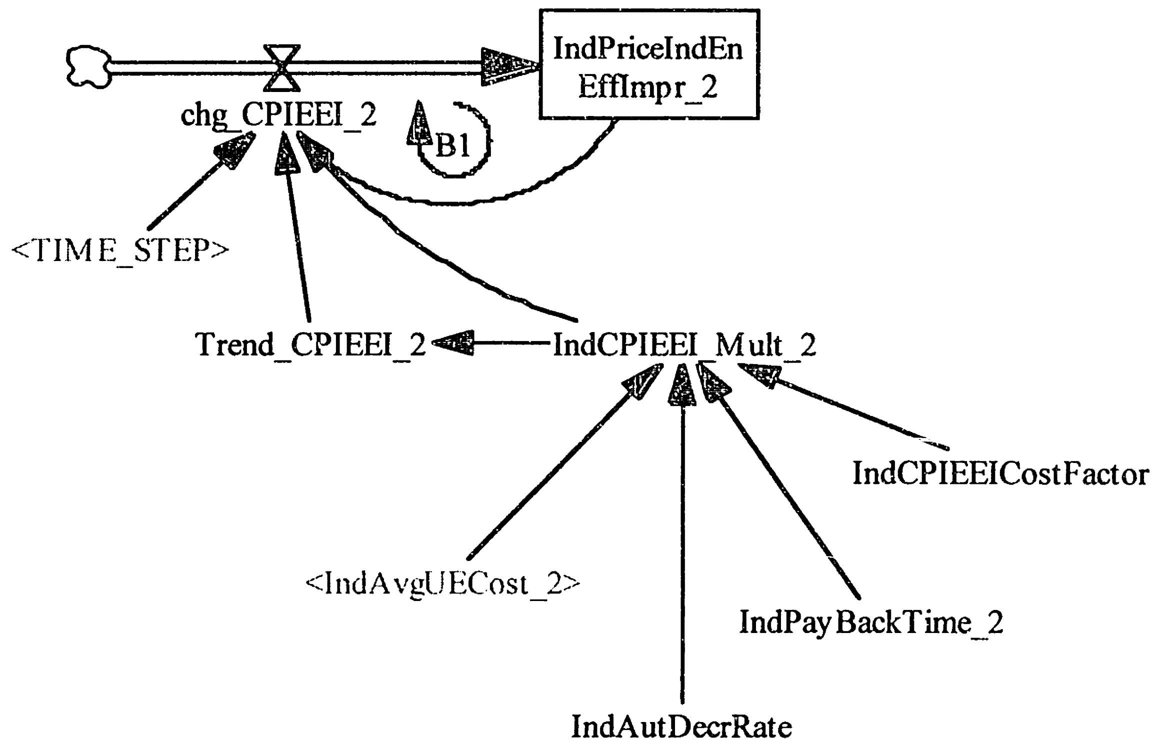
Electric generating capacity in the TIME model has a similar structure, but with an explicit construction delay. Capacity under construction is completed after a delay (B1), and installed capacity depreciates with a fixed lifetime (B2). Orders for capacity adjust the supply line of capital under construction and the stock of existing capacity to a target level (B3 and B4) and replace depreciation (R1). Capacity orders are constrained by the availability of capital for investment (B5).

Figure 22: TIME Thermal Electric Generating Capacity



In addition to the conventional autonomous energy efficiency improvement process, TIME includes irreversible price-induced energy efficiency improvements. When the cost of energy is increasing, energy efficiency improves (B1), but as energy costs fall, there is no corresponding reduction in efficiency.

Figure 23: TIME Irreversible Price-induced Energy Efficiency Improvement

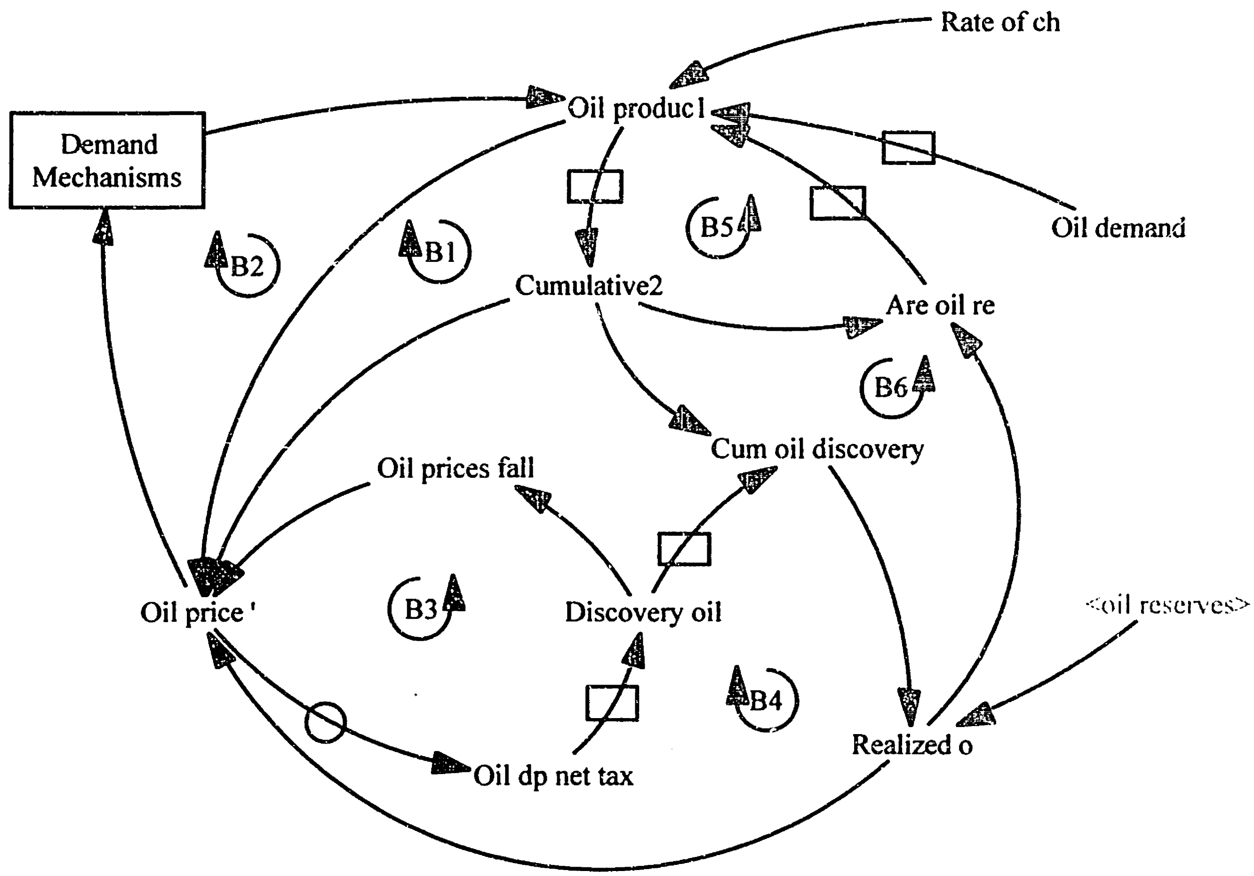


ICAM 2.1R

The feedback structure of energy pricing in ICAM is extremely complex, so it is separated here into several components. The model contains four energy sources (coal, oil, gas, renewable) with generally parallel structures. The structures for oil are presented here.

One component of oil pricing in ICAM is depletion and scarcity. As oil production grows relative to remaining reserves (the realized resource less cumulative production), the oil price rises due to scarcity, diminishing production through several mechanisms (loops B1 and B2). Rising oil prices induce oil discoveries, which in turn cause oil prices to fall directly (loop B3) and indirectly by reducing scarcity (loop B4). Exhaustion of oil reserves constrains oil production to zero (loop B5). However, oil discoveries will normally prevent this from occurring, as discoveries exactly offset production (loop B6).

Figure 24: ICAM Oil Production, Depletion, and Price



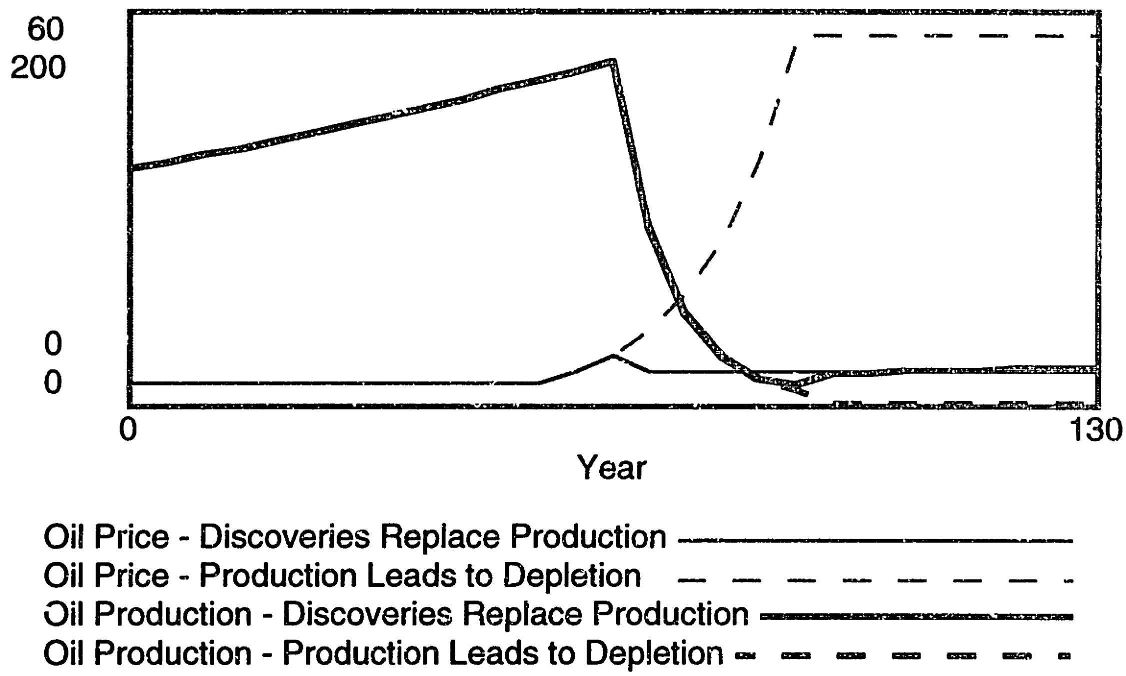
While the feedback structure of the depletion mechanism is plausible, its behavior is not (see Figure 25). Simulation of the depletion mechanism separated from the rest of the model indicates that price and production change in a highly discontinuous fashion. Inspection of the equations shows that prices respond to two logical conditions:

- When the reserve-production ratio falls below 15, prices rise at a constant fractional rate.
- If discoveries increase reserves, prices fall at the same constant fractional rate.

When discoveries are possible at all, they are available in infinite quantity. If depletion constrains production to zero, there is no feedback to the economy, except through price.

The flawed depletion structure severely limits the ability of the ICAM model to realistically consider the implications of depletion. The robustness of this structure could be greatly improved by substituting a continuous extraction cost function for the discrete pricing logic above. In addition, it is essential to ensure that extreme conditions—such as zero oil production—propagate through the model in a reasonable fashion.

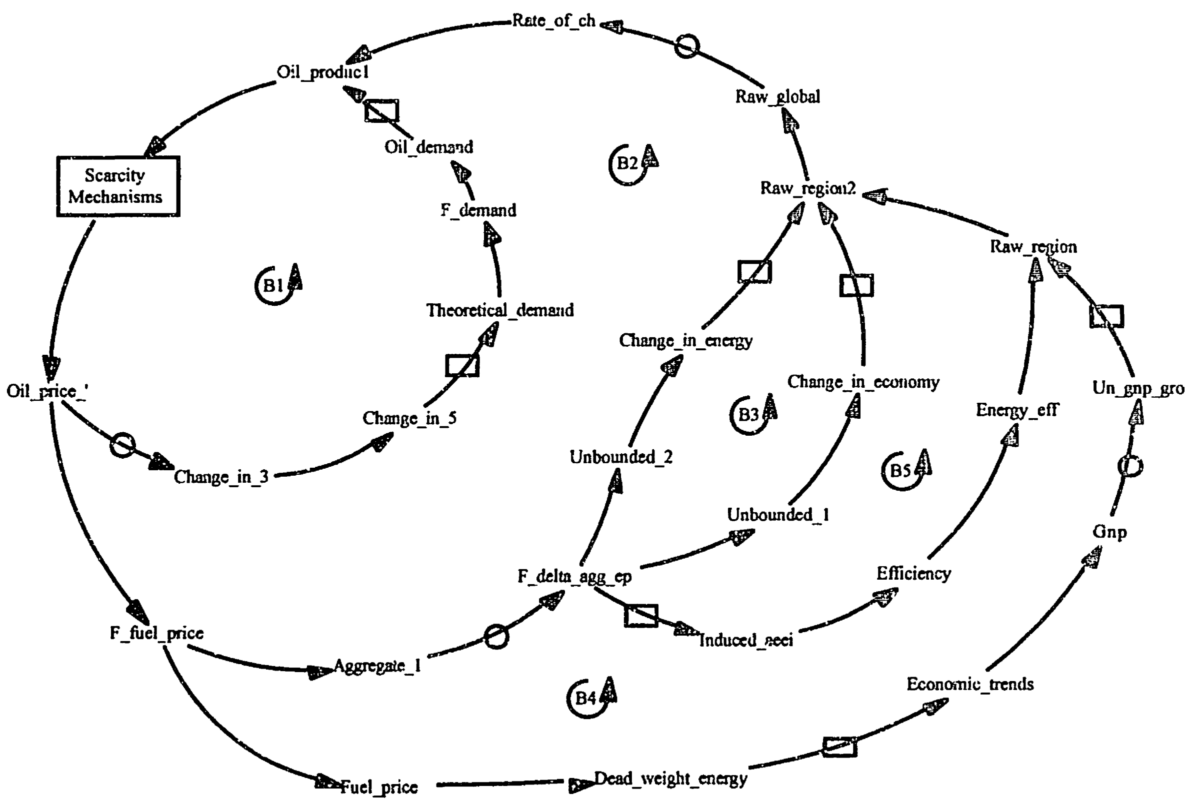
Figure 25: ICAM Oil Price and Production Behavior



Trajectories are shown with and without replenishment of oil reserves by new discoveries. Oil demand (and thus production) is driven by a 3%/year growth trend and responds to price with an elasticity of -1.5 and a 4-period distributed lag.

The oil and energy demand mechanisms through the economy also create several equilibrating mechanisms (Figure 26). Rising oil prices reduce the market share of oil, diminishing demand and reducing price pressure from scarcity (loop B1). Rising oil prices also reduce production pressure through several aggregate mechanisms. Rising oil prices contribute to rising aggregate fuel prices, leading to reduced energy demand through an energy price elasticity effect (loop B2) and two economic growth effects (loops B3 and B4). The economic growth effect in loop B3 is not reflected in actual economic growth, and the two loops have different delays. It is unclear why loops B3 and B4 could not be combined. Finally, rising aggregate energy prices also induce energy efficiency improvements (loop B5).

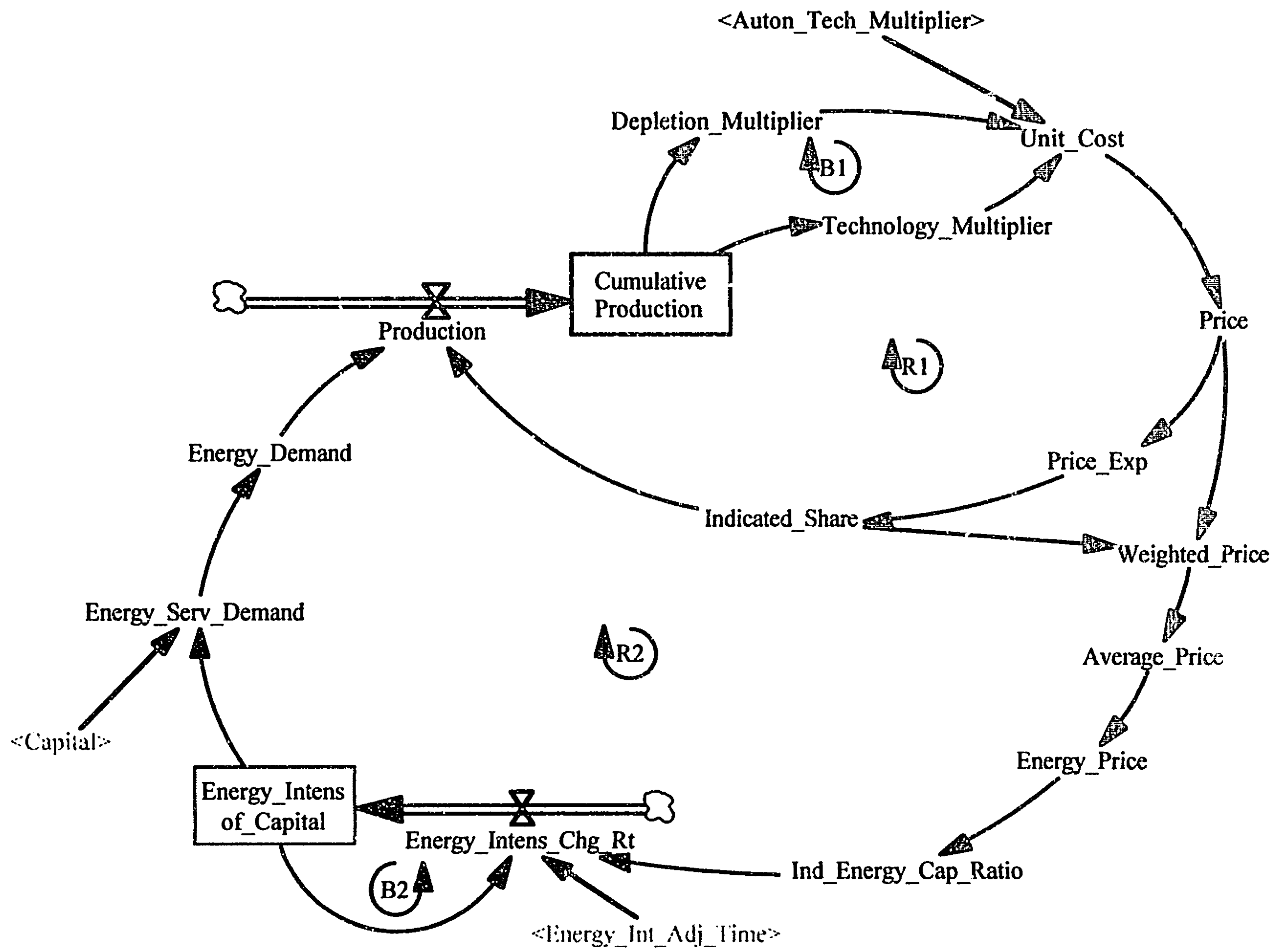
Figure 26: ICAM Oil and Energy Demand



NICE

The energy system of the NICE model is very similar to that of the Connecticut/YOHE model. There are two major differences. First, aggregate energy demand adjusts to energy price changes with a delay rather than instantaneously. The delay is due to the time required to adjust the energy intensity of the capital stock (loop B2). More importantly, cumulative production of energy leads to learning as well as depletion. This creates a set of positive feedback loops for each energy source (R1 and R2). As the production of an energy source increases, cumulative production and learning increase, causing unit costs and price to fall. This increases the market share and production rate of that energy source. Similarly, learning reduces aggregate energy prices, leading to increased aggregate energy demand, greater production, and more learning. These learning loops create the potential for the energy system to lock-in to energy sources that accumulate an early advantage in production.

Figure 27: NICE Energy Intensity and Production

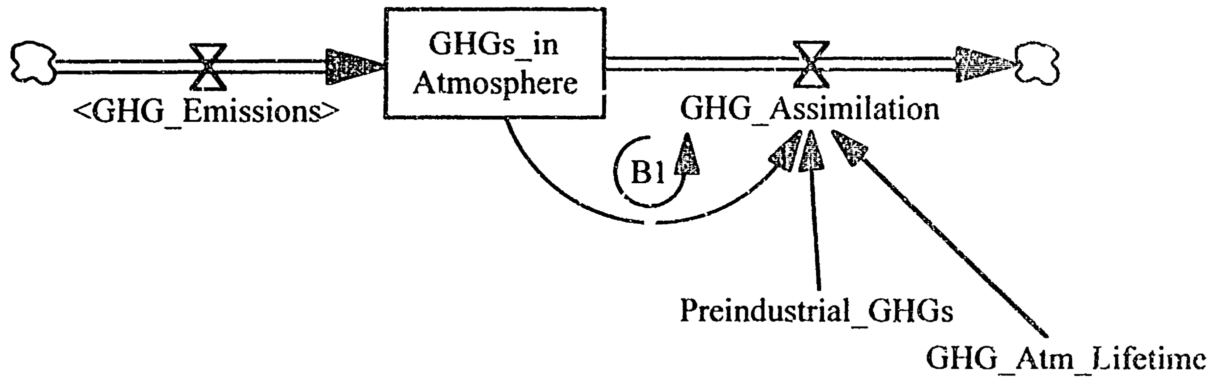


Greenhouse Gas Cycles

Hatlebakk/Moxnes

The Hatlebakk/Moxnes model aggregates all greenhouse gases (GHGs), rather than treating CO_2 alone. The GHG structure is very similar to the carbon cycle of the DICE model; it is also linear and first order. The major difference is that all emissions are initially resident in the atmosphere. Thus the time constant of the GHG assimilation process represents the average time constant of both long and short term storage processes.

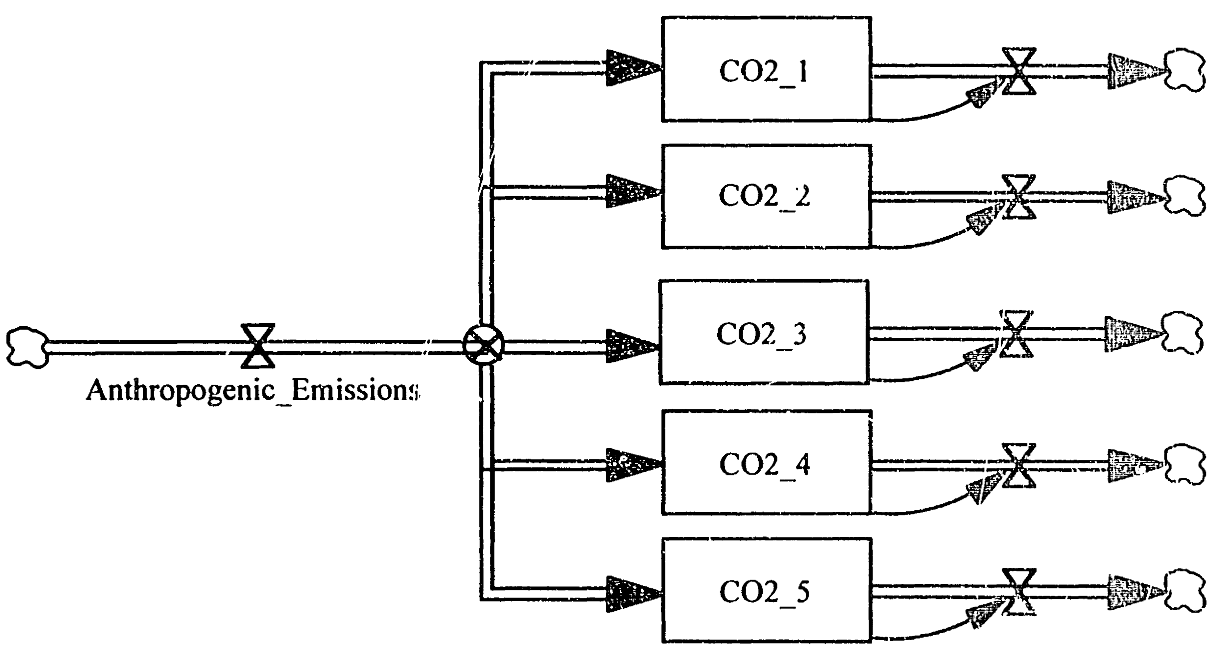
Figure 28: Hatlebakk/Moxnes GHG Cycle



ICAM 2.1R

The ICAM model uses a higher order linear structure to represent the carbon cycle. Emissions are partitioned into five compartments, each of which has a different (first-order) time constant for storage. The time constants range from 1.2 to 1000 years. The model is derived by choosing the parameters of this structure to best fit the 2xCO_2 response of a more complex, physically explicit carbon cycle model. The rate of storage of carbon depends on the atmospheric concentrations in a strictly proportional fashion, and there is no sink constraint to carbon uptake. The ICAM model also incorporates simple first order linear models for N_2O and Methane.

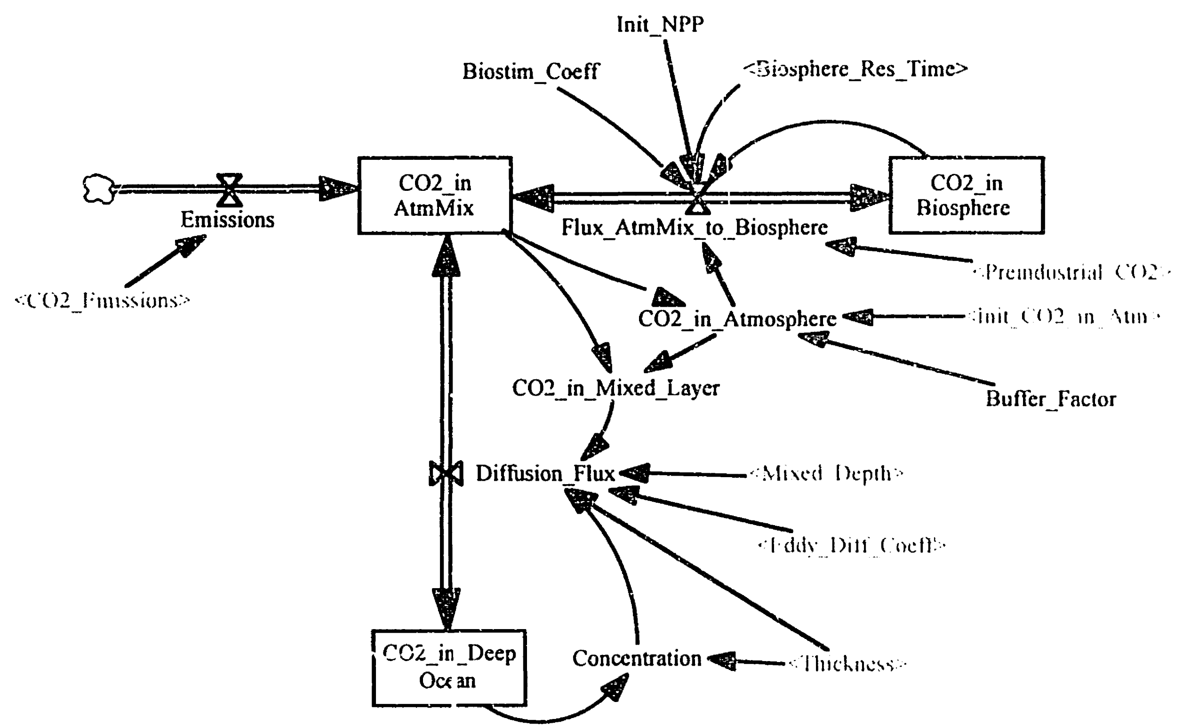
Figure 29: ICAM Carbon Cycle



NICE

The carbon cycle in the NICE model is a reduced form version of that in FREE, in which the atmosphere and mixed layer of the ocean are assumed to equilibrate quickly, so that the two stocks may be aggregated. It is similar to several other simple physical models (Oeschger, Siegenthaler et al. 1975; Goudriaan and Ketner 1984; Rotmans 1990). The system is 12th order (with stocks of carbon in the atmosphere and surface ocean, biosphere, and 10 layers of the deep ocean). There are two major differences between this structure and the carbon cycles of DICE, Hatlebakk/Moxnes, and ICAM. First, the uptake of carbon by the ocean and biosphere is constrained by the capacities of these sinks. Second, there are nonlinearities in ocean chemistry and primary production that cause the uptake of carbon to increase less than proportionally to the concentration of carbon in the atmosphere.

Figure 30: NICE Carbon Cycle



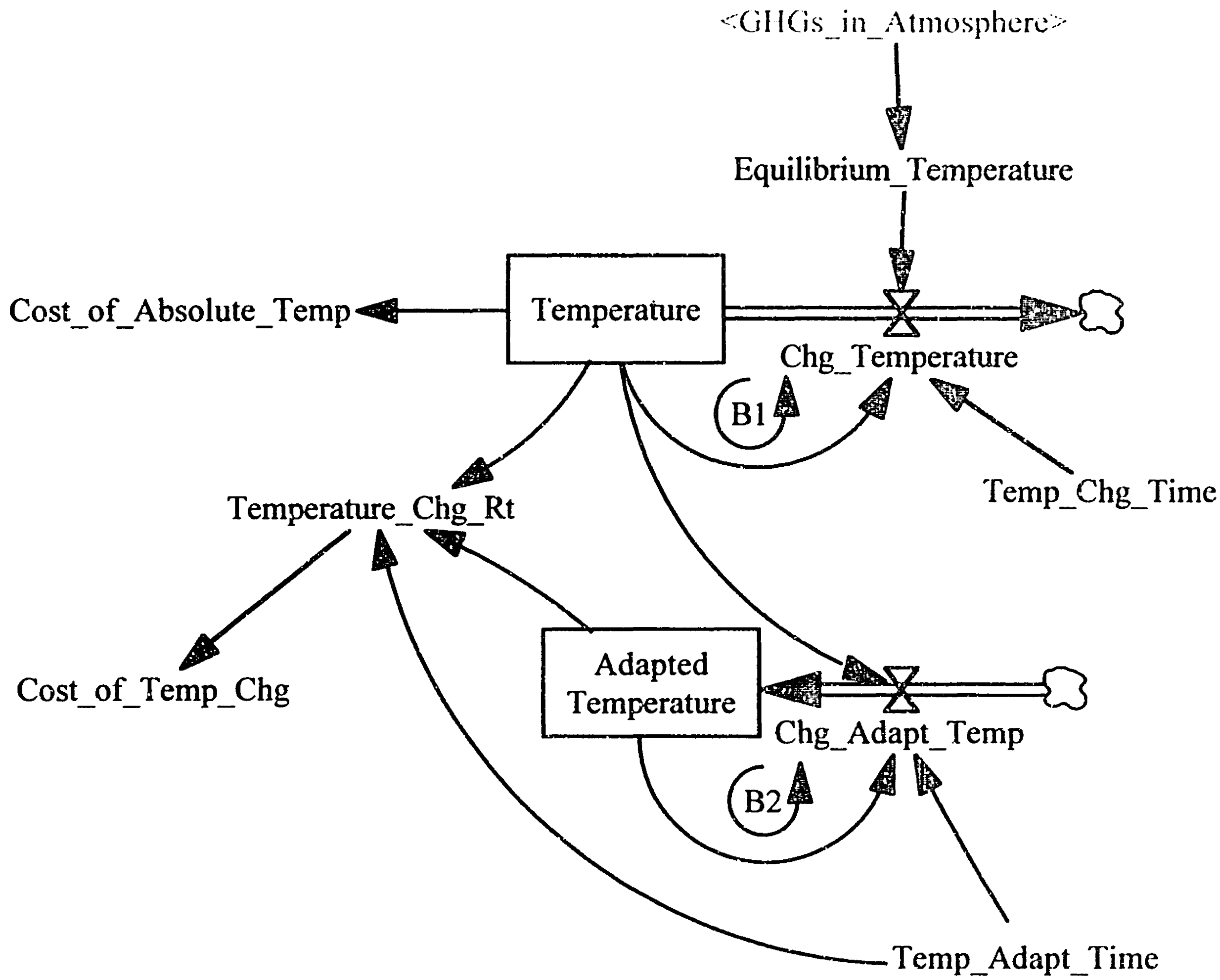
Climate

Hatlebakk/Moxnes

The Hatlebakk/Moxnes model uses a simple, first-order climate system, in which the actual temperature adjusts to the equilibrium temperature with a first-order delay. The equilibrium temperature is a function of the atmospheric GHG concentration, derived from the equilibrium solution to a higher order model.

Climate damages are a function of the absolute temperature change, as in DICE, and of the difference between the current temperature and the temperature to which human and natural systems are adapted. Adaptation occurs with a first-order delay.

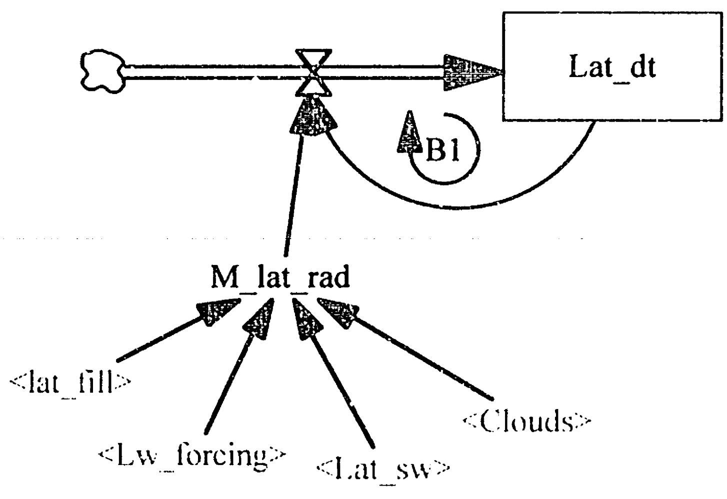
Figure 31: Hatlebakk/Moxnes Climate and Temperature Adaptation



ICAM 2.1R

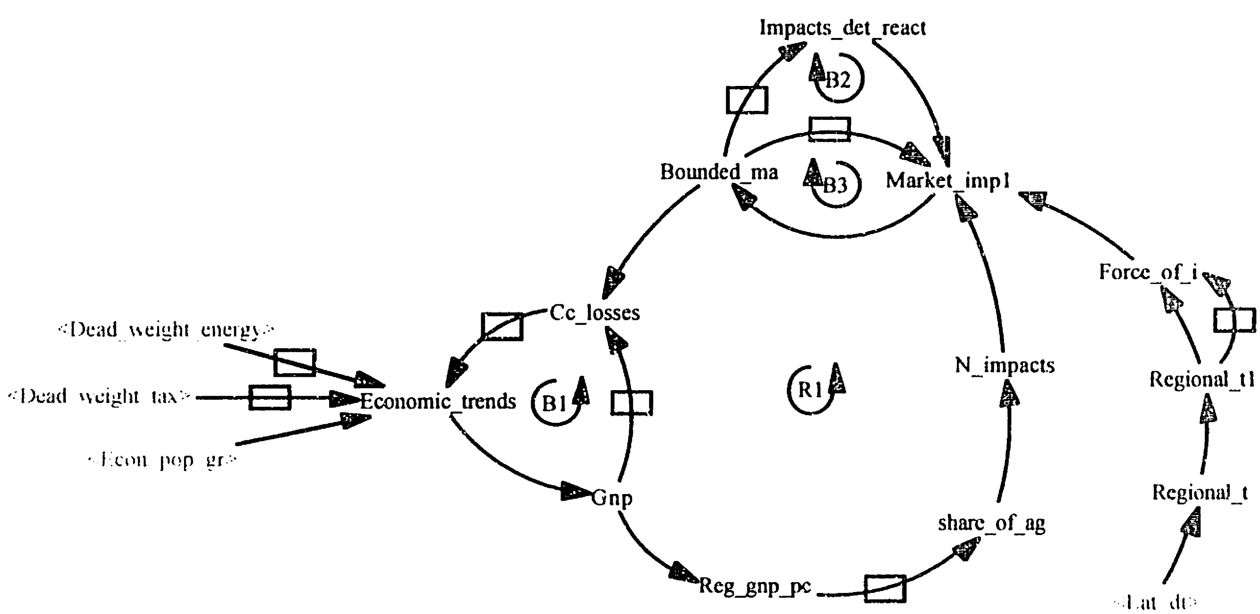
The ICAM model also uses a first-order climate model, which is functionally equivalent to that of the Hatlebakk/Moxnes model (see also Eq. 14). The mean temperature in each latitudinal band adjusts with a delay to its equilibrium value, given radiative forcing. ICAM contains a more detailed representation of radiative forcing than other models, including representation of sulfate aerosols and clouds.

Figure 32: ICAM Climate



The model of climate damages in ICAM includes several unique loops. Increasing GNP increases losses from climate damages, which reduces GNP (loop B1). Falling GNP increases the share of agriculture in output, increasing vulnerability to market impacts and climate change losses, further decreasing GNP, creating a weak positive loop (R1). Market impacts may be reduced by adaptive responses (loop B3), which are initiated only after impacts have exceeded a threshold for perception and action (loop B2).

Figure 33: ICAM Climate Damages



Conclusions

This survey, and other model comparisons, reveal that a number of parallel approaches have emerged for describing parts of the climate-energy-economy system. Among the most convergent model elements are the carbon cycle and climate subsystems. Three representations of the carbon cycle are common—first order linear structures (as in DICE and Hatlebakk/Moxnes), weighted sums of first-order delays fit to complex physical models (as in ICAM), and physical models of varying complexity (as in NICE). The climate system is generally modeled by a low-order linear system, which can be regarded as a lagged adjustment of temperature to an equilibrium value determined by radiative forcing.

Production structures commonly consist of variants of the Ramsey growth model (Ramsey 1928), with nested neoclassical production functions describing the technical frontier. Debate over the economic costs of greenhouse gas abatement has often focused on a few key parameters, such as the rate of autonomous energy efficiency improvement or the elasticity of substitution, that conveniently summarize much of the behavior of this type of model.

Certain generic problems, like irreversibility in emissions abatement, have been widely discussed, but have not yet become subject to any commonly accepted formulation. Hatlebakk/Moxnes and TIME incorporate irreversible price-induced emissions reductions, but in rather different forms. Adjustment costs receive a variety of treatments as well, including first order adjustment processes in Hatlebakk/Moxnes and rate-dependent costs (Grubb, Duong et al. 1994; Grubb, Chapuis et al. 1995). The basis for adjustment costs is more explicit in complex models like EPPA and Global 2100 (Manne and Richels 1992; Yang, Eckaus et al. 1996), which incorporate putty-clay production structures and capital vintaging, but these models still assume that new capital vintages are fully flexible.

Some issues have received rather lopsided treatment in models. While there is an extensive literature documenting the debate over the potential for energy efficiency improvements (Wilson and Swisher 1993; Huntington 1994), only the TIME model takes the side of those who argue that substantial costless or negative cost emissions reductions are available (Lovins and Lovins 1991). The arguments around the energy efficiency gap focus on the efficiency of markets for energy consuming or conserving products. There is also substantial disagreement over the performance of decision makers and markets in general. Here, a wider range of assumptions are embedded in models, from perfect foresight (DICE) to myopic optimization (Connecticut/YOHE, among others). Still, no models take an explicitly behavioral perspective, incorporating the systematic biases, long delays, or other imperfections in perception and action that are especially likely to arise with problems of global scale and long time horizons.

One common feature of most models is the use of exogenous forecasts for factor productivity, population, autonomous energy efficiency improvement, and energy production technologies. While there are good reasons for the exogenous treatment of these variables, it is also clear that each represents a possible set of excluded feedback loops which may affect policy conclusions significantly. Estimates of the autonomous energy efficiency trend, for example, probably include many feedback processes related to environmental or cost issues which should properly be endogenous.

While the consequences of various model structures and parameter choices have received considerable attention, the consequences of simulation method choices have received much less. This survey reveals an alarming number of weaknesses in the representation of dynamics, some of which have serious policy implications. Fortunately, adherence to a few basic principles and practices would eliminate most of these problems:

- Models should be described and implemented in continuous time. This does not preclude the inclusion of discrete or stochastic events, and facilitates many of the other tests described below. If it is necessary to use discrete time (i.e. for optimization purposes), models should at least be prototyped in continuous time.
- The accuracy of numerical integration should be checked by simulating models with different time steps and integration methods. For fast dynamics, appropriately short time steps or equilibrium solutions should be used.
- Stock-flow distinctions should be made clear and model variables should have a clear operational meaning (Senge 1978).
- Dimensional consistency must be verified. This provides an important formal check on model structure and helps to ensure that model relationships do not contain hidden time constants.
- Basic tests should be performed to ensure the robustness and correctness of model formulations. It is important at some time to actually look at the behavior over time of every variable in a model, in order to ensure that the output is plausible given the inputs. Models should be tested to ensure that they converge to plausible equilibria and behave appropriately when subjected to test inputs like step or pulse functions (Forrester 1980; Barlas 1989).
- In complex models, partial model simulations can be used to verify the performance of subunits before integration into a full model (Homer 1983).
- Optimization and sensitivity analysis are useful tools for discovering model flaws. However, models should pass the other dynamic tests above before extensive optimization or sensitivity analysis is performed for policy evaluation.

These principles apply regardless of one's position on various contentious issues like the choice of optimization vs. bounded rationality or the top-down/bottom-up debate. Modeling software can greatly facilitate (or impede) the use of these tests; there is clearly room for considerable improvement in the tools available to integrated modelers.

As in the natural sciences, confidence in a model can be greatly enhanced by independent replication. While there were some difficulties involved in replicating the models reviewed, in general the quality of model documentation is much improved over earlier eras in global modeling (Meadows 1982). The ready availability of models in electronic form is especially helpful and should be encouraged.

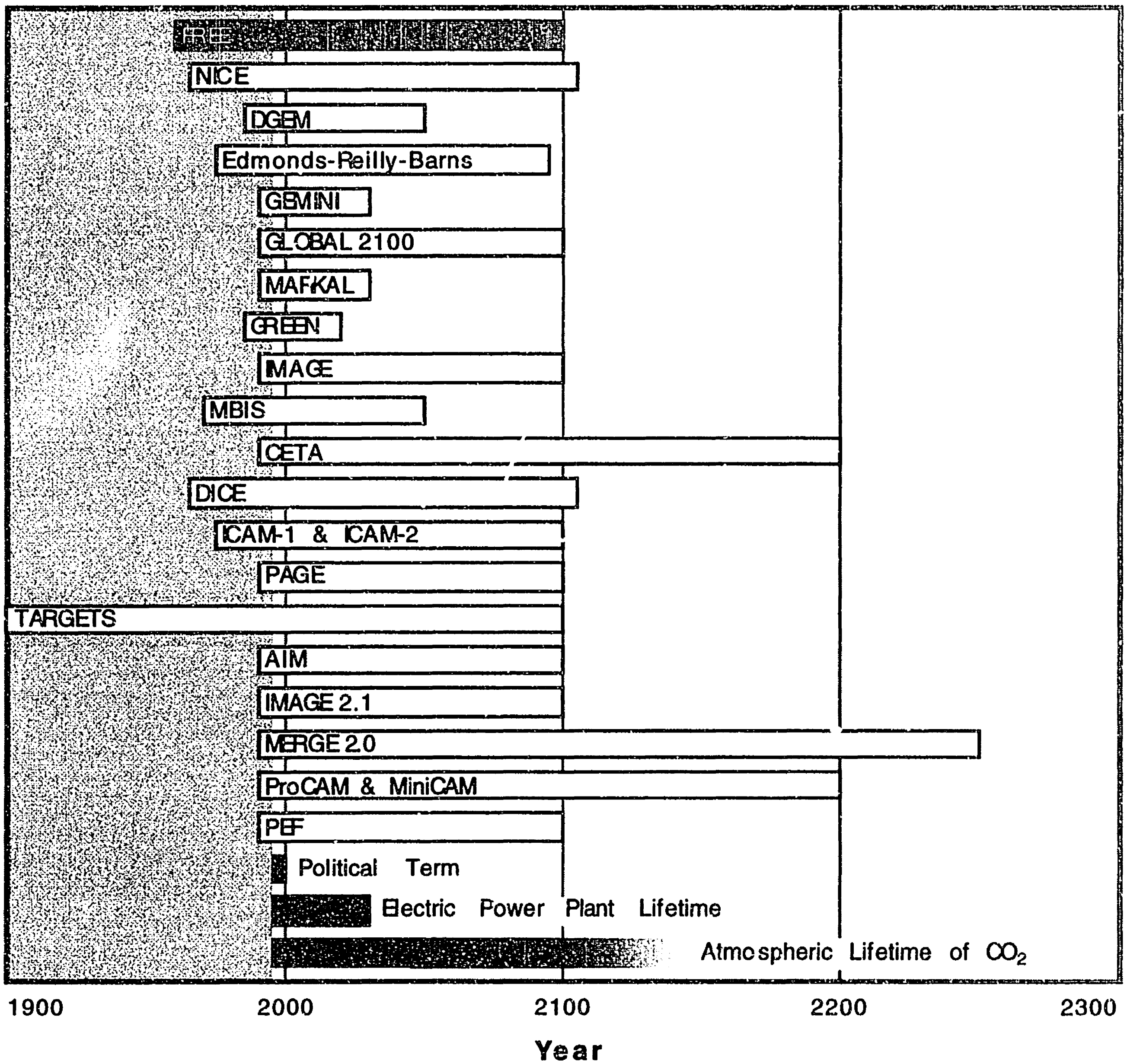
Model Description

This chapter describes the assumptions, structure, and key parameters of the model developed for this research, FREE (Feedback-Rich Energy Economy model). Because the model is quite large, only selected important equations are presented and discussed. Users should refer to the model documentation in the appendices where greater detail is desired.

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.

Figure 34: 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.

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.

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. The impact of omitted feedback in energy technology development is explored in the Policy Analysis chapter.

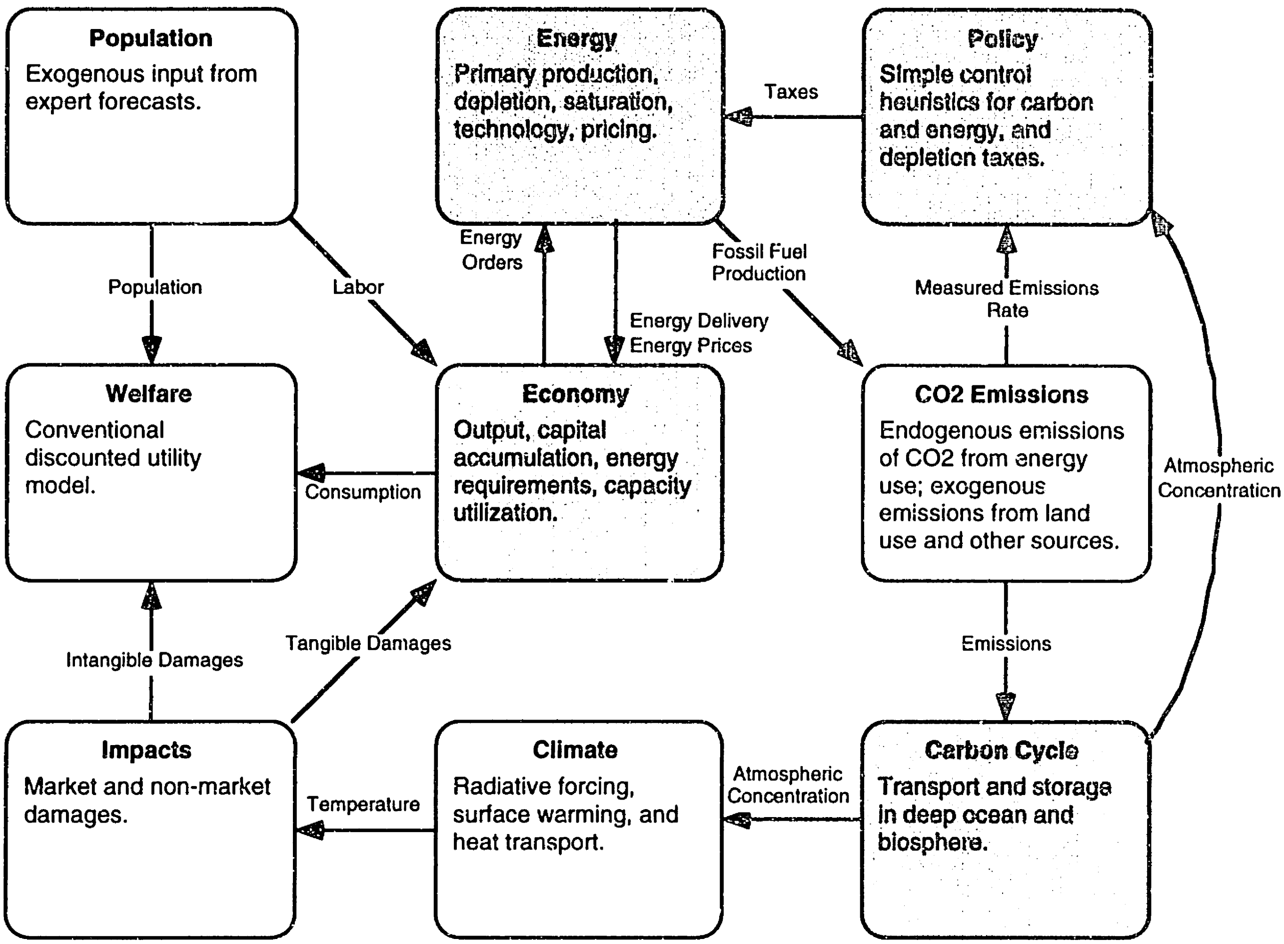
For simplicity, many features have been omitted from the model. There is no regional or sectoral disaggregation (except in the energy sector). Non-energy natural resources are ignored. While the energy sector includes several distinct energy sources, energy conversion activities (such as the generation 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 7: 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 with relatively sparse interactions with the remainder of the model. Figure 35 illustrates the sector boundaries, and each sector is described individually in the following sections.

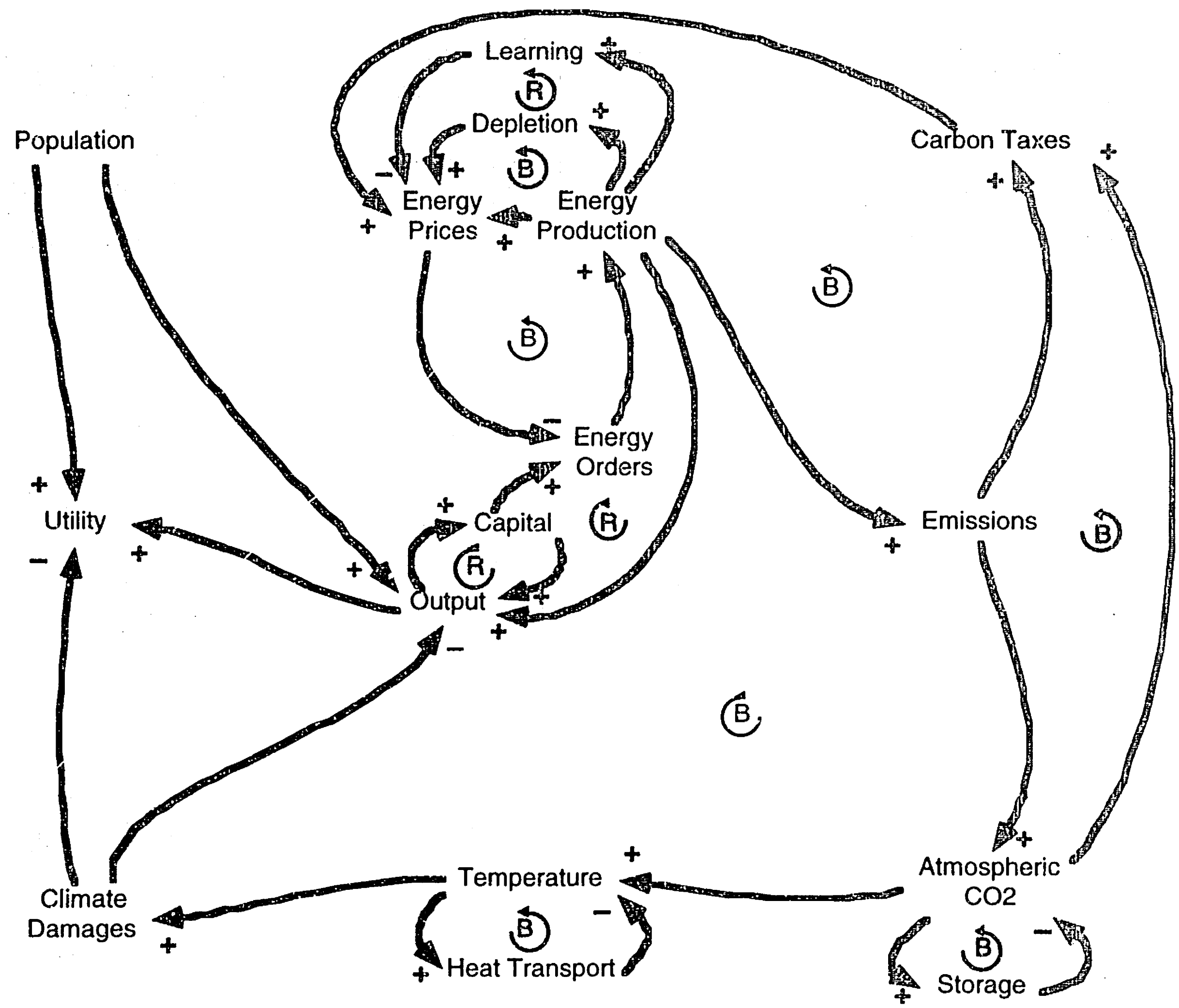
Figure 35: Sector Boundary Diagram



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 36. 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 36: 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.

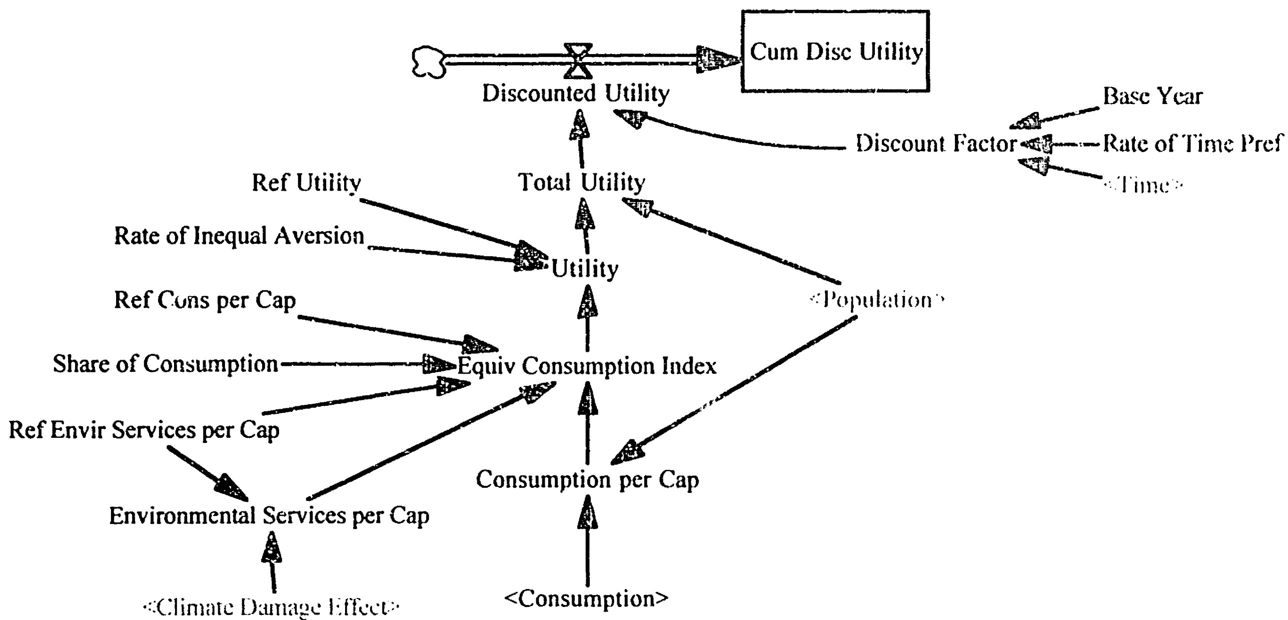
The energy-economy systems in the model draw heavily on Sterman's energy-economy model and the System Dynamics National Model (Senge 1978; Sterman 1980; Sterman 1981). In general, the structures for capital investment and embodiment of energy requirements in capital have been closely copied, while most 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).

Welfare

The welfare sector provides a single indicator of social welfare for use in policy evaluation and optimization. It provides no direct feedback to the rest of the model. Because the objective function for policy selection is decoupled from investment, interest rate, and energy allocation decisions in the the model, it is possible for behavior to be inconsistent with social welfare maximization. This is more realistic than the typical assumptions of intertemporal optimization models, but makes policy evaluation more challenging. The optimal carbon tax may be affected not only by climate change considerations, but also by other market failures. Insufficient valuation of nonrenewable resources may bias the tax considerably (see the Policy Analysis chapter). Consumption and savings decisions may be suboptimal from an intergenerational perspective, suggesting the imposition of an investment subsidy (see Interest Rate section below).

Figure 37: Welfare Sector



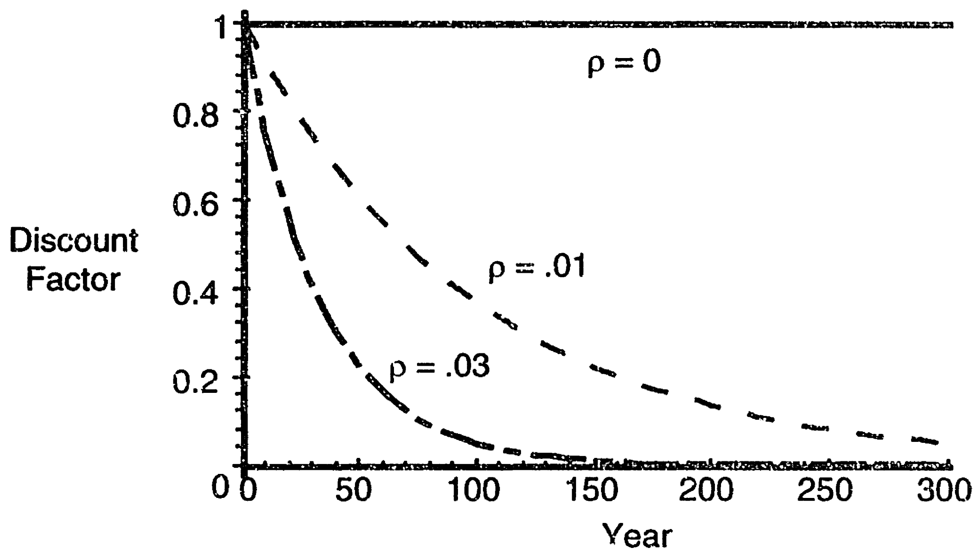
The measure of social welfare is the conventional concept of cumulative discounted utility (Eq. 20), in which the utility of a representative individual is weighted by the population and a discount factor for pure time preference.

$$CDU = \int e^{(-\rho\, t)}\, L(t)\, U(t)\, dt \qquad \text{Eq. 20}$$

CDU = cumulative discounted utility
ρ = rate of time preference
L = population
U = utility of representative individual

Generations with larger populations receive greater weight in the calculation of social welfare. If the rate of time preference is positive, the utility of future generations receives a diminishing weight in the calculation of cumulative welfare as time progresses (Figure 38).

Figure 38: Effect of Discounting for Pure Time Preference



With $\rho = 0$, the welfare of all generations is weighted equally. For $\rho = .01$, the relative weight declines by half in 69 years, while for $\rho = .03$, it declines by half in only 23 years.

The utility of a representative individual depends on the consumption of goods and intangible environmental services (Eq. 21). Goods and environmental services are aggregated by a Cobb-Douglas production function (Eq. 22).

$$U = \frac{ECI^{(1-\theta)} - 1}{1 - \theta} \qquad \text{Eq. 21}$$

ECI = equivalent consumption index

θ = rate of inequality aversion

$$ECI = \left(\frac{c}{c_0}\right)^{\Omega} \left(\frac{S}{S_0}\right)^{(1-\Omega)} \qquad \text{Eq. 22}$$

c = consumption per capita

c_0 = reference consumption per capita

S = environmental services

S_0 = reference environmental services

Ω = share of consumption in utility

$$S = S_0 D_n \qquad \text{Eq. 23}$$

D_n = intangible (non-market) climate damage effects

Environmental services are assumed to be available in a fixed per capita quantity regardless of the population. This is an optimistic assumption, as it ignores effects of crowding or resource degradation, except as caused by climate change (see Impacts section).

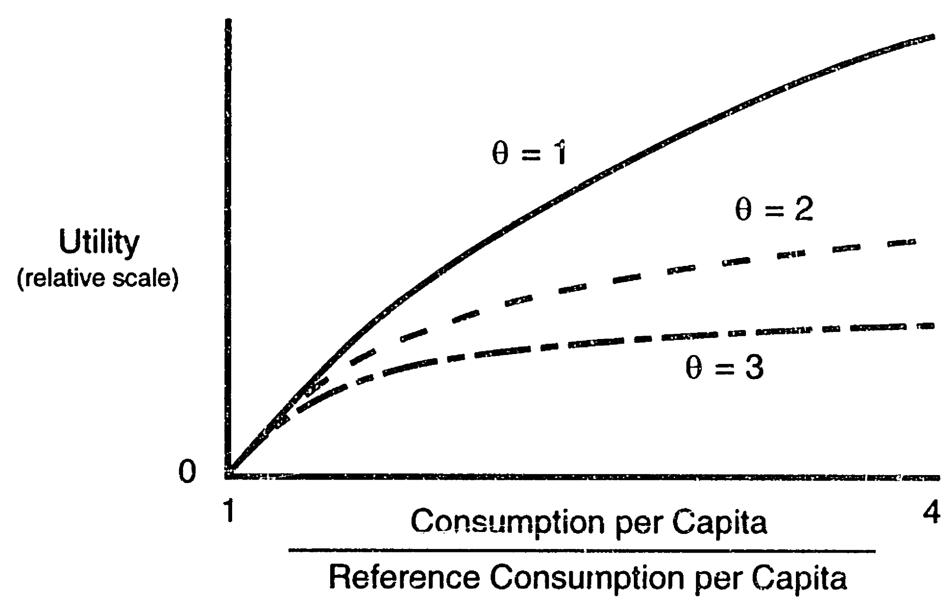
Normally, $\Omega = 1$ in Eq. 22, so an individual's utility is assumed to be purely a function of consumption. In that case, Eq. 22 reduces to the more conventional Eq. 24. If $\theta = 1$, utility is logarithmic.

$$U = \frac{\left(\frac{c}{c_0}\right)^{(1-\theta)} - 1}{1-\theta} \qquad \text{Eq. 24}$$

If $\Omega < 1$, environmental services play a role in welfare creation. Because they are available in fixed supply, their importance increases as wealth (consumption per capita) increases. Thus the willingness to pay to avoid climate effects that damage the environment increases as wealth increases.

With this formulation, the marginal utility of an additional unit of consumption declines with increasing wealth, so that an equivalent 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 (Figure 39). Note that setting $\Omega \neq 1$ changes the effective rate of inequality aversion on consumption.

Figure 39: Effect of Inequality Aversion



For $\theta = 1$, utility is a logarithmic function of consumption per capita. For $\theta > 1$, marginal utility diminishes more quickly as consumption increases.

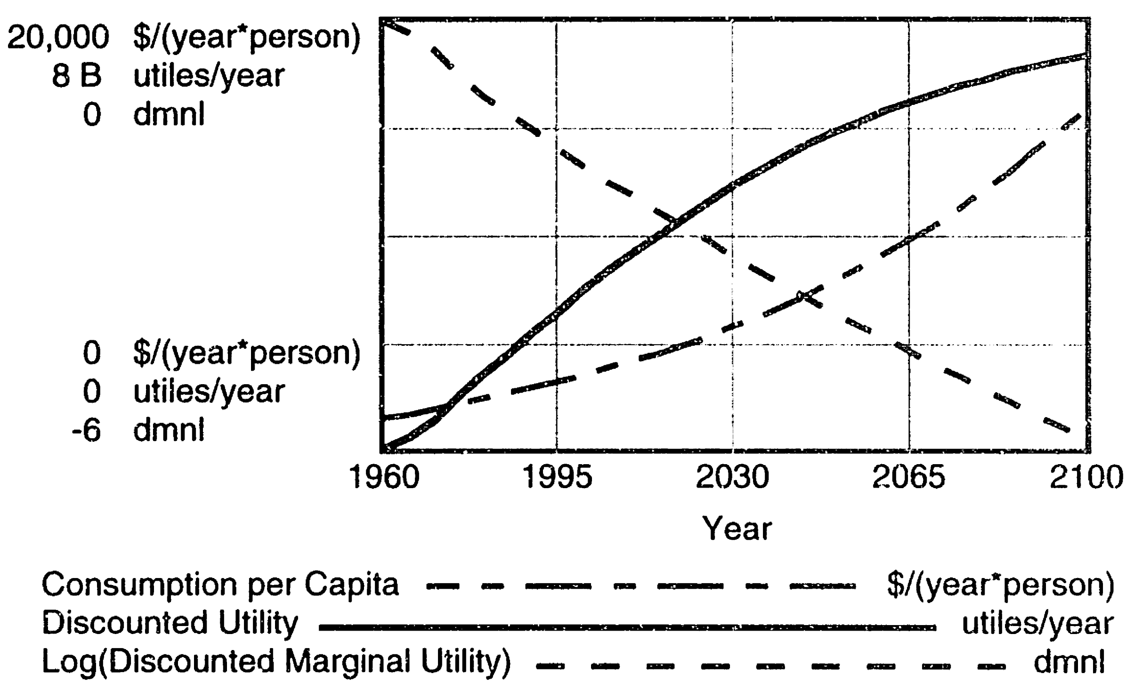
Models using this discounting framework, like DICE, often choose a positive rate of time preference of about 3% and a rate of inequality aversion of 1 (Nordhaus

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. This means that the welfare of future generations is of little importance for the formulation of climate change policy.

The primary motivation for this parameter choice is correspondence with observed rates of investment and 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). Additionally, many economists and philosophers reject pure time preference on ethical grounds (Ramsey 1928; Cline 1992).

The central scenario of the FREE model uses an alternative set of parameters. 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 40).

Figure 40: Utility Behavior



This parameterization creates some practical problems. It requires a longer simulation time horizon in optimization runs, for example—an expected consequence of increased concern for the future. However, it is clearly worthwhile to investigate climate policy on an intergenerationally fair basis. There are several possible interesting extensions of the model along these lines, perhaps incorporating alternative approaches to discounting (Rothenburg 1993; Becker and Mulligan 1994).

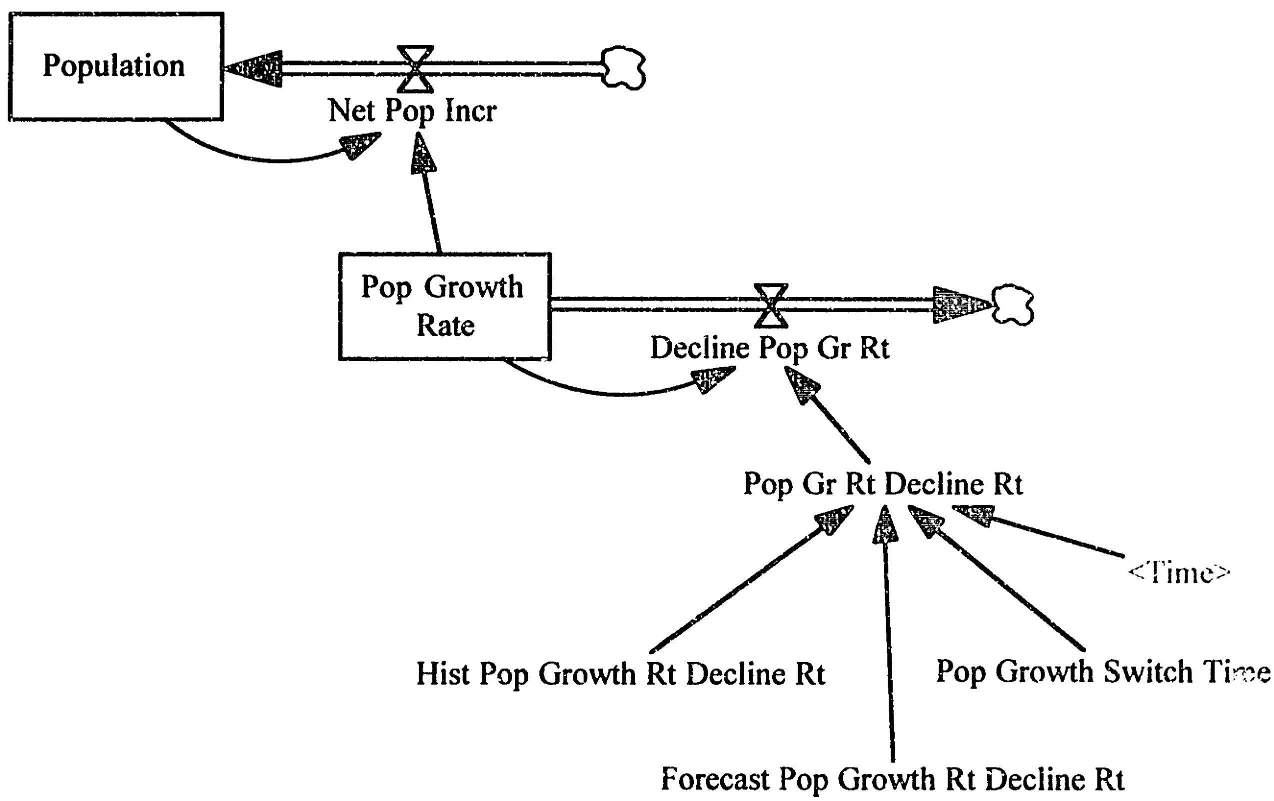
Table 8: Welfare Parameters

Parameter	Alias	Value	Units
Rate of Time Preference	ρ	0	1/year
Rate of Inequality Aversion	θ	2.5	dmnl
Share of Consumption in Utility	Ω	1	dmnl

Population

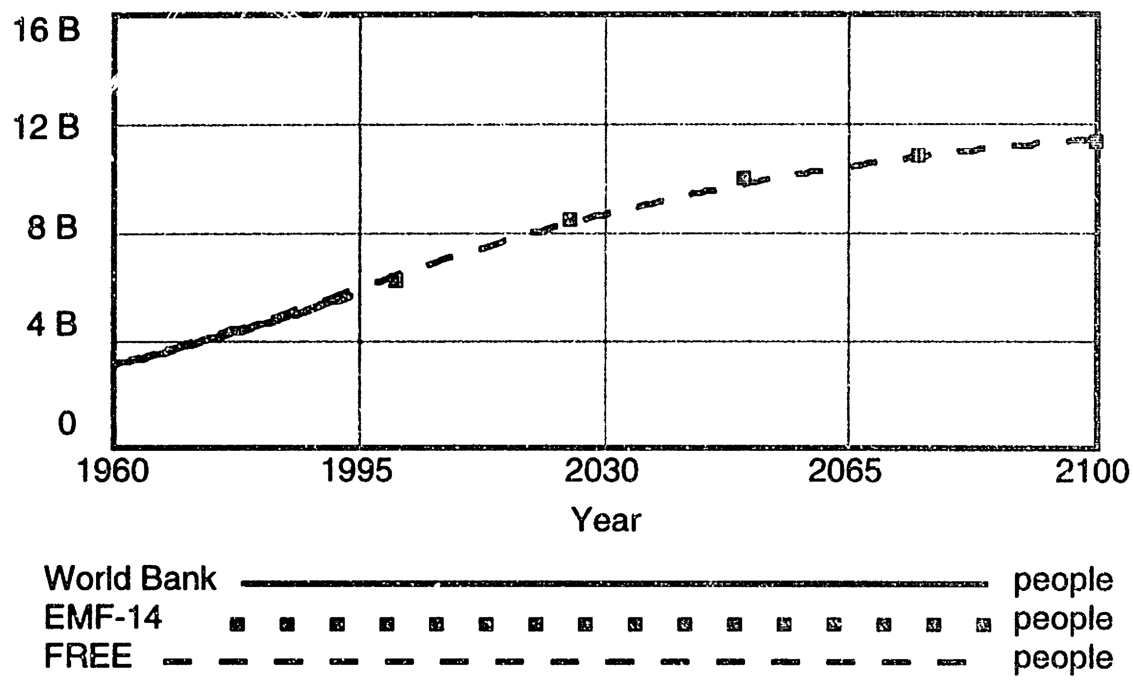
Population in the model is exogenous. The population structure is borrowed from the DICE model, with one refinement. Population is a stock, which grows over time at a diminishing population growth rate. In the DICE model, the rate of population growth diminishes at roughly 2% per year. This rate of change is inconsistent with the 1% rate of decline observed over the model's historical period (1960-1995). Therefore, the rate of decline of the population growth rate is separated into a historical value and a forecast value.

Figure 41: Population Sector



While a more detailed population sector was beyond the scope of this project, it might be desirable for several reasons. Age disaggregation into at least a fourth-order aging chain would reveal that there are important demographic consequences of the rapid decline in population growth rates, which may be inconsistent with the savings and factor productivity assumptions in the model. If increasing wealth is an important determinant of declining population growth rates, then policy choices would be biased towards increasing current consumption.

Figure 42: Population



(Weyant 1995; World Bank 1995)

The assumption of a relatively rapid decline in population growth rates significantly reduces pressure on the climate system. If population rises to a significantly higher level than forecast, the economy grows larger, pressure on the climate system is greater, and the welfare of future generations is more important (Fiddaman 1995; Fiddaman 1996; Kelly and Kolstad 1996).

Table 9: Population Parameters

Parameter	Value	Units	Notes
Initial Population	3.041e9	people	(World Bank 1995)
Initial Population Growth Rate	.0224	1/year	Calibrated to World Bank data
Historic Population Growth Rate Decline Rate	.01	1/year	Calibrated to World Bank data
Forecast Population Growth Rate Decline Rate	.02	1/year	Calibrated to EMF-14 scenario (Weyant 1995)

Interest Rate

Investment decisions for the goods and energy producing capital stocks balance the prevailing rate of interest against the marginal product of capital, net of depreciation. Thus the interest rate in the model is the key determinant of the balance between consumption and investment.

In intertemporal optimization models, investment is determined in order to maximize social welfare. While this may be attractive as a normative policy, it is not a plausible description of actual behavior, as decisions made in this way assume perfect knowledge of the future and of system structure.

The system dynamics litereature provides a number of alternative behavioral models for investment and interest rate determination. Implementation of these theories would increase the model complexity significantly. A disaggregated population structure and explicit accounting of money flows might be required, for example. Since investment behavior is not really the focus of this work, an alternative structure was sought, which remains close to the neoclassical, intertemporally optimal case, but uses only information plausibly available to agents.

One possibility is to convert the equality describing the optimal consumption path in the Ramsey model (the intertemporal optimization model at the heart of DICE and other models) into a behavioral heuristic (Ramsey 1928). Along the steady-state growth path in the Ramsey model, the real interest rate is equal to the sum of the rate of pure time preference and the product of the rate of inequality aversion and the fractional rate of growth of per capita consumption:

$$r = \frac{\left(\frac{\partial}{\partial t} c(t)\right) \theta_c}{c(t)} + \rho_c \qquad \text{Eq. 25}$$

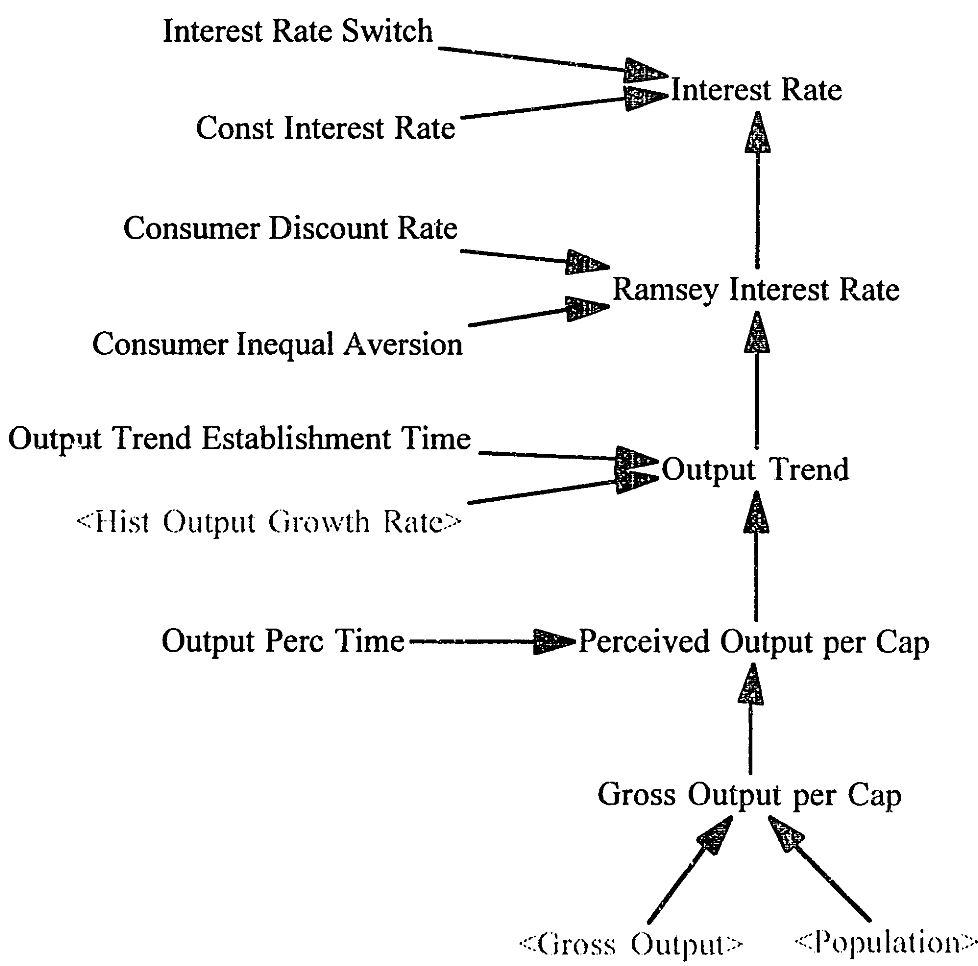
c = per capita consumption $\qquad$ θ_c *= rate of inequality aversion*
r = interest rate $\qquad$ ρ_c *= rate of time preference*

Agents can implement this insight by measuring the rate of consumption growth and adjusting the interest rate accordingly. The Connecticut/YOHE model apparently implements such a rule, though it is not documented with the model (Yohe 1996).

While this is a useful description of the optimal growth path, it is a poor decision rule for discovering that path. It tends to be oscillatory or unstable for some plausible parameter values, particularly when subjected to external shocks. When one examines the feedback structure this decision rule creates, it is apparent why this is so (see Figure 15). Since consumption is a function of both output and the interest rate, the rate of change of consumption depends on the growth rate of output and on the rate of change of the interest rate. Thus, if an external shock reduces output, consumption falls, and the interest rate falls. Investment rises in response to lower interest rates, leading to a further decline in consumption. This positive loop is ordinarily dominated by other loops, but can lead to catastrophic collapse of the economy under many conditions.

This model avoids this problem by exploiting the fact that, in steady state, the growth rates of consumption and output must be equal. The growth rate of output per capita, rather than consumption per capita, is used to determine the interest rate. In disequilbrium conditions, this means that the component of the rate of change in consumption due to changes in investment is neglected, eliminating the positive loop. This leads to stable behavior for a wide range of parameter values.

Figure 43: Interest Rate Sector



The actual value of output per capita is perceived only with a delay, and the trend in output is established over a long historical period. This reflects the fact that changes in savings involve long delays both to filter short term economic fluctuations and because behavior patterns are slow to change.

The parameters of Eq. 25 normally used to describe consumer (or investor) behavior embody the typical assumptions of logarithmic utility and a 3% per year rate of pure time preference. While time preference may be unethical in an intergenerational context, it is likely and sensible for it to play a role in an individual's consumption and investment decisions (Schelling 1995). If the social welfare function used for policy evaluation uses a lower rate of time preference, it may be optimal to implement an investment subsidy, among other policies. This may bias the apparent optimal carbon tax, though it appears that carbon taxes and investment behavior are relatively insensitive to one another.

The model also provides the option of using a constant (exogenous) interest rate, as in most cost-benefit analyses. However, a constant interest rate is only consistent with the typical model outcome of declining economic growth rates if pure time preference is high and inequality aversion is low.

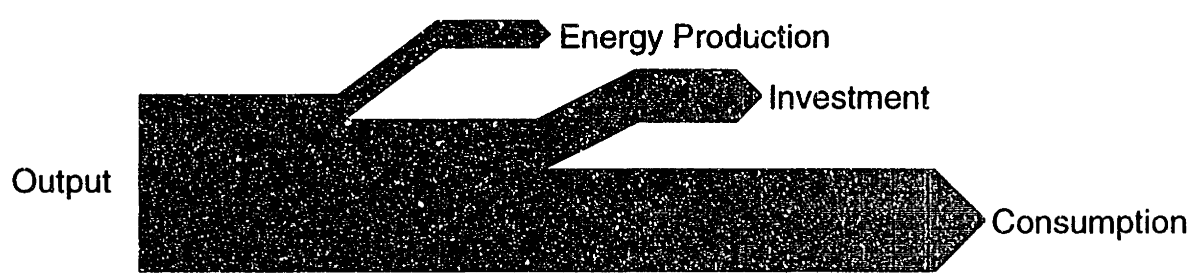
Table 10: Interest Rate Parameters

Parameter	Alias	Value	Units	Notes
Constant Interest Rate		.055	1/year	Not normally active. (Weyant 1995)
Consumer Discount Rate	ρ_C	.03	1/year	
Consumer Inequality Aversion	θ_C	1	dmnl	Logarithmic utility.
Output Perception Time		5	years	
Output Trend Establishment Time		20	years	

Goods Allocation

The goods allocation sector distributes economic output among energy production requirements, investment requirements, and consumption. The short-term variable costs required for energy production have first call on output. Then, investment requirements are deducted, and the residue is allocated to consumption.

Figure 44: Goods Allocation

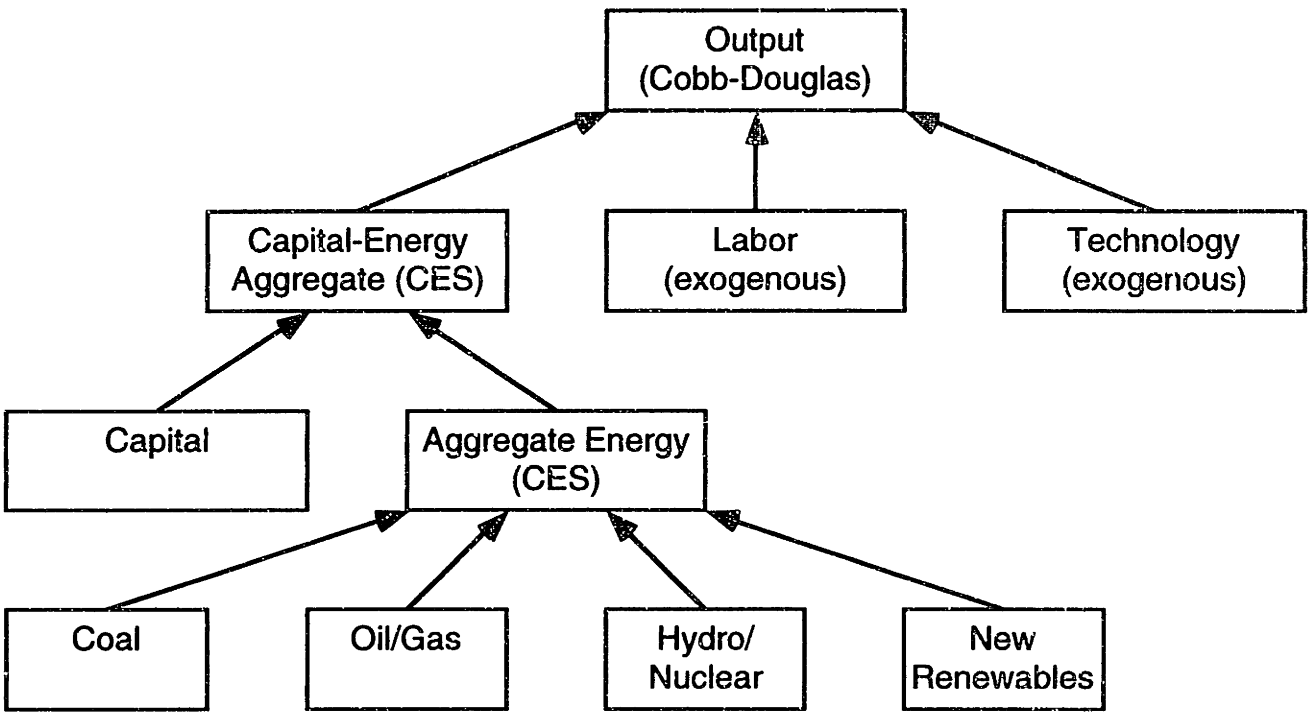


For robustness under extreme conditions, the actual input of goods and services to energy production and investment is constrained to be less than or equal to the quantity actually available. In practice, this constraint is never binding.

Goods Production

In the long run, the goods production sector is structured much like other economic and system dynamics models, with a nested structure of CES and Cobb-Douglas production functions:

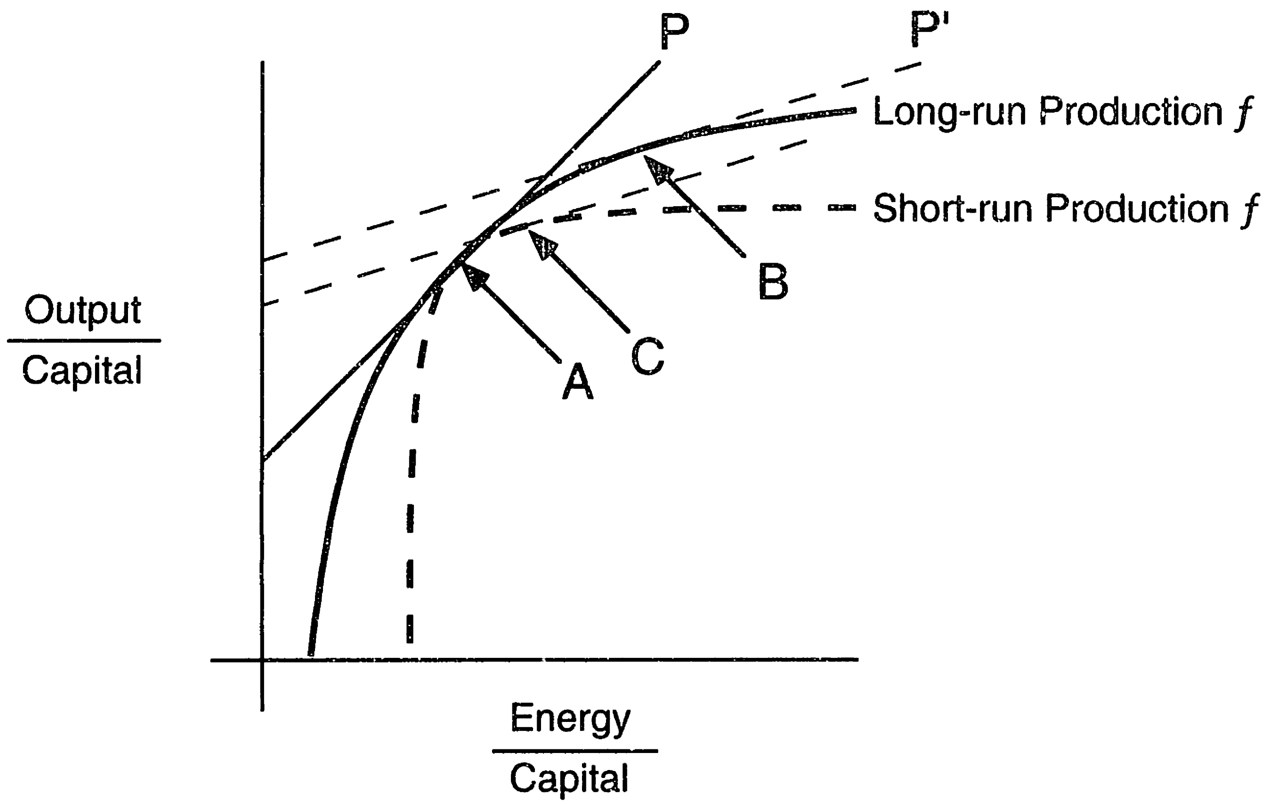
Figure 45: Long-run Production Structure



The major feature that differentiates the production structure of the FREE model from that of other small climate-economy models is that energy requirements are embodied in in the capital stock. That is, once capital is constructed, it is only possible to adjust its energy intensity along a more restricted (i.e. lower elasticity) production function. This reflects the fact that, in the real world, energy consumption depends on the energy requirements of durable products like automobiles, machinery, and homes. For example, once an automobile rolls off the assembly line, there is little that can be done to alter its fuel efficiency, so changes in fuel consumption must be acheived largely through changes in driving patterns. Models like DICE, by contrast, assume that gas-guzzling full-size pickup trucks can be immediately and costlessly converted to fuel-sipping subcompacts.

Embodiment of energy requirements in capital allows one to distinguish between the costs of suboptimal capital utilization during a transition to a different energy system and the true long-run costs of that system. It also allows the long-run elasticity of substition among energy supply technologies to be realistically high, without generating unrealistic short-term behavior, because the substitution induced by price changes takes effect only gradually, as the capital stock is replaced.

Figure 46: Long vs. Short-run Production Functions



A decrease in energy prices from P to P′ promotes limited substitution of energy for capital in the short run (A to C), but a much larger change in the long run (A to B).

Output

Output is generated by a Cobb-Douglas production function between the short-run capital-energy aggregate good, labor, and technology (Eq. 26). Labor participation is assumed to be constant; households thus make no substitutions between income and household labor input or leisure time. Also, the labor intensity of capital is flexible, so that there is always full employment. Variations in productivity from climate damages or changing energy prices thus lead instantaneously to variations in the wage.

$$Y = Y_0 \, T \, D_m \left(\frac{L}{L_0}\right)^{\alpha} \left(\frac{KO}{KO_0}\right)^{(1-\alpha)}$$ Eq. 26

Y = gross output
Y_0 = reference gross output
T = factor productivity
L = labor
L_0 = initial labor
KO = operating capital
KO_0 = reference operating capital
α = value share of labor

In the standard scenario, output closely replicates historical GDP. Over the future horizon of the model, output growth is calibrated by adjusting the rate of factor productivity growth to correspond roughly with the EMF-14 scenario. To achieve this fit, the factor productivity growth rate must fall to .75% per year—half its initial value of 1.5% per year.

Figure 47: Gross Output

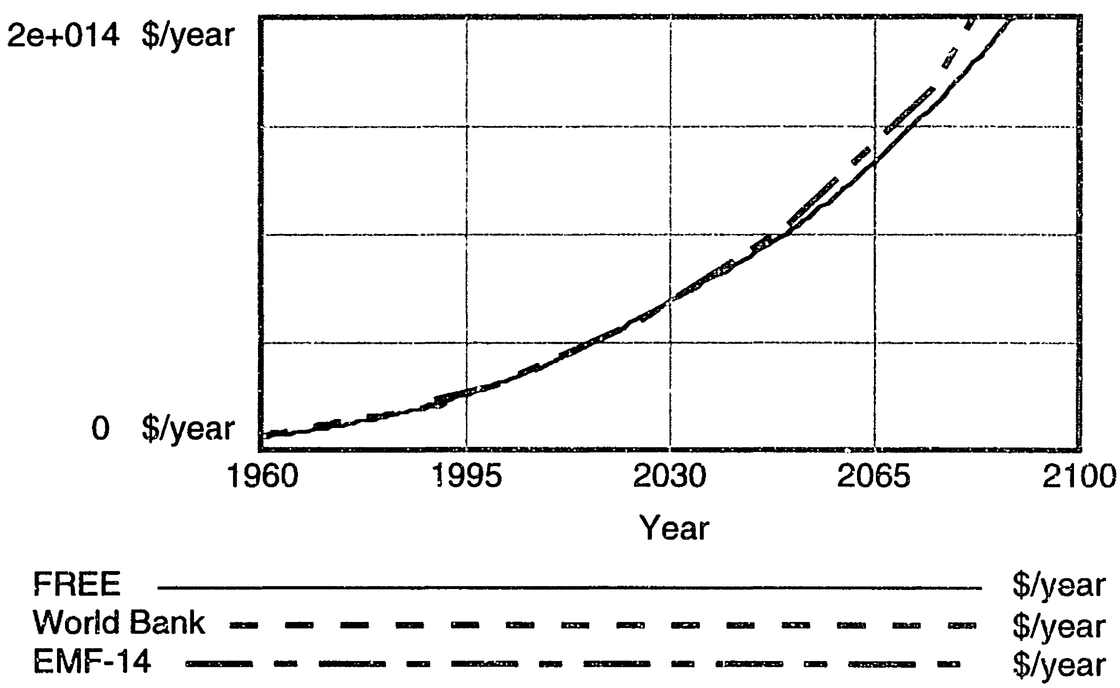


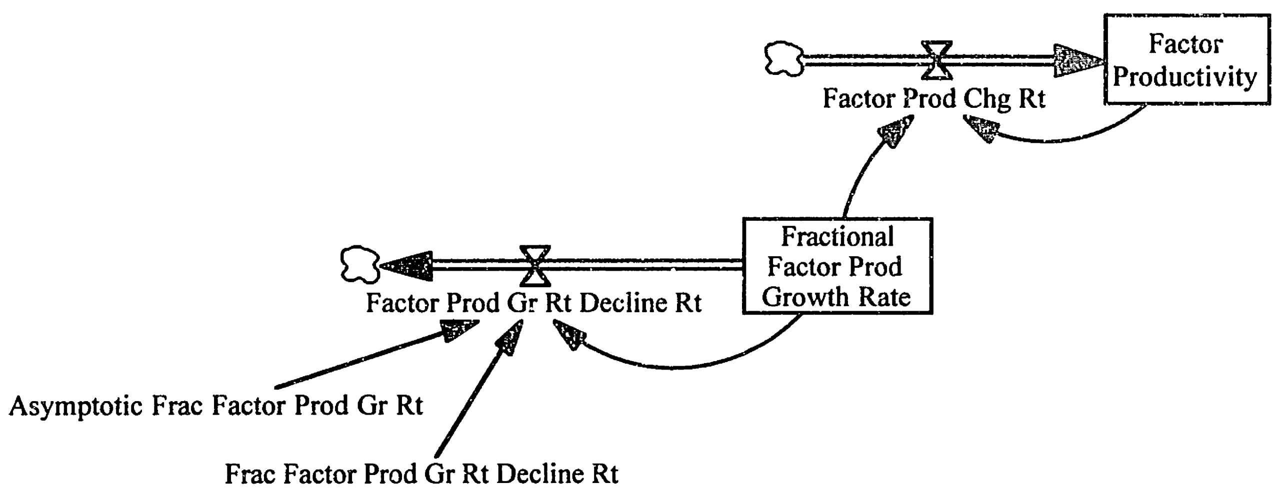
Table 11: Output Parameters

Parameter	Alias	Value	Units	Notes
Value Share of Labor	α	.7	dmnl	
Reference Output	Y_0	6.124e12	$/year	Model is denominated in constant 1990 dollars.

Factor Productivity

As in other models, factor-neutral improvement in productivity is an important driver of economic growth. Factor productivity grows at an exogenous fractional rate. The growth rate itself declines exogenously to a constant asymptotic value.

Figure 48: Factor Productivity



If the asymptotic growth rate is zero, technical progress eventually ceases, as in the DICE model. If it is nonzero (as in the standard scenario of the FREE model), factor productivity improvement continues to drive economic growth.

Figure 49: Factor Productivity

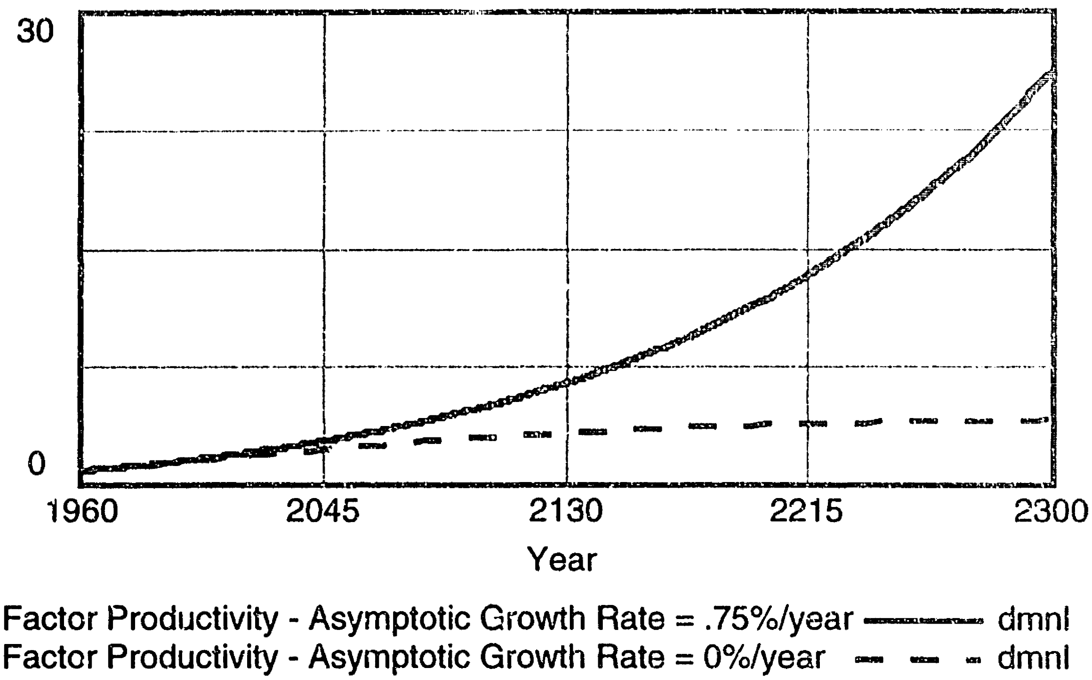


Table 12: Factor Productivity Parameters

Parameter	Value	Units	Notes
Initial Factor Productivity Growth Rate	.015	1/year	(Nordhaus 1994)
Factor Productivity Growth Rate Decline Rate	.01	1/year	(Nordhaus 1994)
Asymptotic Factor Productivity Growth Rate	.0075	1/year	Calibrated to EMF-14 scenario (Weyant 1995)

Short-run Production Structure

In the short run, the utilization of capital is varied in response to changing energy prices. If energy prices are higher than the values for which the capital stock was designed, utilization falls, as only the most efficient capital is operated. Operating capital is a function of the normal capital-energy aggregate, the actual input of the aggregate energy good, and the normal aggregate energy requirement of capital (Eq. 27). The short-run value share coefficient for energy inputs is chosen such that the short-run production function is tangent to the long-run production function (Eq. 31) at normal utilization of capital.

$$KO = KN\left(\beta_{sr} + \left(1-\beta_{sr}\right)\left(\frac{EI}{EN}\right)^{\rho_{ke,sr}}\right)^{\left(\frac{1}{\rho_{ke,sr}}\right)} \qquad \text{Eq. 27}$$

KN = normal short-run capital-energy aggregate
EI = actual aggregate energy input
EN = normal aggregate energy input
β_{sr} = *value share of capital in short-run capital-energy aggregate*
$\rho_{ke,sr}$ = *short-run capital-energy substitution coefficient*

$$\rho = \frac{\sigma - 1}{\sigma} \qquad \text{Eq. 28}$$

ρ = *substitution coefficient*
σ = *substitution elasticity*

Similarly, the short-run aggregate energy good is a function of the actual delivered energy input for each source and the energy requirements embodied in capital (Eq. 29). Again, the short-run value share coefficients for energy sources are chosen such that the short-run production function is tangent to the long-run production function (Eq. 32) when the normal mix of energy sources is used.

$$EI = EN\left(\sum_{i} \gamma_{i,sr}\left(\frac{ED_i}{ER_i}\right)^{\rho_{e,sr}}\right)^{\left(\frac{1}{\rho_{e,sr}}\right)} \qquad \text{Eq. 29}$$

ED_i = *energy delivery rate*
ER_i = *embodied energy requirement*
i = subscript for energy sources
$\gamma_{i,sr}$ = *value share of energy sources in short-run aggregate energy product*
$\rho_{e,sr}$ = *short-run energy substitution coefficient*

Energy ordered is delivered by the energy sector with a one-quarter delay, provided that the energy sector's capacity constraints are not binding (see below). Energy orders are determined by adjusting the current energy delivery rate for the current price and marginal product of energy.

$$EO_i = ED_i \left(\frac{M_{i,sr}}{P_i} \right)^{\eta} \qquad \text{Eq. 30}$$

EO_i = *energy order rate*
ED_i = *energy delivery rate*
$M_{i,sr}$ = *short-run marginal product of energy*
P_i = *perceived energy price*
η = *energy order adjustment coefficient*

Long Run Production Structure

The long-run production function is similar to the short-run structure, with the exception that elasticities of substitution between capital and the aggregate energy good and among energy sources are higher.

$$KN = KN_0 \left(\left(1 - A\beta_{lr}\right) \left(\frac{K}{K_0} \right)^{\rho_{ke,lr}} + A\beta_{lr} \left(\frac{EN}{EN_0} \right)^{\rho_{ke,lr}} \right)^{\left(\frac{1}{\rho_{ke,lr}} \right)} \qquad \text{Eq. 31}$$

KN = *normal capital-energy aggregate*
KN_0 = *reference capital-energy aggregate*
K = *capital*
K_0 = *reference capital*
EN = *normal aggregate energy input*
EN_0 = *reference aggregate energy input*
A = *embodied autonomous energy efficiency improvement*
β_{lr} = *long-run value share of energy*
$\rho_{ke,lr}$ = *long-run capital-energy substitution coefficient*

$$EN = EN_0 \left(\sum_i \gamma_{i,lr} \left(\frac{ER_i}{ER_{i,0}} \right)^{\rho_{e,lr}} \right)^{\left(\frac{1}{\rho_{e,lr}} \right)} \qquad \text{Eq. 32}$$

ER_i = *embodied energy requirement*
$\gamma_{i,lr}$ = *value share of energy source*
$\rho_{e,lr}$ = *long-run energy substitution coefficient*

Table 13: Production Structure Parameters

Parameter	Alias	Value	Units	Notes
Long Run Capital-Energy Substitution Elasticity	$\sigma_{ke,lr}$	.75	dmnl	Behavior may lower effective long-run elasticity. See Energy Requirements section for details.
Long Run Inter-Energy Substitution Elasticity	$\sigma_{e,lr}$	2	dmnl	
Short Run Capital-Energy Substitution Elasticity	$\sigma_{ke,sr}$	.1	dmnl	
Short Run Inter-Energy Substitution Elasticity	$\sigma_{e,sr}$	.2	dmnl	

Capital

Capital for goods production increases with investment, and is discarded after a fixed average lifetime (Eq. 33). There is no vintaging of capital, so the depreciation process behaves like a first-order exponential decay.

$$K(t) = \int I(t) - \delta K(t)\, dt \qquad \text{Eq. 33}$$

K = *capital*
I = *investment rate*
δ = *fractional depreciation rate*

Capital orders respond to three pressures (Eq. 34). Orders first replace depreciation (loops B1 and R1 in Figure 50). They also correct the gap between desired and actual capital over the capital correction time (loop B3). The desired capital stock is anchored on the actual capital stock and adjusted for the relative cost and marginal product of capital (loops B2 and R2, Eq. 35). Finally, orders augment the capital stock in order to anticipate growth in output (loop R3); otherwise capital would continously lag its optimal value.

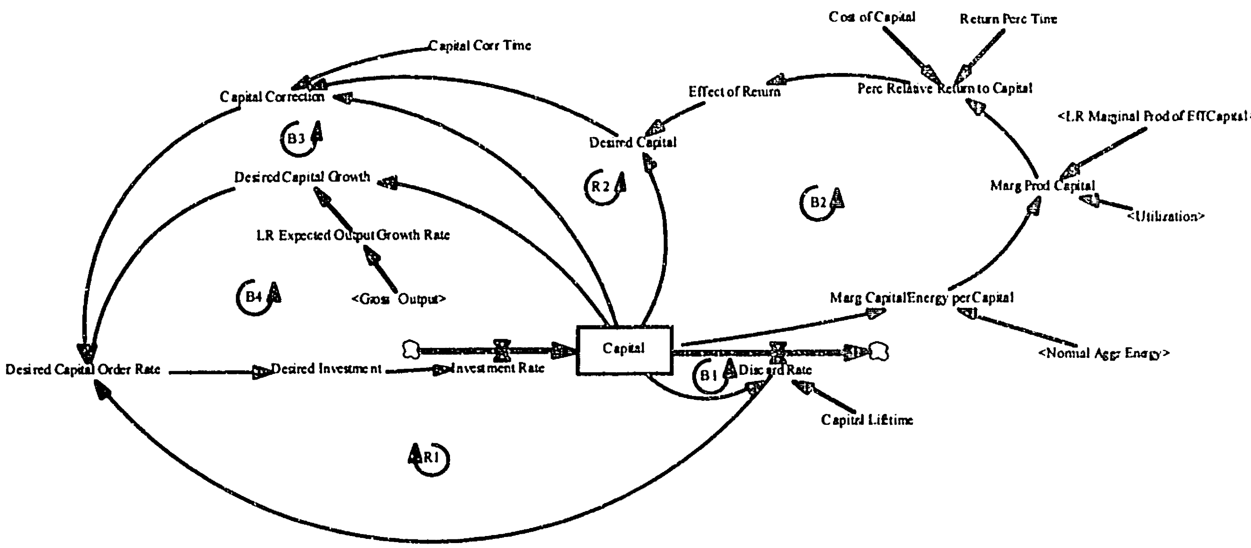
$$I = \mathrm{MAX}\left(0, \delta K + \frac{DK - K}{\tau_k} + K\,G\right) \qquad \text{Eq. 34}$$

DK = *desired capital*
τ_k = *capital correction time*
G = *perceived fractional growth rate of output*

$$DK = \frac{K M_k}{r} \qquad \text{Eq. 35}$$

M_k = *marginal product of capital*
r = *interest rate*

Figure 50: Capital



Loop B2, profit-driven capital stock correction, is the only loop that exists in general equilibrium models. This is unrealistic, as firms and consumers do not make decisions on the basis of current returns alone and cannot instantaneously perceive the marginal product of capital. While the profit feedback loop is sufficient to control the capital stock when the model is simulated to equilibrium at each time step, it performs poorly if used in isolation in a disequilibrium model.

Table 14: Capital Parameters

Parameter	Alias	Value	Units
Capital Lifetime	$1/\delta$	15	years
Time to Correct Capital	τ_k	4	years

Energy Requirements

Energy requirements for each source are embodied in the capital stock (Sterman 1981). Energy requirements are tracked separately for each of the four sources, under the assumption that they have significantly different carriers (i.e. solid fuel vs. electricity) and thus are not highly substitutable in the short run. The capital stock is not subdivided into vintages; all ages are assumed to be well-mixed.

The assumptions of perfect mixing and distinct energy carriers are somewhat restrictive. Larger models like EPPA (Yang, Eckaus et al. 1996) typically maintain separate vintages for each discrete time step and include a near-perfect substitute for each major fuel. The practical difference between the two approaches arises only when there are extreme changes in energy costs, as might occur if depletion of oil and gas were to happen very suddenly. In a model like EPPA, this would lead to immediate substitution of backstop fuels for oil and gas, and the use of older capital vintages would be discontinued. Capacity utilization in new and recent capital vintages, which would be better adapted to the new costs, could remain high, though. In the FREF model, by contrast, utilization across the entire capital stock would have to fall, and the short-run transition to backstop fuels would be limited.

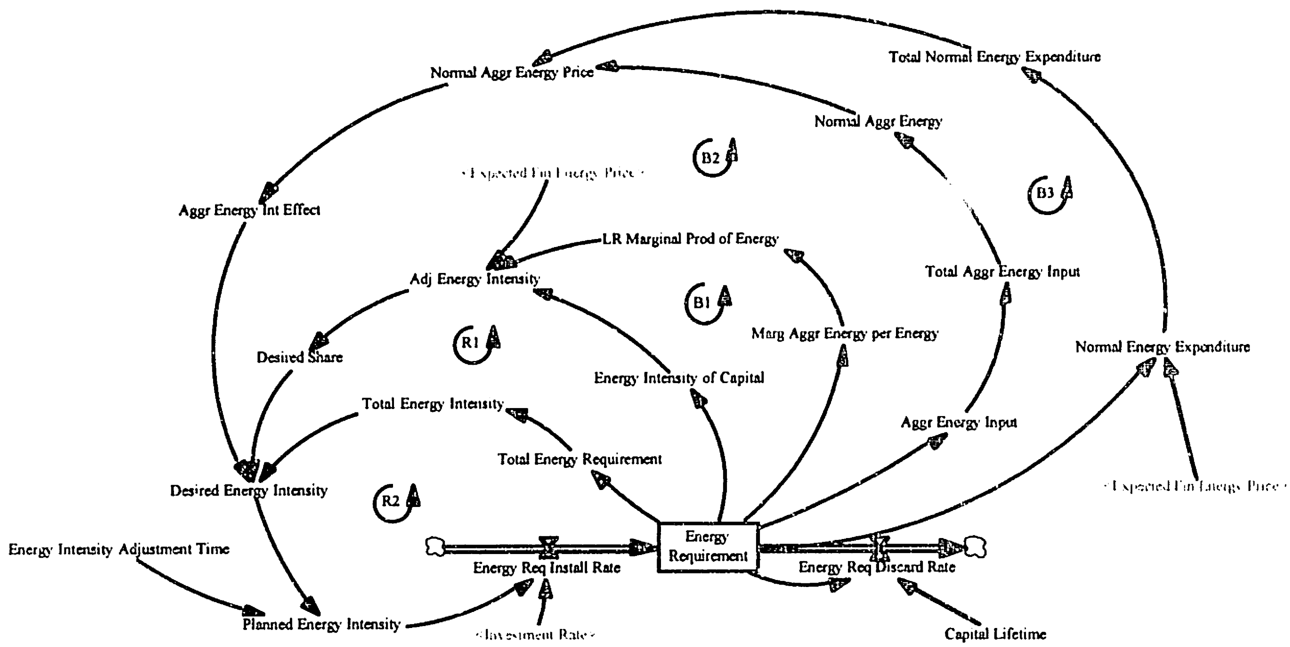
The rates of installation and discard of energy requirements are co-flows with capital investment and discards. In addition, retrofits adjust the energy requirements of existing capital to the current planned energy intensity of new capital. Retrofits thus function like an accelerated rate of capital discard, with costless replacement.

$$ER_i(t) = \int N_i(t)\,(\mathrm{I}(t) + \varepsilon\,\mathrm{K}(t)) - (\delta + \varepsilon)\,ER_i(t)\,dt \qquad \text{Eq. 36}$$

ER_i = *energy requirement*	I = *investment rate*
N_i = *planned energy intensity of new capital*	ε = *fractional retrofit rate*
	δ = *fractional discard rate*

In reality, retrofits are not free, and the rate of retrofitting varies according to the relative cost and the potential savings gained by retrofitting a unit of capital. When the energy intensity of the existing capital stock is far from the planned energy intensity of new capital, the potential savings are large, and retrofits are implemented rapidly. However, these effects are neglected, and retrofits are not normally active in the standard scenario of the model. Retrofit potential is captured instead in the short-run substitution elasticity.

Figure 51: Energy Requirements



Note: retrofits are omitted from the diagram for clarity.

The energy requirements of new capital are determined by anchoring to the existing energy intensity of capital, and adjusting for the price of each energy source relative to its marginal product in the long-run production function. Two delays influence this process. First, it takes time to form expectations of future energy prices (energy forecasts may also include extrapolation of past trends). Second, it takes time to incorporate the desired energy intensity into planned products.

$$N_i(t) = \int \frac{ND_i(t) - N_i(t)}{\tau_n} dt \qquad \text{Eq. 37}$$

N_i = planned energy intensity of new capital

ND_i = desired energy intensity of new capital

τ_n = energy intensity planning delay

The energy intensity adjustment has two components: an adjustment to the aggregate energy intensity (loops B2 and B3 in Figure 51), and an adjustment to the relative shares of individual energy sources (loop B1). Each adjustment process operates by anchoring to the current energy intensity (loops R1 and R2), and adjusting for the relative price and marginal product of energy.

$$ND_i = N_T \, AE \, DS_i \qquad \text{Eq. 38}$$

N_T = *total energy intensity of capital*

AE = *aggregate energy intensity adjustment*

DS_i = *desired share*

$$N_T = \frac{\sum_i ER_i}{K} \qquad \text{Eq. 39}$$

ER_i = *energy requirement*

K = *capital*

The first component, the adjustment to aggregate energy intensity, compares the marginal product of the aggregate energy good to the aggregate price of energy from all sources. This is, in effect, a decision about total energy efficiency—the insulation thickness in homes, or the balance of public transport vs. private automobiles.

$$AE = \left(\frac{M_T}{P_T} \right)^{\left(\omega \, \sigma_{ke,lr} \right)} \qquad \text{Eq. 40}$$

M_T = *long-run marginal product of aggregate energy*

P_T = *perceived aggregate energy price*

ω = *energy intensity adjustment coefficient*

$\sigma_{ke,lr}$ = *long-run capital-energy substitution elasticity*

The second component, adjustment to the relative shares of individual energy sources, corresponds to decisions about fuel switching—gas vs. electric appliances, or coal-fired electric vs. solar water heating.

$$DS_i = \frac{AI_i}{\sum_j AI_j} \qquad \text{Eq. 41}$$

AI_i = *adjusted energy intensity*

i,j = *subscripts for energy sources*

$$AI_i = \frac{ER_i \left(\frac{M_{i,lr}}{P_i} \right)^{\left(\omega \, \sigma_{e,lr} \right)}}{K} \qquad \text{Eq. 42}$$

$M_{i,lr}$ = long-run marginal product of energy

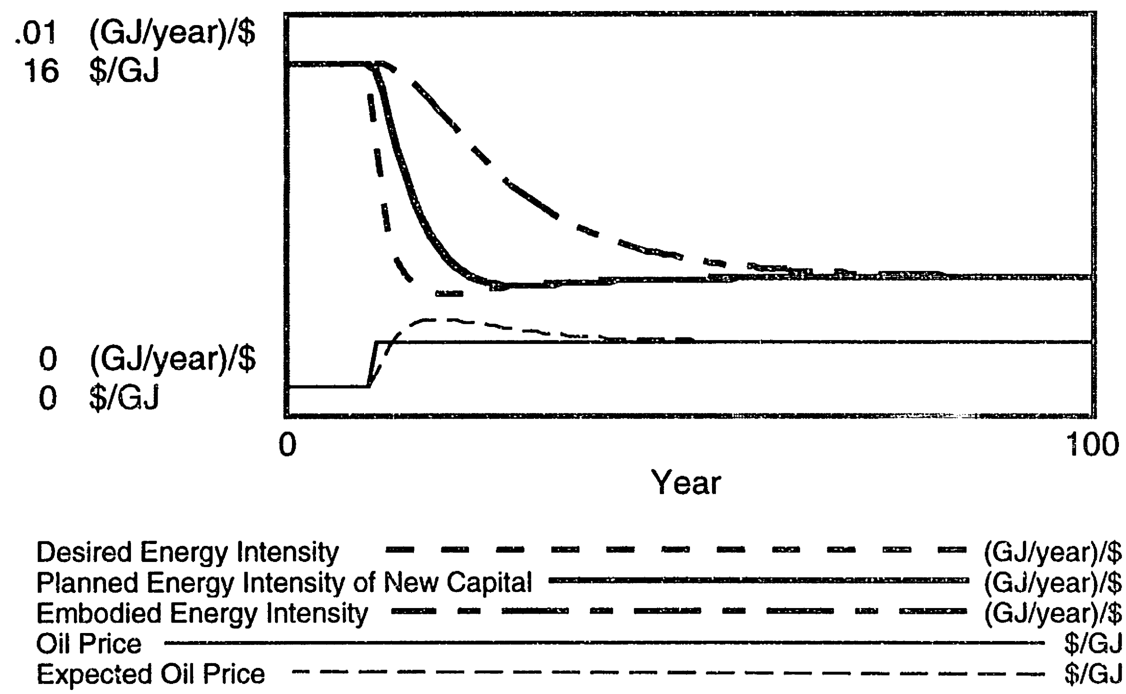
P_i = perceived energy price

ω = energy intensity adjustment coefficient

$\sigma_{e,lr}$ = long-run inter-energy substitution elasticity

If the energy intensity adjustment coefficient in Eq. 40 and Eq. 42, ω, is set equal to 1, the model will behave like a general equilbrium model with a putty-clay structure. In this case, a change in energy prices results in an immediate adjustment of the energy intensity of new capital (neglecting perception and planning delays) to its optimal value.

Figure 52: Energy Intensity Adjustment

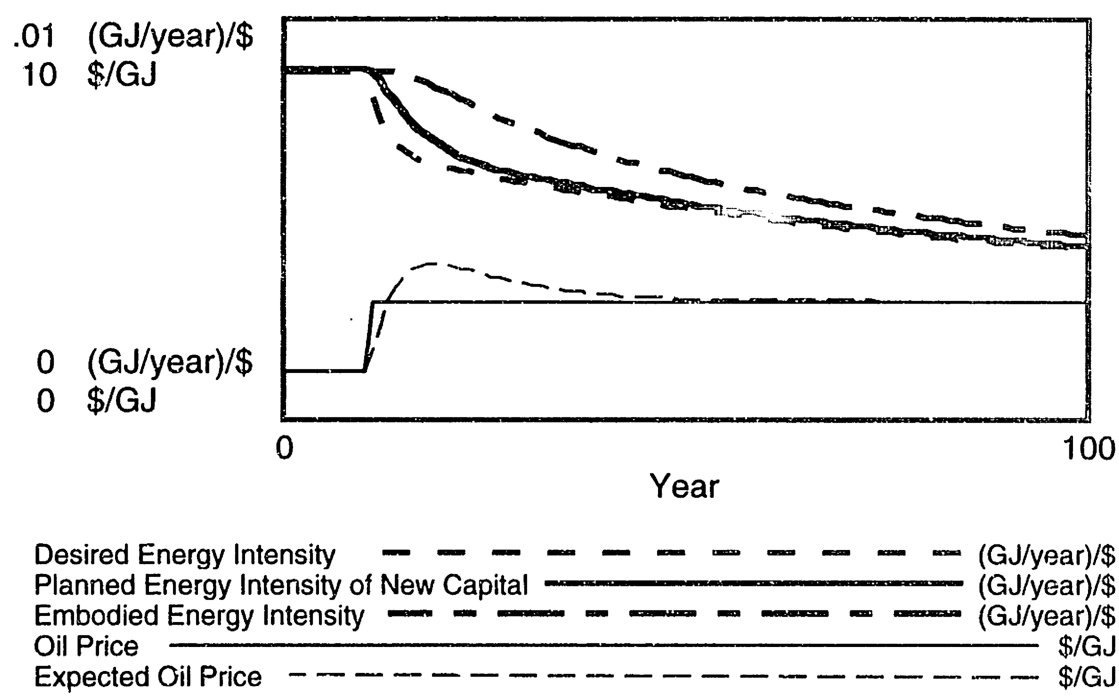


Response of embodied energy requirements for oil to a step increase in oil prices for ω = 1. The expected oil price overshoots the actual oil price significantly, due to extrapolation of the price trend. Desired energy intensity rapidly adjusts to the new, lower optimal value given expected prices, and then relaxes slightly upward as the expected price overshoot diminishes. The planned energy intensity of new capital lags desired energy intensity by the time required to change the product mix. The energy intensity embodied in the capital stock adjusts more slowly, as the capital stock is replaced. Compare with Figure 53.

If ω = 1, the long-run interfuel substitution elasticity must be less than 1 in order for the model to behave realistically when subjected to shocks like the OPEC oil price increases. But in the CES production structure, a substitution elasticity of less than 1 implies that economic output must be zero if any fuel is eliminated from the energy mix. This is clearly not the case in reality, and use of such low elasticities leads to a model which is not robust.

In addition, consumers and firms do not know the true long-run production function of the economy; they must climb local gradients to improve performance. In the case of energy, which represents a small fraction of total output, these gradients are likely to be perceived weakly. More importantly, these gradients are biased toward the energy characteristics of existing capital by path-dependency effects. For example, the productivity of investment in a particular transportation mode is influenced not only by the long-run optimal transportation mix, but also by the infrastructure built up around the current transportation mix (Hourcade and Chapuis 1994).

Figure 53: Constrained Energy Intensity Adjustment



Response of embodied energy requirements for oil to a step increase in oil prices. ω = .33, so the effective adjustment in the energy intensity of new capital has one-third the magnitude that one would expect given the long run capital-energy and interfuel substitution elasticities. Prices and price expectations are the same as in Figure 52. Desired energy intensity now adjusts much more slowly, as it is biased toward the embodied energy intensity of capital, which changes only as capital is replaced. Compare with Figure 52.

Considering behavior, robustness, and path dependency arguments, it seems likely that the adjustment of the energy intensity of new capital toward the economy's true long-run production frontier is not instantaneous; that is, $\omega < 1$. In this case the adjustment of the energy intensity of the capital stock to its long-run optimal value is substantially slower (see Figure 53).

Since prior estimates of elasticities rely on models with substantially different structures from that presented here, the model was parameterized by first setting the capital-energy and interfuel substitution elasticities σ_{lr} to plausibly high a priori values and then using ω to calibrate the model to historical data. The resulting values for the true long run substitution elasticities are at the high end of the range found in other models (Table 13), while the effective response of the new capital adjustment process is at the low end (Nordhaus and Yohe 1983; Burniaux, Nicoletti et al. 1992; Manne, Mendelsohn et al. 1995; Yang, Eckaus et al. 1996; Yohe and Wallace 1996). The balance between behavioral (ω) and structural (σ) factors in the determination of substitution potential is a crucial area for sensitivity analysis.

Table 15: Energy Requirement Parameters

Parameter	Alias	Value	Units	Notes
Energy Intensity Adjustment Coefficient	ω	.33	dmnl	
Energy Intensity Adjustment Time	τ_n	4	years	Sum of perception and implementation delays in Sterman (1981)

Autonomous Energy Efficiency Improvement

Like energy requirements, autonomous energy efficiency improvements (AEEI) are embodied in the capital stock. The AEEI of new capital adjusts exponentially to a nonzero asymptotic value. The energy intensity of capital has practical and thermodynamic lower limits, so AEEI cannot reach zero. As capital is installed, discarded, or retrofitted, the average AEEI embodied in the capital stock adjusts as a co-flow.

$$A(t) = \frac{\int AEEI(t)\,(I(t) + \varepsilon K(t)) - (\delta + \varepsilon)\,A(t)\,dt}{K(t)} \qquad \text{Eq. 43}$$

A = average embodied AEEI of capital
AEEI = autonomous energy efficiency improvement level of new capital
K = capital
I = investment rate
ε = fractional retrofit rate
δ = fractional discard rate

$$\mathrm{AEEI}(t) = \int \alpha_a \left(AEEI_\infty - \mathrm{AEEI}(t) \right) dt \qquad \text{Eq. 44}$$

$AEEI_\infty$ = asymptotic energy efficiency improvement level

α_a = fractional autonomous energy efficiency improvement rate

Figure 54: Embodied Autonomous Energy Efficiency Improvement

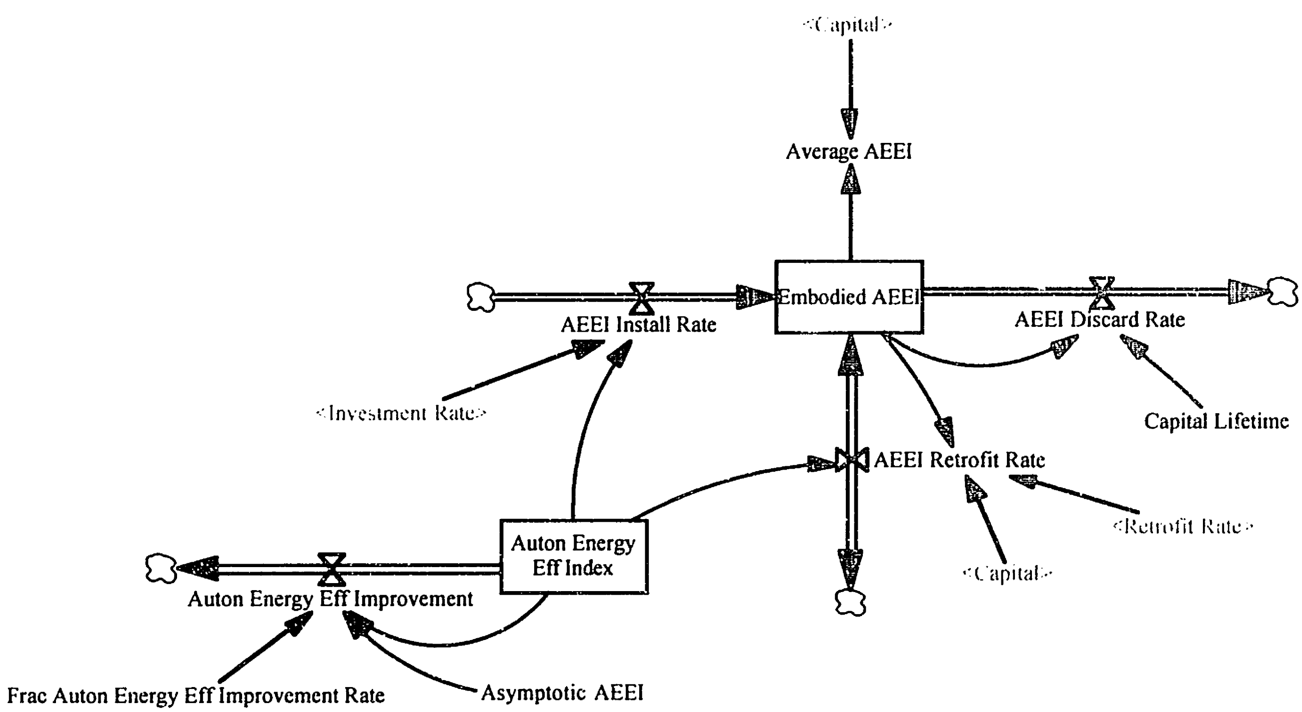
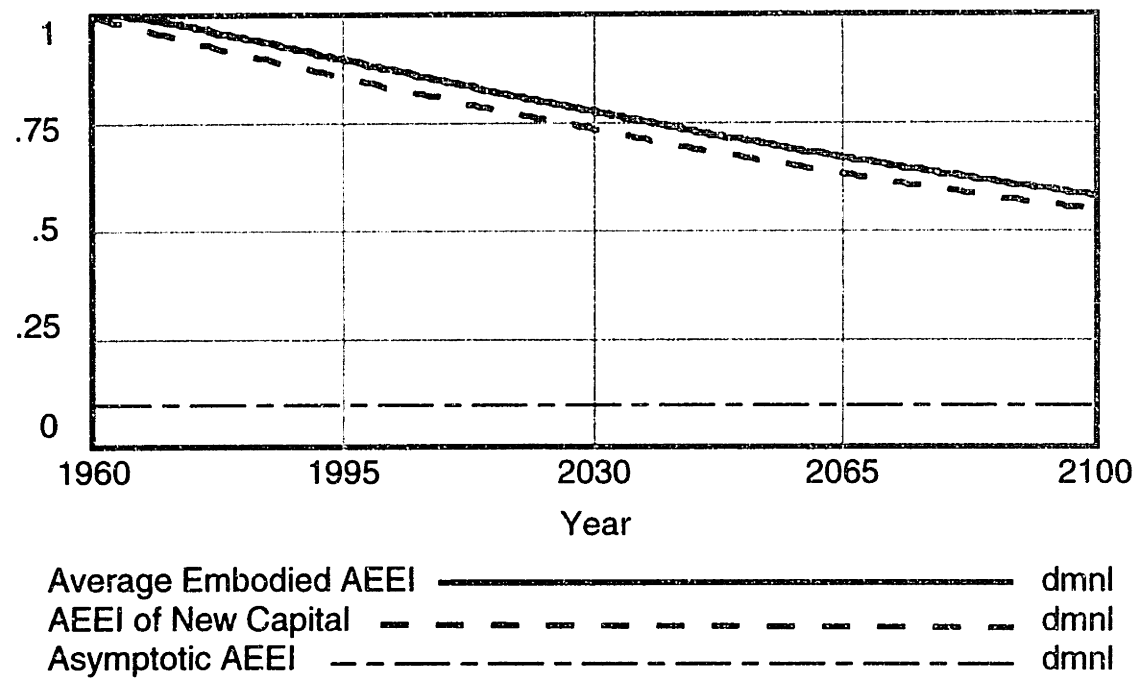


Figure 55 shows the behavior of autonomous energy efficiency improvement. The average embodied AEEI declines at the same rate at the AEEI of new capital, but lags it by about 10 years. If the capital stock is in equilibrium, with investment just replacing depreciation, the embodied AEEI lags the AEEI of new capital by the capital lifetime, 15 years. If investment grows rapidly, the lag is shorter, as most of the capital stock consists of recently-installed capital with characteristics close to the AEEI of new capital. With no investment, the embodied AEEI remains constant, even though the potential AEEI of new capital continues to improve.

Figure 55: Autonomous Energy Efficiency Improvement Behavior



Under normal conditions, when the fractional autonomous energy efficiency improvement rate is low and the rates of growth and turnover of capital are relatively constant, the AEEI in this model does not behave significantly differently from the unembodied AEEI in simpler models. Differences arise mainly in extreme conditions, when investment rates change dramatically, for example.

Table 16: Autonomous Energy Efficiency Improvement Parameters

Parameter	Alias	Value	Units	Notes
Autonomous Energy Efficieny Improvement Rate	α_a	.005	1/year	Lower bound of typical range (Beaver 1993)
Asymptotic AEEI	$AEEI_\infty$	.1	dmnl	(Gilli, Nakicenovic et al. 1996)

Energy

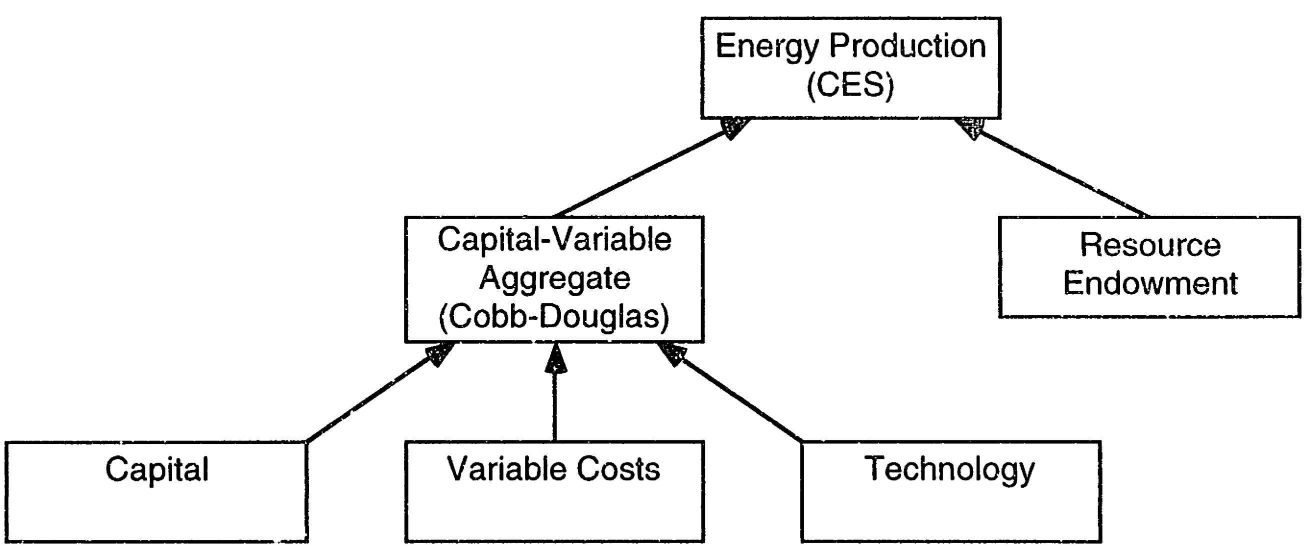
The energy sector produces energy to meet orders from the goods producing sector. In the short run, energy producing capital is fixed, and the energy sector varies production by adjusting the rate of variable (goods) inputs to set capacity utilization to the required level. In the long run, the energy sector adjusts its capacity by varying the capital stock in reponse to production pressure and profit incentives.

There are two types of energy sources: nonrenewable fossil fuels, and noncarbon renewables. Nonrenewables are disaggregated into coal (and other solid fuels) and an oil/gas composite. Nonrenewable fuels are subject to increasing production costs as resource stocks are depleted, and have an upper limit to the rate at which the remaining resource can be depleted. There are two noncarbon sources - hydro and nuclear electricity, and new renewables like biomass liquid fuels or wind electricity. Renewable energy sources have an upper limit to their production rate, as these resources are limited by flows like the flux of incoming solar radiation.

Hydro and nuclear electricity are aggregated, though they actually have substantially different characteristics. Hydro electricity is subject to diminishing returns to expansion as the best sites are exploited, while nuclear power could be available at a relatively constant marginal cost. Hydro is truly renewable, while nuclear fuel resources are depletable (though they are large if breeder technology is used). The two sources are aggregated as a matter of convenience because they have the same carrier.

This is not a problem if further expansion of nuclear power generation is politically constrained, so that the marginal cost of expansion of the hydro/nuclear aggregate is determined by limited hydro resources. This is the case in the standard model scenario. Similarly, if nuclear potential is unlimited, this can be simulated by raising the resource constraint for hydro/nuclear to a very high level, in which case the marginal cost of supply would be nearly constant. To simulate other, intermediate cases would require disaggregation.

Figure 56: Energy Production



In the long run, production capacity is determined by the supply of producing capital for each energy source. In addition, technology augments the effectiveness of intensive inputs (goods and capital) and depletion and saturation effects limit productivity in the nonrenewable and renewable sectors, respectively.

$$EP_i = EP_{i,0}\left(\alpha_{i,r}\left(\frac{R_i}{R_{i,0}}\right)^{\rho_{i,r}} + \left(1-\alpha_{i,r}\right)EII_i^{\rho_{i,r}}\right)^{\left(\frac{1}{\rho_{i,r}}\right)} \qquad \text{Eq. 45}$$

EP_i = *energy production*
$EP_{i,0}$ = *initial energy production*
R_i = *resource remaining*
$R_{i,0}$ = *initial resource remaining*
EII_i = *effective input intensity*
$\alpha_{i,r}$ = *resource share*
$\rho_{i,r}$ = *resource substitution coefficient*

The coefficient α is chosen such that there is an upper limit to the rate of energy production, representing the minimum time required to extract the remaining resource (for nonrenewables) or the maximum resource flux available (for renewables).

$$\alpha_{nonren,r} = \left(\frac{R_{i,0}}{\tau_r EP_{i,0}}\right)^{\rho_r} \qquad \alpha_{renew,r} = \left(\frac{R_{i,0}}{EP_{i,0}}\right)^{\rho_r} \qquad \text{Eq. 46}$$

τ_r = *minimum time to deplete resource*

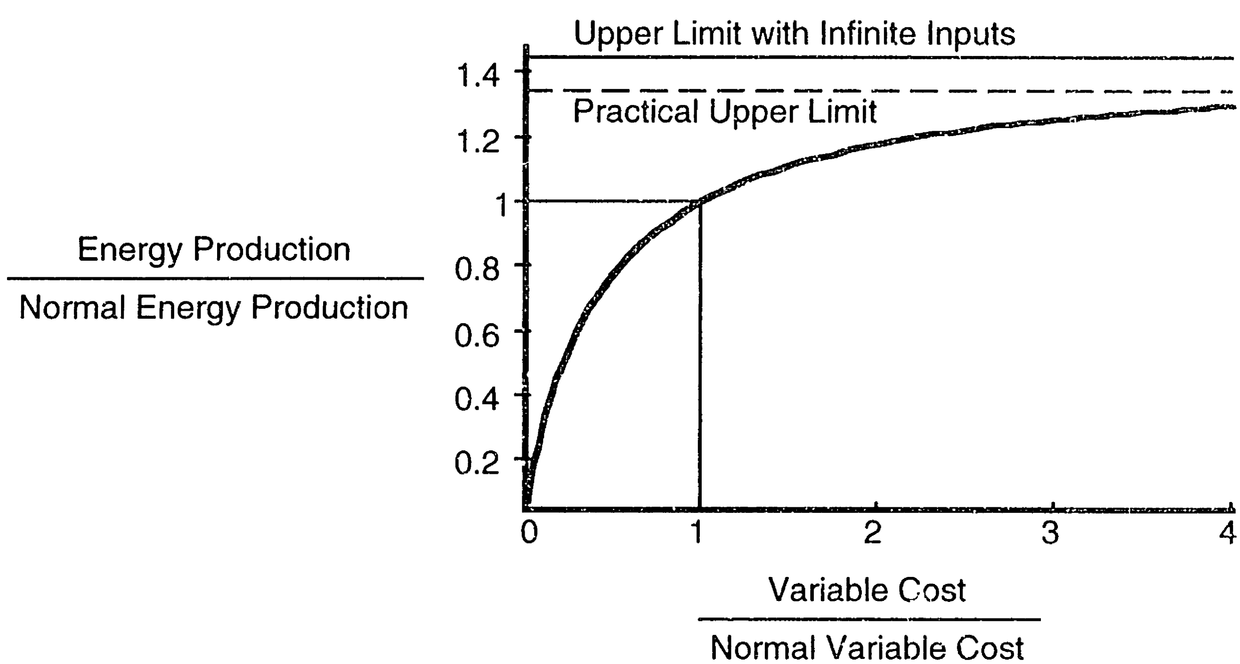
The effective input intensity represents the relative effort devoted to resource extraction. It depends on the level of technology and capital and variable (goods) inputs to production.

$$EII_i = TE_i\left(\frac{KE_i}{KE_{i,0}}\right)^{\beta_{i,kv}}\left(\frac{V_i}{V_{i,0}}\right)^{\left(1-\beta_{i,kv}\right)} \qquad \text{Eq. 47}$$

TE = *energy technology*
KE_i = *capital*
$KE_{i,0}$ = *initial capital*
V_i = *variable (goods) input*
$V_{i,0}$ = *initial variable input*
$\beta_{i,kv}$ = *capital share*

This formulation implies that there are limits to the rate of production of energy. In the short run, capital and the resource endowment are fixed, so the energy sector can only vary its output by varying the intensity of variable (goods) inputs. Since the elasticity of substitution between resources and other inputs is less than 1, energy production has an upper limit as variable costs approach infinity. Since infinite variable costs are unrealistic, the variable inputs are constrained by limiting scheduled production to the minimum of orders or a maximum production rate, determined by a maximum practical rate of variable input.

Figure 57: Energy Short-run Supply Curve



Because the inputs to energy production are capital and goods, an important positive feedback loop is excluded. Energy production is itself a capital- and energy-intensive activity. This means that if the price of energy increases, the cost of energy production increases, contributing to further increases in energy prices. A more complex specification of the energy sector, which included energy and labor factors, would capture this effect.

Table 17: Energy Production Parameters

Parameter	Alias	Value	Units	Notes
Capital Share	$\beta_{i,kv}$			
(nonrenewable)		.6	dmnl	(Sterman 1981; International
(renewable)		.8	dmnl	Energy Agency 1992)
Resource Elasticity	$\rho_{i,r}$			
(nonrenewable)		.7	dmnl	Calibrated to yield
(renewable)		.5	dmnl	appropriate depletion profiles.
Minimum Depletion Time	τ_r	20	years	
Initial Resource	$R_{i,0}$			
(coal)		3e14	GJ	EMF-14 assumptions
(oil/gas)		3.05e13	GJ	(Weyant 1995)
(hydro/nuclear)		1.28e11	GJ/year	(Goldemberg, Johansson et
(new)		1.9e12	GJ/year	al. 1987; International Energy Agency 1992; Schipper and Meyers)

Depletion

In the long run, Eq. 45 implies additional limits to production from depletion and saturation. The depletion effect represents the diminishing productivity of nonrenewable energy production as the resource remaining declines. The opportunity cost of resource depletion is treated as an externality, so the resource depletion path will be suboptimal unless resource owners (typically governments) intervene to restore efficiency by imposing a depletion tax, for example. The saturation effect represents the increasing marginal cost of supply for both renewable and nonrenewable energy production as the intensity of effort directed at extracting a fixed resource endowment increases.

In Eq. 45, as the fraction of the initial resource endowment remaining declines to zero, energy production also declines to zero. This must be the case, since there can be no production when there is no resource. For a given extraction effort (constant technology, capital, and variable inputs), the rate of energy production declines as the resource remaining declines (Figure 58). This creates a negative feedback loop (B1 in Figure 59). As the resource remaining declines, the rate of energy production decreases, reducing the rate of decline of the resource.

Figure 58: Oil Depletion Effect

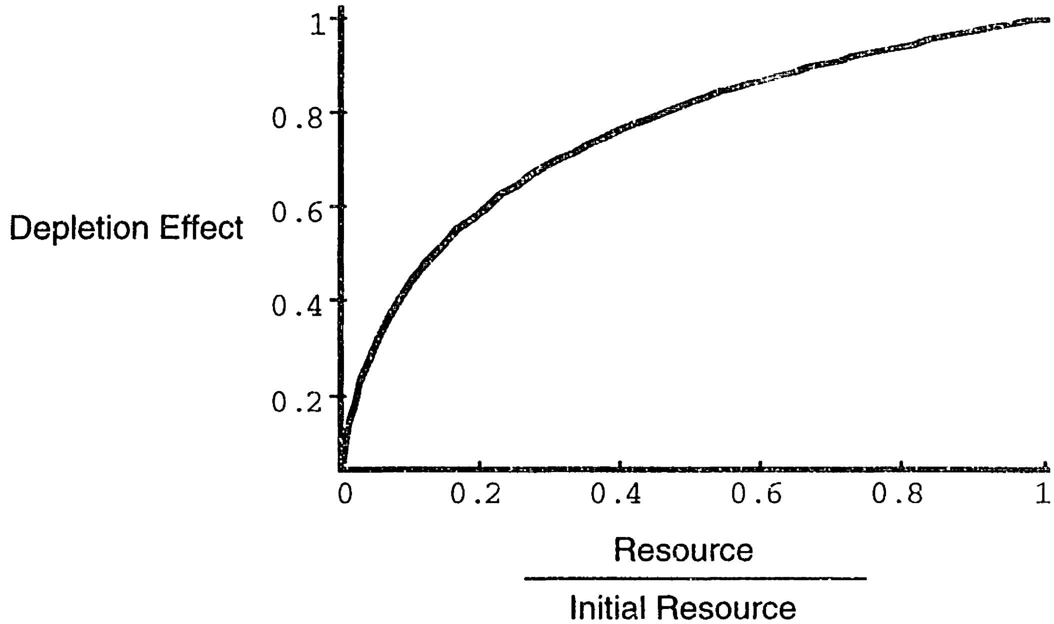
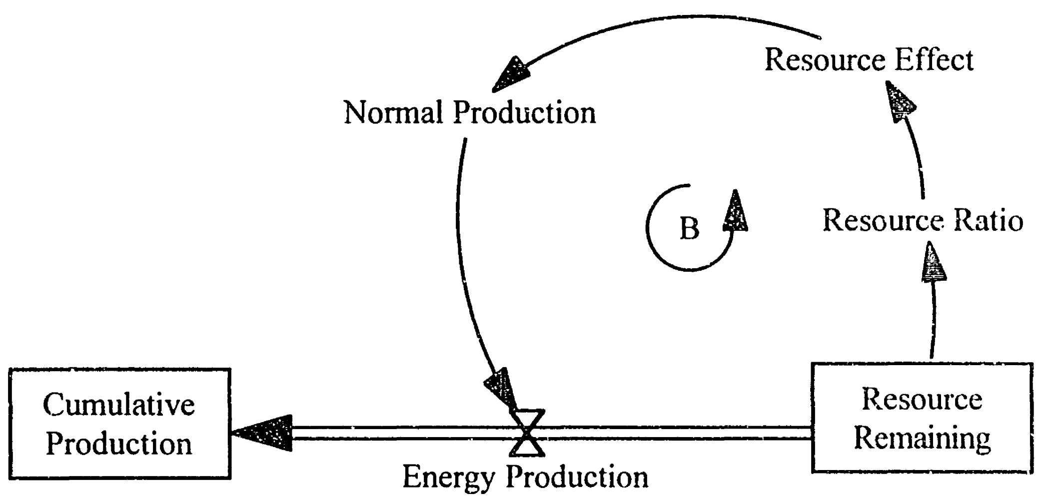


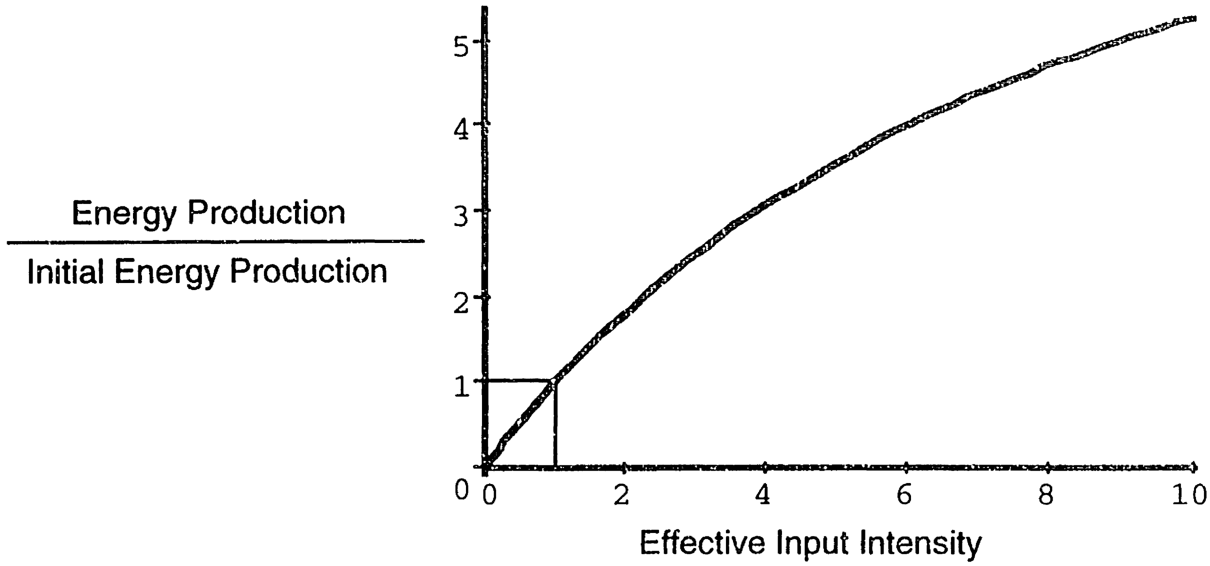
Figure 59: Nonrenewable Resource Depletion



Saturation

Even if the resource endowment remains fixed, there are diminishing returns to energy production effort. For renewables, sites with the highest wind, solar, or hydro potential or the most conventient locations are exploited first. For nonrenewables, field pressure gradients or mine congestion limit the extraction rate, causing diminishing returns to additional extraction effort.

Figure 60: Hydro/Nuclear Saturation Effect



Energy Capital

Energy capital stocks, like the goods production capital stock, adjust in response to production pressure, profit, and growth. Unlike the goods producing sector, the energy sector also includes a significant capital construction delay.

Capital depreciates with a fixed lifetime (Eq. 48 and loop B1 in Figure 61). Similarly, capital under construction is completed after a fixed delay (provided sufficient investment goods are available; a constraint which is not normally binding and is omitted from Eq. 49 for clarity).

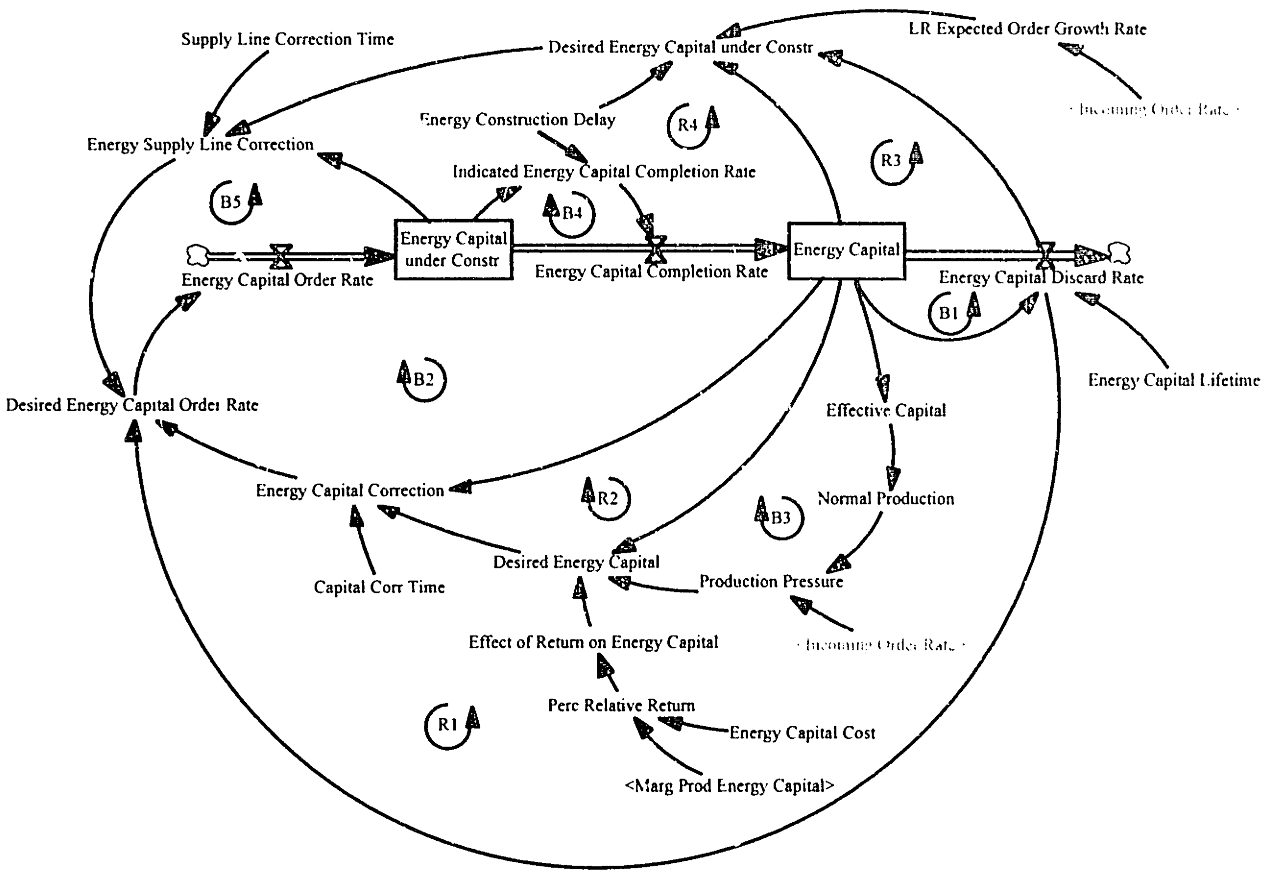
$$KE_i(t) = \int \frac{KC_i(t)}{\tau_c} - \delta_i KE_i(t)\, dt \qquad \text{Eq. 48}$$

KE_i = *energy capital*
KC_i = *energy capital under construction*
τ_c = *capital construction delay*
δ_i = *energy capital lifetime*

$$KC_i(t) = \int EKO_i(t) - \frac{KC_i(t)}{\tau_c}\, dt \qquad \text{Eq. 49}$$

EKO_i = *energy capital order rate*

Figure 61: Energy Capital



Orders for capital replace discards (R1) and adjust the capital stock and supply line of capital under construction to desired levels (B2 and B3). The desired capital stock, Eq. 51, is anchored to the current capital stock (R2), with adjustments for the relative price and marginal productivity of capital (B3) and for production pressure. The desired supply line of capital under construction, Eq. 52, is the quantity required to ensure that the completion rate of capital (B4) is sufficient to replace discards and to provide for growth in orders (R3 and R4).

$$\mathrm{EKO}(t) = \mathrm{MAX}\left(0, \delta_i KE_i(t) + \frac{DKC_i(t) - KC_i(t)}{\tau_{kc}} + \frac{DKE_i(t) - KE_i(t)}{\tau_k} + KE_i(t)\, GE_i(t)\right) \qquad \text{Eq. 50}$$

DKC_i = *desired energy capital under construction*

DKE_i = *desired energy capital*

τ_k = *time to correct capital*

τ_{kc} = *time to correct capital under construction*

GE_i = *perceived growth rate of energy orders*

$$DKE_i = \frac{KE_i M_{i,k} EO_i}{r\, NEP_i} \qquad \text{Eq. 51}$$

$M_{i,k}$ = marginal product of energy capital
r = interest rate
EO_i = energy order rate
NEP_i = normal energy production rate

$$DKC_i = KE_i\left(\delta_i + GE_i\right)\tau_{kc} \qquad \text{Eq. 52}$$

Capital construction costs are overnight costs. In other words, no physical inputs from the goods producing sector are required until the moment construction is completed. In addition, the rate of capital completion is normally unconstrained by capital goods availability, since there is no explicit capital goods producing sector.

Table 18: Energy Capital Parameters

Parameter	Alias	Value	Units	Notes
Capital Lifetime	$1/\delta_i$			
(coal)		20	years	(Sterman 1981; International
(oil/gas)		20	years	Energy Agency 1992)
(hydro/nuclear)		40	years	
(new)		30	years	
Construction Delay	τ_c	10	years	
Capital Correction Time	τ_k	4	years	(Sterman 1981)
Supply Line Correction Time	τ_{kc}	4	years	(Sterman 1981)

Technology

While depletion and saturation increase costs in the energy sector, technology reduces them. Two representations of technology are incorporated in the model, as well as a cost-reducing effect of scale economies. The cost reduction from all three effects is subject to a lower bound, implying that there are some irreducible costs of energy production (Eq. 53). It is also possible to drive energy technology with data from another simulation (not shown here).

$$TE_i = \frac{1}{LL_i + \frac{1 - LL_i}{ET_i^{\nu} AT_i^{(1-\nu)} S_i}} \qquad \text{Eq. 53}$$

TE_i = energy technology level
LL_i = lower limit to cost reductions from technology
ET_i = endogenous technology (learning curve)
AT_i = autonomous technology
S_i = scale economy effect
ν = fraction of technology endogenous

Endogenous technological change is implemented as a standard learning curve, with cumulative investment in energy capital as its input. While it is more common to use cumulative production, investment was chosen as the driver in order to make it easier to implement an explicit research and development sector in the future. While there are good arguments for either choice, in practice investment and production experience are highly correlated, and it is difficult to determine which is actually the more relevant input to technological improvement. Arrow's original formulation of the learning curve was based on cumulative investment (Arrow 1962).

$$ET_i = \beta_t \ln\left(\frac{C_i}{C_{i,0}}\right) \qquad \text{Eq. 54}$$

$C_{i,0}$ = initial cumulative investment
C_i = cumulative investment
β_t = learning curve coefficient

$$C_i(t) = \int I_i(t)\, dt \qquad \text{Eq. 55}$$

I_i = energy investment rate (=energy capital completion rate)

The conventional technology treatment involves an autonomous exponential improvement in technology (Eq. 56). The scale effect (Eq. 57) is not really a form of technology per se, but is included here as it may be treated analogously. The benefits of scale economies are assumed to accrue to the industry as a whole, so they are an externality for any individual firm.

$$AT_i = e^{\left(\alpha_t t\right)}$$ Eq. 56

α_t = *fractional autonomous energy technology growth rate*

$$S_i = \left(\frac{KE_i}{KE_{i,0}}\right)^{\gamma_s}$$ Eq. 57

KE_i = *energy capital* γ_s = *scale coefficient*
$KE_{i,0}$ = *initial energy capital*

Figure 62: Energy Technology

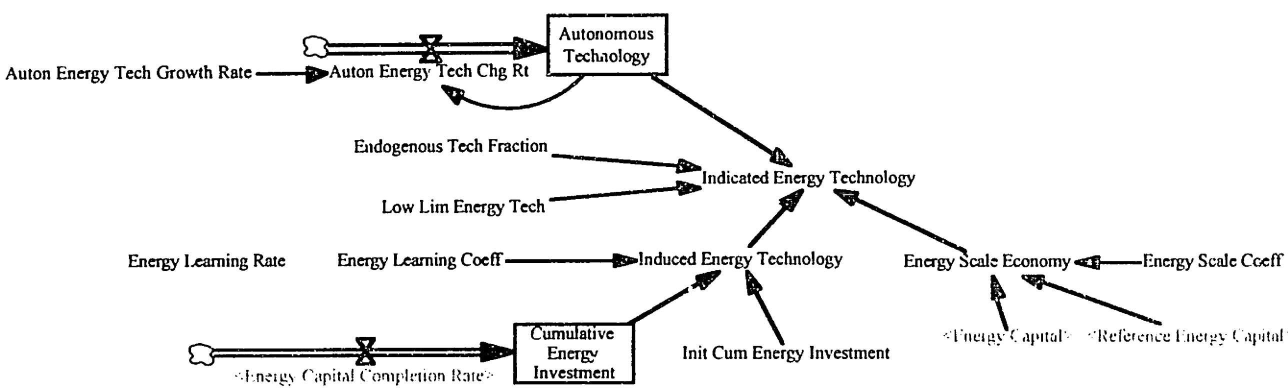


Table 19: Energy Technology Parameters

Parameter	Alias	Value	Units	Notes
Fraction of Technology Endogenous	ν	1	dmnl	
Learning Rate	β_t	.8	dmnl	(Argote and Epple 1990; Christiansson 1995; Messner 1996)
Technology Lower Limit				
(coal)	LL_i	.1	dmnl	
(oil/gas)		.1	dmnl	
(hydro/nuclear)		.1	dmnl	
(new)		.01	dmnl	

Pricing

The energy sector posts prices to the goods producing sector. The price to to the goods producing sector consists of the price paid to energy producers plus taxes, distribution charges, and depletion rent (Eq. 58). The producer price adjusts to the desired price level with a short delay (Eq. 59).

$$P_i = PP_i + \mu_i + D_i + T_i \qquad \text{Eq. 58}$$

P_i = *energy price*
PP_i = *producer price*
μ_i = *depletion rent*
D_i = *distribution cost*
T_i = *total taxes*

$$PP_i(t) = \int \frac{IP_i(t) - PP_i(t)}{\tau_p}\, dt \qquad \text{Eq. 59}$$

IP_i = *indicated producer price*
τ_p = *price adjustment time*

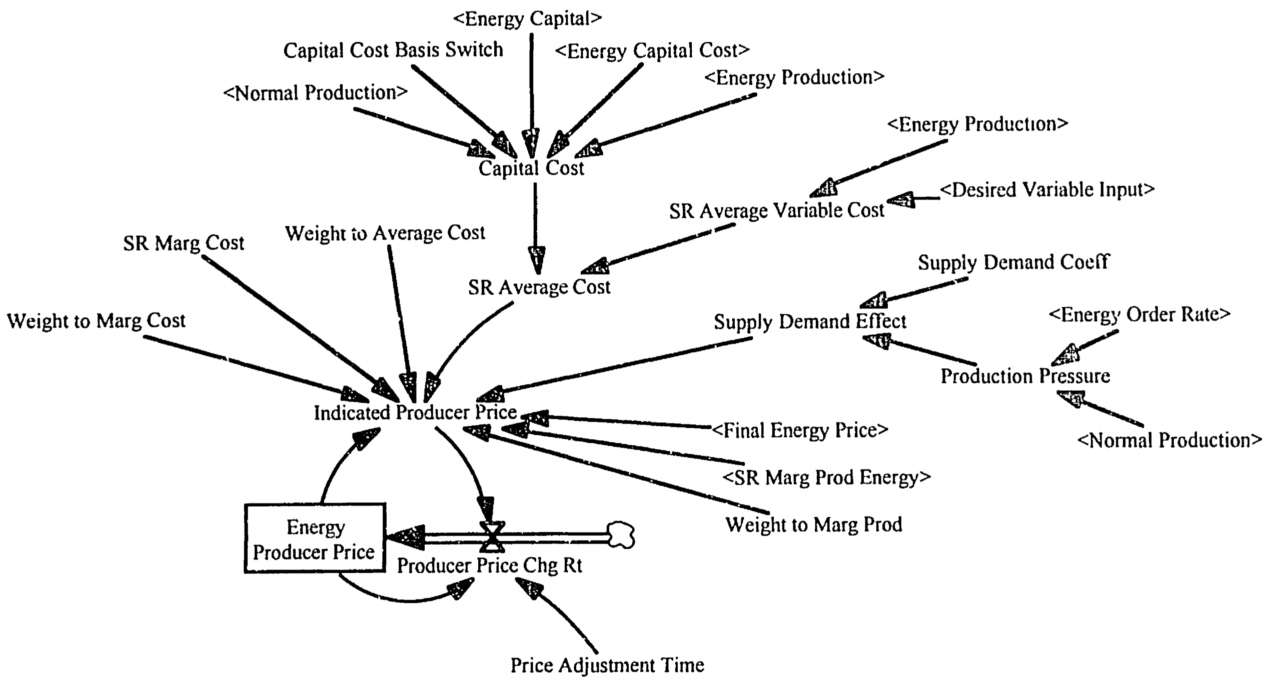
The desired producer price is anchored to the current price and may be adjusted for effects of short term marginal costs (as in general equilibrium models), average costs, production pressure, and the short term marginal productivity of energy in goods production. Normally, not all of these factors are active.

$$IP_i = PP_i \left(\frac{AC_i}{PP_i}\right)^{\gamma_a} \left(\frac{MC_i}{PP_i}\right)^{\gamma_m} \left(\frac{EO_i}{NEP_i}\right)^{\gamma_d} \qquad \text{Eq. 60}$$

AC_i = *average cost of energy production*
γ_a = *weight to average cost*
MC_i = *marginal cost of energy production*
γ_m = *weight to marginal cost*
EO_i = *energy order rate*
NEP_i = *energy production at normal capacity utilization*
γ_d = *weight to demand pressure*

True marginal cost pricing is somewhat unrealistic in this setting, because short run marginal costs are volatile and it is difficult for energy producers to know true marginal cost. The average cost pricing rule provides an attractive alternative. By this rule, producers allocate fixed costs across normal production to calculate an overhead, add average short term variable costs, and correct for supply and demand pressures. In equilibrium, this rule sets the same price as marginal cost pricing, and has the advantage of greater stability and reliance on readily available information. Utility regulation generally sets electricity prices on an average cost basis, and there is evidence for average cost pricing in coal contracts as well (Joskow 1987).

Figure 63: Energy Pricing



While variations in the weights to various factors influencing price do affect model behavior, experiments indicate that policy conclusions are relatively insensitive to the pricing method chosen.

Table 20: Energy Pricing Parameters

Parameter	Alias	Value	Units
Price Adjustment Time	τ_p	1	year
Unit Distribution Costs	D_i	0	$/GJ
Initial Producer Price			
(coal)		1.278	$/GJ
(oil/gas)		1.297	$/GJ
(hydro/nuclear)		6.648	$/GJ
(new)		60	$/GJ
Weight to Average Cost	γ_a	1	dmnl
Weight to Marginal Cost	γ_m	0	dmnl
Supply/Demand Coefficient	γ_d	2	dmnl

Policies

The model incorporates three tax policies that influence energy prices. A depletion tax may be applied to the nonrenewable energy sources. An energy tax may be applied to all sources equally. A carbon tax may be applied to the nonrenewable energy sources. The model also allows for several other policy levers (investment subsidies or taxes for example), but these have not been implemented to date.

Carbon and Energy Taxes

The carbon tax is a simple control heuristic with a constant term and inputs from the perceived rate of CO_2 emissions and the atmospheric concentration of CO_2. A constant energy tax (i.e. BTU tax) may also be applied to all sources. Both are subject to an implementation delay, modeled as a first-order adjustment process.

$$T_i = \varepsilon_i T_c + T_e \qquad \text{Eq. 61}$$

T_i = *total tax*
ε_i = *carbon content*
T_c = *carbon tax*
T_e = *energy tax*

$$T_e(t) = \int \frac{DT_e(t) - T_e(t)}{\tau_t} dt \qquad \text{Eq. 62}$$

DT_e = *desired energy tax*
τ_t = *tax implementation time*

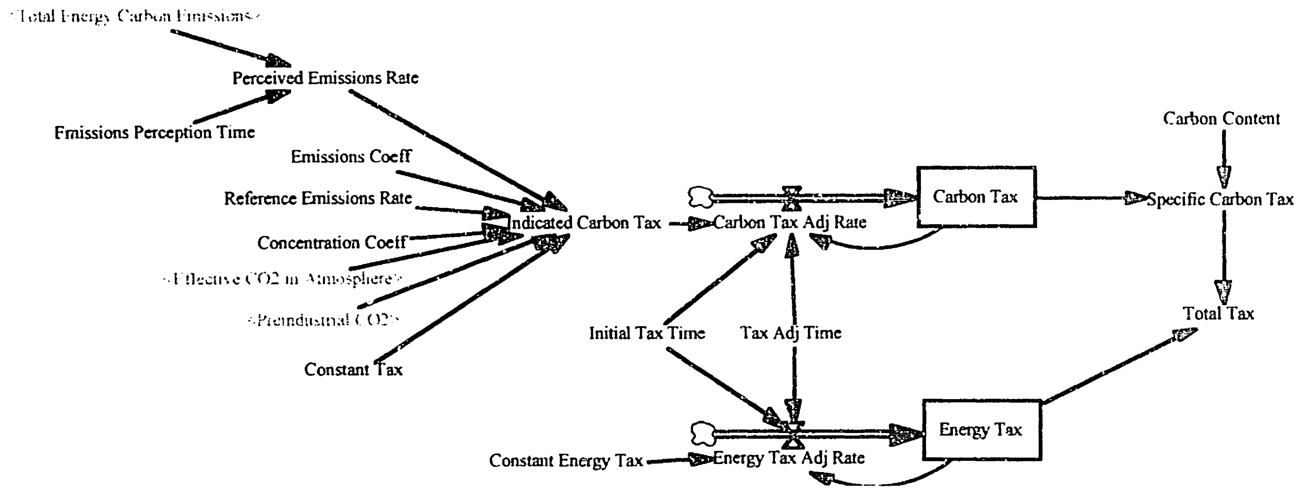
$$T_c(t) = \int \frac{DT_c(t) - T_c(t)}{\tau_t} dt \qquad \text{Eq. 63}$$

DT_c = *desired carbon tax*

$$DT_c = T_0 + \frac{T_1 E}{E_0} + \frac{T_2 C_a}{C_{a,0}} \qquad \text{Eq. 64}$$

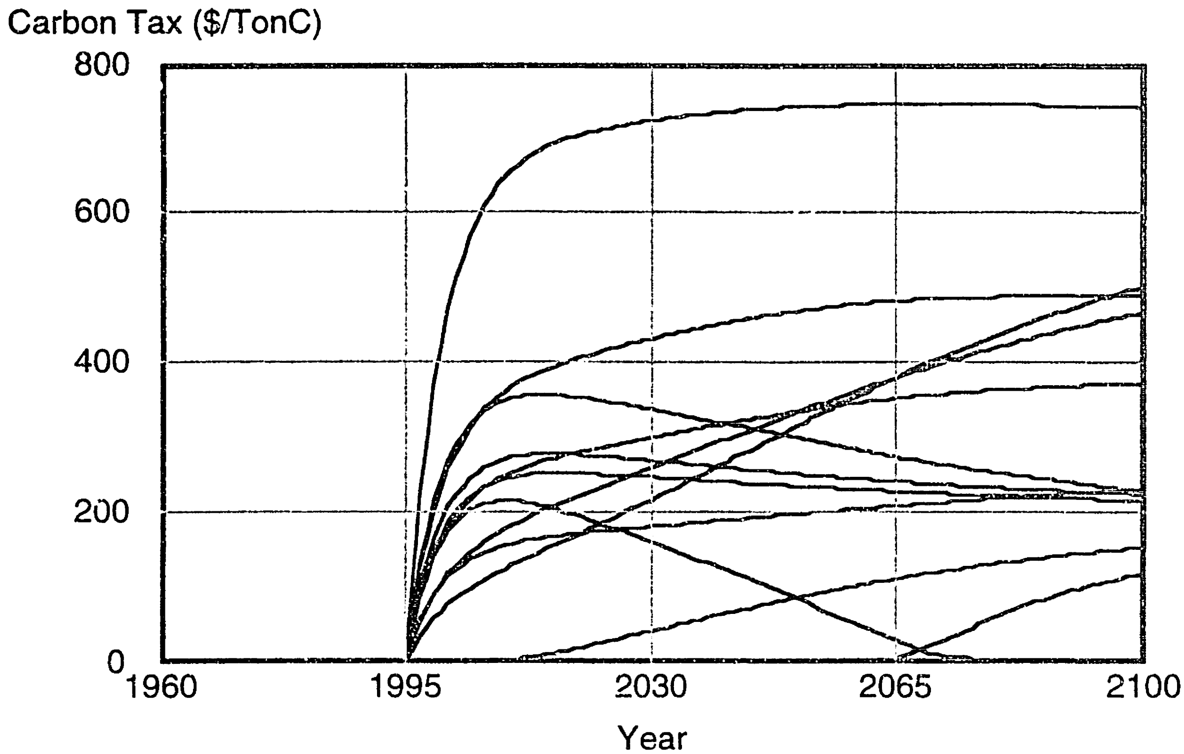
$T0$ = *carbon tax constant*
$T1$ = *carbon tax emissions coefficient*
$T2$ = *carbon tax concentration coefficient*
E = CO_2 *emissions rate*
E_0 = *reference emissions rate*
C_a = *atmospheric* CO_2 *content*
$C_{a,0}$ = *reference atmospheric* CO_2 *content*

Figure 64: Carbon Taxes



In carbon tax optimization runs, optimal values of the carbon tax constant and the coefficients on emissions and atmospheric concentration are sought. This differs somewhat from the typical approach, in which the optimal tax is represented as a vector of points over time. The disadvantage of this simplified representation is that the tax trajectories achievable by this rule may not include the true optimal tax pattern. This is of limited concern, as the structure is quite flexible, and complex tax trajectories would be difficult to implement anyway. The significant advantages of this approach are that the search space for optimal policies has low dimensionality and that the resulting policies can be interpreted in terms of emissions and concentration constraints. Figure 65 illustrates a number of representative tax trajectories.

Figure 65: Representative Tax Trajectories



Carbon tax trajectories from 20 Monte Carlo simulations of the model, with Latin hypercube sampling of the carbon tax constant (T_1) and concentration (T_2) coefficients over the interval [-500,500] $/tonC.

Table 21: Tax Policy Parameters

Parameter	Alias	Value	Units
Tax Adjustment Time	τ_t	5	years

Depletion Rent

Since the FREE model has nearly 100 state variables, it is obviously impossible to develop an analytic expression for an optimal depletion tax that restores intertemporal efficiency. Instead, a simplification is used. A typical optimal control formulation of the problem is to maximize the discounted flow of net benefits from resource consumption (Eq. 65), subject to the state equation for the resource (Eq. 66).

$$\int_0^T e^{(-r\,t)}\,(\mathrm{U}(Q,t) - \mathrm{C}(R,Q,t))\,dt$$ Eq. 65

U = utility
C = resource extraction cost
Q = resource consumption rate
R = resource remaining
r = interest rate
T = planning horizon

$$\frac{\partial}{\partial t}\mathrm{R}(t) = -Q \qquad \left\{0 \le \mathrm{R}(T), \mathrm{R}(0) = R_0\right\}$$ Eq. 66

The current value Hamiltonian for the problem is given by Eq. 67. Differentiating with respect to the control and state variables and solving for the shadow price of the resource, μ, indicates that efficiency requires charging a depletion rent, μ, that drives a wedge between the price of the resource (i.e. its marginal utility) and the marginal extraction cost (Eq. 68).

$$J = \mathrm{U}(Q,t) - \mathrm{C}(R,Q,t) - \mu\,Q$$ Eq. 67

J = current value Hamiltonian
μ = shadow price (co-state variable) of resource

$$\mu = \left(\frac{\partial}{\partial Q}\mathrm{U}(Q,t)\right) - \left(\frac{\partial}{\partial Q}\mathrm{C}(R,Q,t)\right)$$ Eq. 68

$$\frac{\partial}{\partial t}\mu(t) = \mu\,r + \left(\frac{\partial}{\partial R}\mathrm{C}(R,Q,t)\right)$$ Eq. 69

Over time, the depletion rent μ rises at the interest rate - the standard result. Rising extraction costs will create a countervailing pressure, diminishing μ, since the derivative of cost with respect to the resource remaining is negative. In the FREE model, the extraction cost approaches infinity as the resource remaining approaches zero, and the marginal utility of resource consumption approaches infinity as the resource consumption rate approaches zero. This implies that the optimal depletion program will have infinite duration. Within a finite planning period, some of the resource will remain unconsumed, so the terminal depletion rent must be zero. This means that the depletion rent will first rise at the interest rate, then decline toward zero as extraction costs increase.

This structure is implemented in the model by adding a tax on resource extraction, which changes according to Eq. 69. Since the initial value of the tax, $\mu(0)$, is unknown, optimization is used to discover an appropriate value. There are several problems with this approach. Since the problem structure is a simplification of the full model, the behavior of the optimal tax may be distorted, unless the rest of the model is already behaving in a fashion consistent with optimal depletion. More importantly, the optimal tax implies an unrealistic degree of foresight and structural knowledge on the part of decision makers, even in its simplified form.

The depletion tax representation is reasonably robust. Early in the simulation, when oil and gas consumption is high, the tax trajectory is relatively insensitive to small variations in the initial tax. Errors grow large only late in the simulation period, when they are unimportant because oil and gas consumption is near zero. Experiments with small perturbations to the tax trajectory indicate that only tiny improvements in welfare are possible, and that climate policy is insensitive to these perturbations.

CO_2 Emissions

Emissions of greenhouse gases from energy production are endogenous in the model. Emissions from coal and the oil-gas composite good equal the rate of production multiplied by the carbon content of the fuel. For the oil and gas composite, the carbon content is the average of the carbon contents of oil and gas, weighted by resources. Nonenergy (mostly land use) CO_2 emissions are treated as an exogenous forcing, with values drawn from IPCC scenarios.

Figure 66: CO_2 Emissions

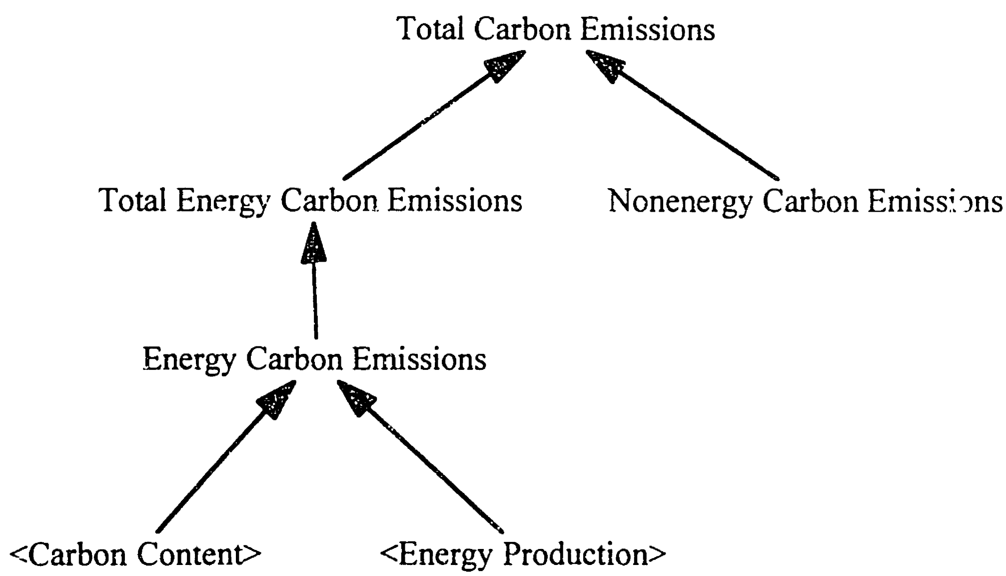


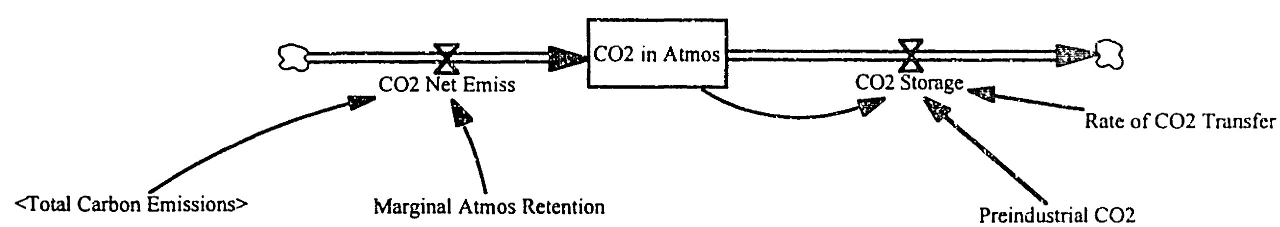
Table 22: Emissions Parameters

Parameter	Alias	Value	Units
Carbon Content	ε_i		
(coal)		.0247	TonC/GJ
(oil/gas)		.0171	TonC/GJ

Carbon Cycle

The carbon cycle sector includes two alternative carbon cycle models. The simpler of the two is drawn unaltered from the DICE model. This is a first-order linear structure, in which a fraction of emissions accumulate in the atmosphere in the short run, and is gradually stored in the deep ocean in the long run.

Figure 67: DICE Carbon Cycle



The FREE carbon cycle (Figure 68) is an eddy diffusion model with stocks of carbon in the atmosphere, biosphere, mixed ocean layer, and 10 deep ocean layers. The model couples the atmosphere-mixed ocean layer interactions and net primary production of the Goudriaan and Kettner and IMAGE 1.0 models (Goudriaan and Ketner 1984; Rotmans 1990) with an 11-layer eddy diffusion ocean based on (Oeschger, Siegenthaler et al. 1975) and a 2-box biosphere based on (Goudriaan and Ketner 1984).

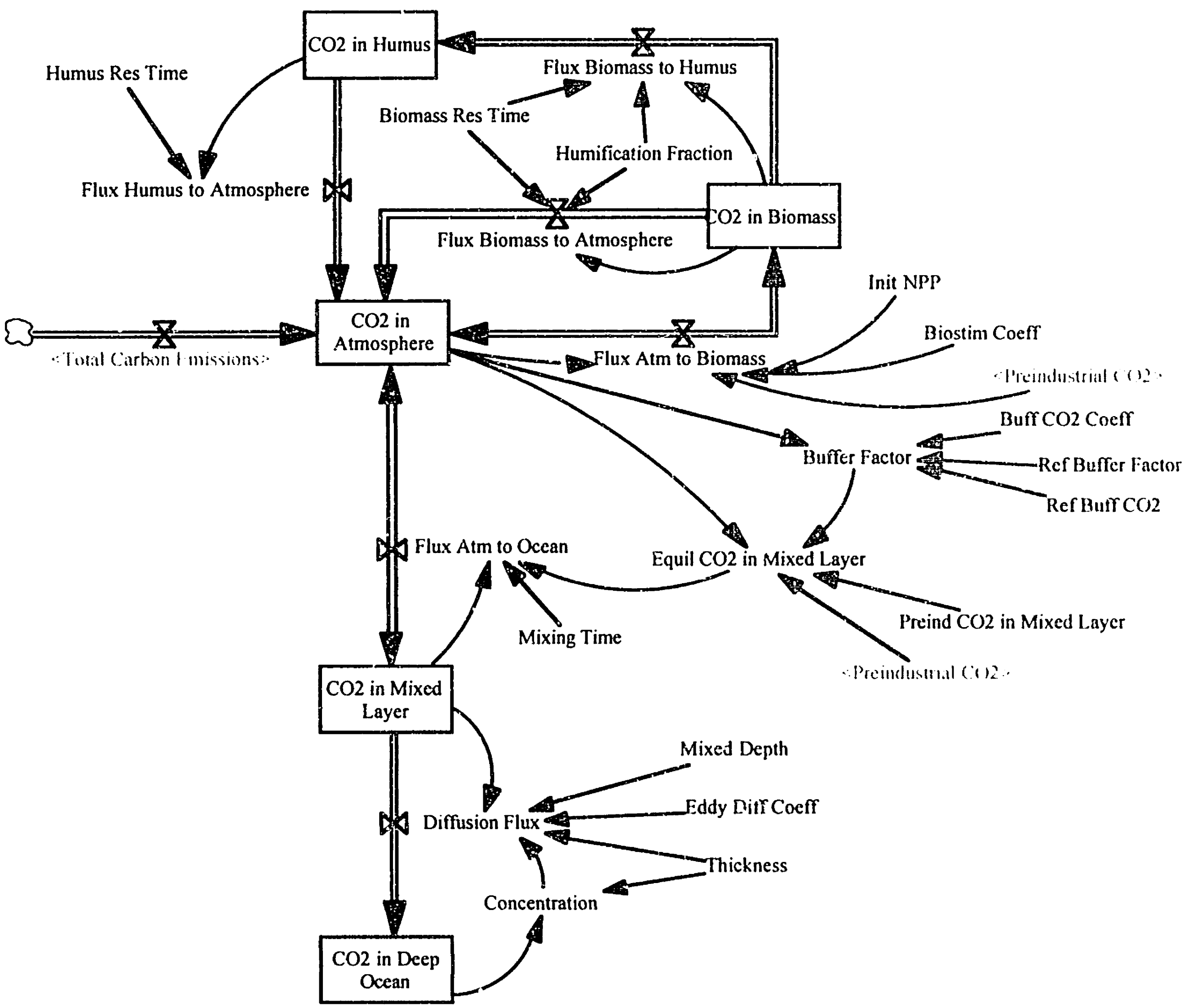
In the FREE model, all emissions initially accumulate in the atmosphere. As the atmospheric concentration of CO_2 rises, the uptake of CO_2 by the ocean and biosphere increases, and carbon is gradually stored. The atmospheric flux to the biosphere consists of net primary production. Net primary production grows logarithmically as the atmospheric concentration of CO_2 increases (Wullschleger, Post et al. 1995), according to:

$$NPP = NPP_0 \left(1 + \beta_b \ln \left(\frac{C_a}{C_{a,0}} \right) \right) \quad \text{Eq. 70}$$

NPP = net primary production
NPP_0 = reference net primary production
β_b = biostimulation coefficient
C_a = CO_2 in atmosphere
$C_{a,0}$ = reference CO_2 in atmosphere

Because the relationship is logarithmic, the uptake of CO_2 by the biosphere is less than proportional to the increase in atmospheric CO_2 concentration. Effects of the current biomass stock, temperature, and human disturbance are neglected.

Figure 68: FREE Carbon Cycle



It is worth noting that this formulation is not robust to large deviations in the atmospheric concentration of CO_2. As the atmospheric concentration of CO_2 approaches zero, net primary production approaches minus infinity, which is not possible given the finite positive stock of biomass. As the concentration of CO_2 becomes very high, net primary production can grow arbitrarily large, which is also not possible in reality. Neither of these constraints is a problem for reasonable model trajectories, though.

The Goudriaan and Ketner and IMAGE models (Goudriaan and Ketner 1984; Rotmans 1990) have detailed biospheres, partitioned into leaves, branches, stems, roots, litter, humus, and charcoal. To simplify the model, these categories are aggregated into stocks of biomass (leaves, branches, stems, roots) and humus (litter, humus). Aggregate first-order time constants were calculated for each category on the basis of their equilibrium stock-flow relationships. Charcoal is neglected due to its long lifetime. The results are reasonably consistent with other partitionings of the biosphere and with the one-box biosphere of the Oeschger model (Oeschger, Siegenthaler et al. 1975; Bolin 1986).

$$C_b(t) = \int \mathrm{NPP}(t) - \frac{C_b(t)}{\tau_b}\,dt \qquad \text{Eq. 71}$$

C_b = *carbon in biomass* τ_b = *biomass residence time*

$$C_h(t) = \int \frac{\phi C_b(t)}{\tau_b} - \frac{C_h(t)}{\tau_h}\,dt \qquad \text{Eq. 72}$$

C_h = *carbon in humus* ϕ = *humification fraction*
τ_h = *humus residence time*

The interaction between the atmosphere and mixed ocean layer involves a shift in chemical equilibria (Goudriaan and Ketner 1984). CO_2 in the ocean reacts to produce HCO_3^- and $CO_3^=$. In equilibrium,

$$C_m = C_{m,0}\left(\frac{C_a}{C_{a,0}}\right)^{\left(\frac{1}{\zeta}\right)} \qquad \text{Eq. 73}$$

C_m = CO_2 in mixed ocean layer
$C_{m,0}$ = reference CO_2 in mixed ocean layer
C_a = CO_2 in atmosphere
$C_{a,0}$ = reference CO_2 in atmosphere
ζ = buffer factor

The atmosphere and mixed ocean adjust to this equilibrium with a time constant of 9.5 years.

The buffer or Revelle factor, ζ, is typically about 10. As a result, the partial pressure of CO_2 in the ocean rises about 10 times faster than the total concentration of carbon (Fung 1991). This means that the ocean, while it initially contains about 60 times as much carbon as the preindustrial atmosphere, behaves as if it were only 6 times as large.

The buffer factor itself rises with the atmospheric concentration of CO_2 (Goudriaan and Ketner 1984; Rotmans 1990) and temperature (Fung 1991). This means that the ocean's capacity to absorb CO_2 diminishes as the atmospheric concentration rises. The temperature effect (which is omitted in this model) is one of several possible feedback mechanism between the climate and carbon cycle.

$$\zeta = \zeta_0 + \delta_b \ln\left(\frac{C_a}{C_{a,0}}\right) \qquad \text{Eq. 74}$$

ζ = buffer factor
ζ_0 = reference buffer factor
δ_b = buffer CO_2 coefficient
C_a = CO_2 in atmosphere
$C_{a,0}$ = reference CO_2 in atmosphere

The deep ocean is represented by a simple eddy-diffusion structure similar to that in the Oeschger model, but with fewer layers (Oeschger, Siegenthaler et al. 1975). Effects of ocean circulation and carbon precipitation, present in more complex models (Goudriaan and Ketner 1984; Björkstrom 1986; Rotmans 1990; Keller and Goldstein 1995), are neglected. Within the ocean, transport of carbon among ocean layers operates linearly. The flux of carbon between two layers of identical thickness is expressed by:

$$F_{m,n} = \frac{\left(C_m - C_n\right)e}{d^2}$$ Eq. 75

$F_{m,n}$ = carbon flux from layer m to layer n
C_k = carbon in layer k
e = eddy diffusion coefficient
d = depth of layers

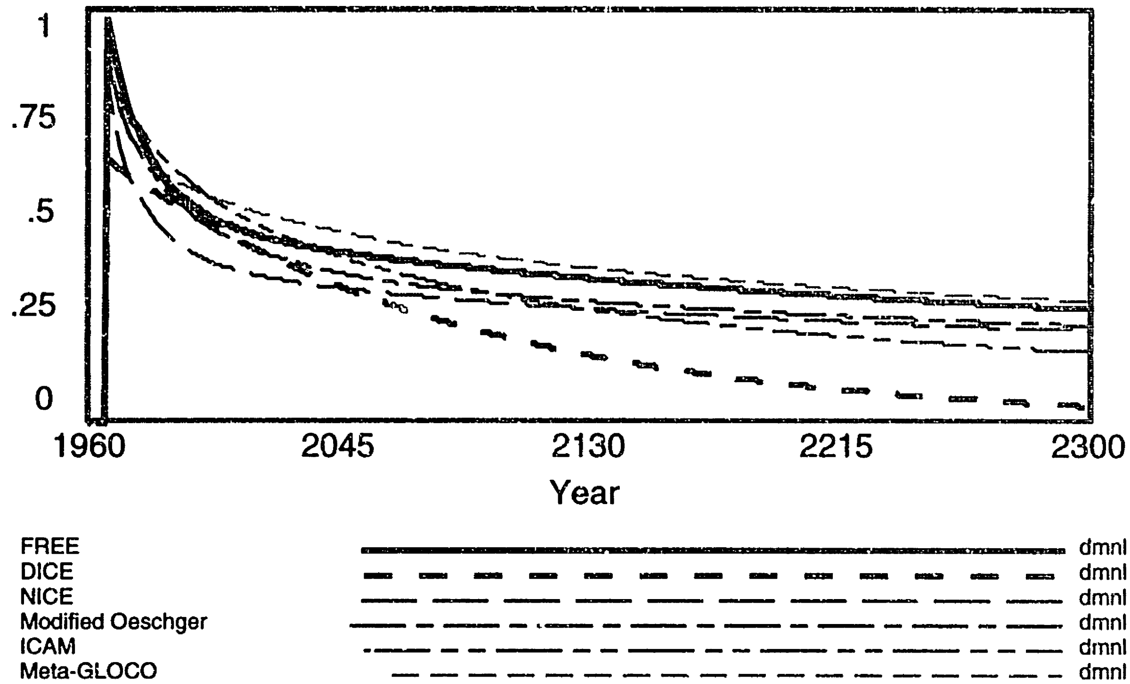
The effective time constant for this interaction, e/d^2, varies with d, the thickness of the ocean layers. Table 23 summarizes time constants for the interaction between identical layers. This model employs a 75 meter mixed layer, five 200 meter middle layers, and five 560 meter deep ocean layers. Models with fewer ocean layers underestimate the short term participation of the ocean in carbon uptake (Oeschger, Siegenthaler et al. 1975) and must increase uptake by other means to compensate.

Table 23: Time Constants for Ocean Carbon Transport

Layer Thickness	Time Constant
75 meters	1.4 years
200 meters	10.0 years
560 meters	78.4 years

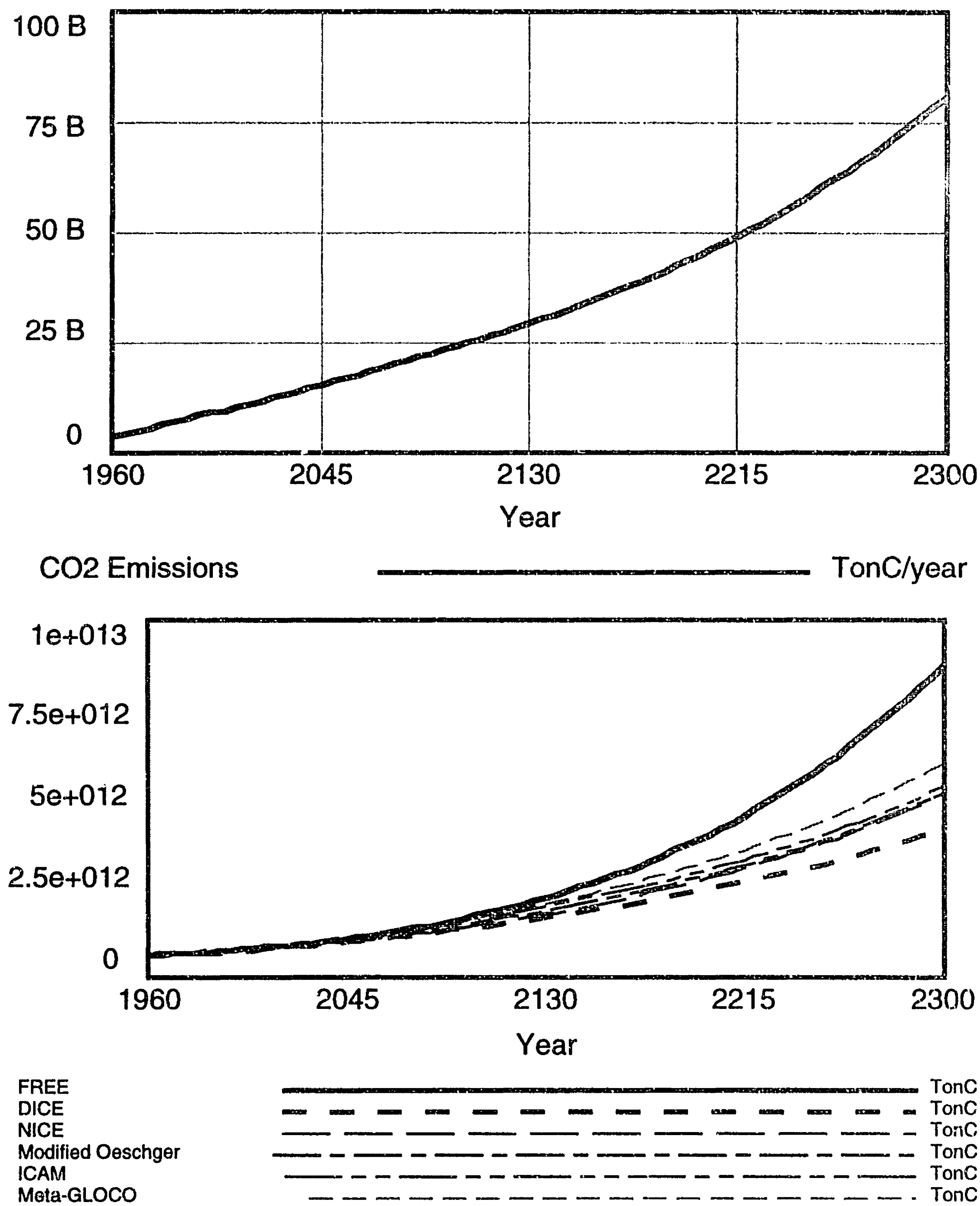
Figure 69 compares the response of carbon cycle models to a pulse of emissions that instantaneously doubles the atmospheric stock of CO_2. The response of the FREE carbon cycle is most similar to that of the GLOCO model (Keller and Goldstein 1995), a complex physical model. The DICE carbon cycle is a conspicuous outlier in this comparison - its uptake of emissions is more rapid in the short run and more complete in the long run.

Figure 69: Retention of 2x CO_2 Emissions Pulse



When subjected to a high emissions scenario, the FREE model stands out from the others. This is because of the nonlinearity of carbon uptake by the ocean and biosphere. The DICE, meta-GLOCO, and ICAM models are linear and thus do not exhibit diminishing carbon uptake rates with increasing atmospheric concentrations. The modified Oeschger and NICE models neglect changes in the buffer factor due to changes in the partial pressure of CO_2 in the atmosphere, and thus also underestimate the diminishing marginal uptake of carbon.

Figure 70: Atmospheric Concentration with High Emissions



Emissions trajectory is from the DICE model, with no abatement and a constant rate of factor productivity growth.

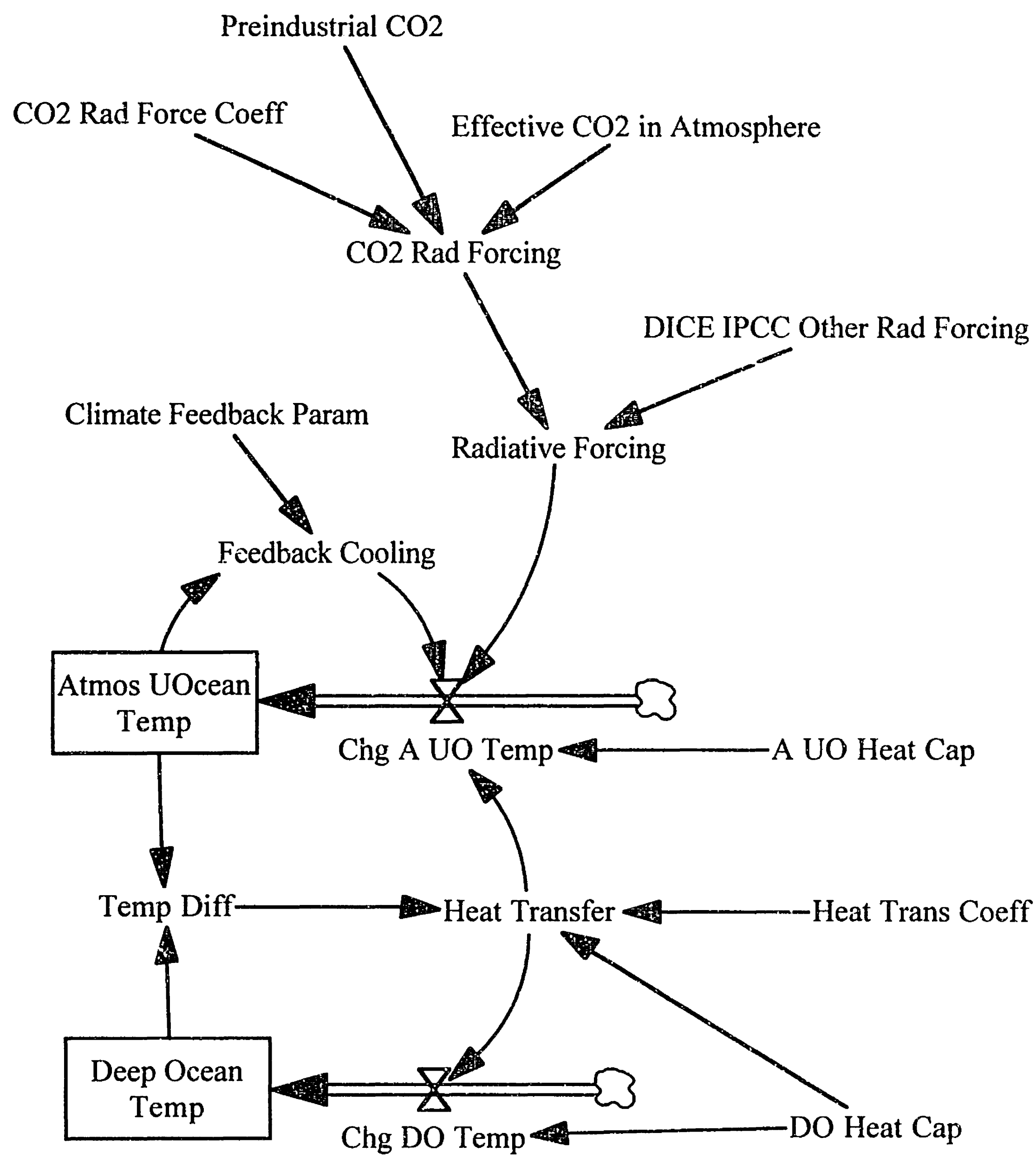
Table 24: Carbon Cycle Parameters

Parameter	Alias	Value	Units	Notes
FREE				
Biomass Residence Time	τ_b	10.6	years	Adapted from Goudriaan (1984)
Biostimulation Coefficient	β_b	.4	dmnl	(Goudriaan and Ketner 1984)
Buffer CO2 Coefficient	δ_b	4.05	dmnl	(Goudriaan and Ketner 1984)
Eddy Diffusion Coefficient	e	4000	meter^2/year	(Oeschger, Siegenthaler et al. 1975)
Humification Fraction	ϕ	.428	dmnl	Adapted from Goudriaan (1984)
Humus Residence Time	τ_h	27.8	years	Adapted from Goudriaan (1984)
Initial Net Primary Production	NPP_0	6e10	TonC/year	Adapted from Goudriaan (1984)
Mixed Ocean Depth	d_m	75	meters	(Oeschger, Siegenthaler et al. 1975)
Reference Buffer Factor	ζ_0	10	dmnl	(Goudriaan and Ketner 1984)
Deep Ocean Layer Thickness	d_n			
(top 5 layers)		200	meters	
(bottom 5 layers)		500	meters	

Climate

The climate sector is drawn from the DICE model without modification. This is a second-order, linear system, with three negative feedback loops. Two loops govern the transport of heat from the atmosphere and surface ocean, while the third represents warming of the deep ocean. Deep ocean warming is a slow process, because the ocean has such a large heat capacity. If the deep ocean temperature is held constant, the response of the atmosphere and surface ocean to warming is first-order.

Figure 71: Climate Sector



Radiative forcing from CO_2 is a logarithmic function of the atmospheric CO_2 concentration. Forcing from other gases is exogenous, using IPCC assumptions from the DICE model (Nordhaus 1994). The equilibrium temperature response to a change in radiative forcing is determined by the radiative forcing coefficient, κ, and the climate feedback parameter, λ.

$$T_{equil} = \frac{\kappa \ln\left(\frac{C_a}{C_{a,0}}\right)}{\lambda \ln(2)}$$ Eq. 76

T_{equil} = equilibrium temperature
C_a = atmospheric CO_2 concentration
$C_{a,o}$ = preindustrial atmospheric CO_2 concentration
κ = radiative forcing coefficient
λ = climate feedback parameter

Figure 72: Equilibrium Temperature Response

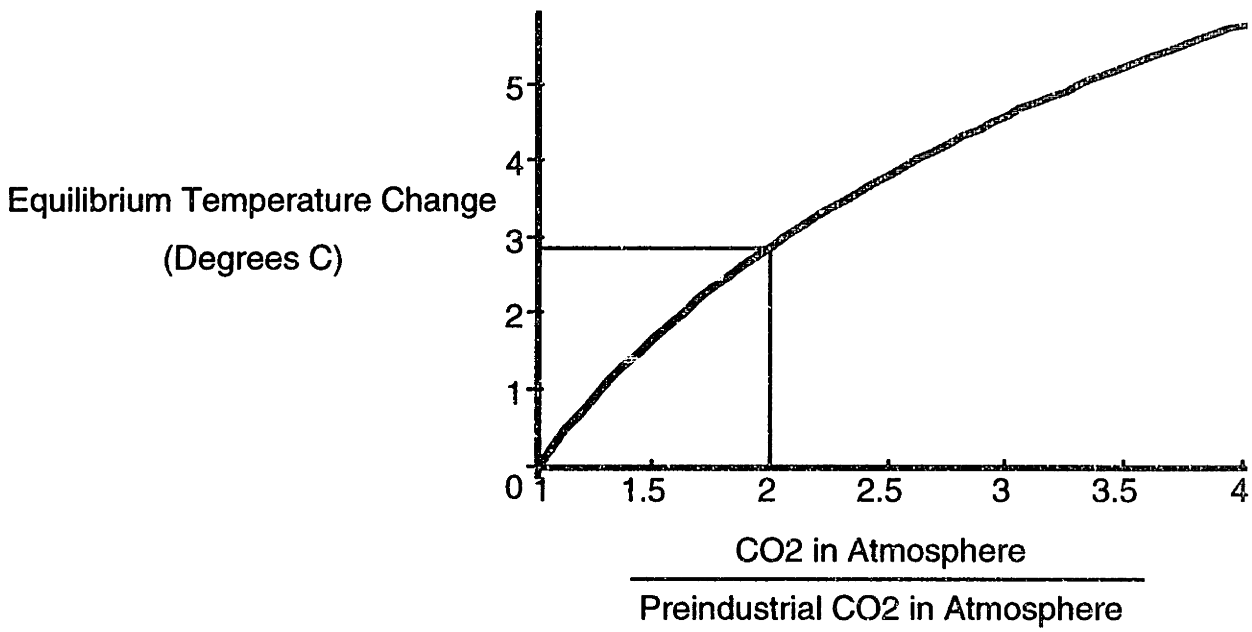


Figure 73 shows the absolute temperature following a pulse doubling of atmospheric CO_2. The response is roughly a first-order smoothing of the pulse response of atmospheric CO_2. The absolute temperature change peaks at about 1.2 degrees, roughly 50 years after the emissions pulse. The 50 year time constant of the temperature response corresponds well with the time constants estimated for more complex models (Schlesinger and Jiang 1990). If the doubling of atmospheric CO_2 were sustained, the eventual equilibrium temperature would be 2.9 degrees in this case. Temperature has a lower peak and decays more quickly with the DICE carbon cycle.

Figure 73: Temperature Response to 2x CO_2 Pulse

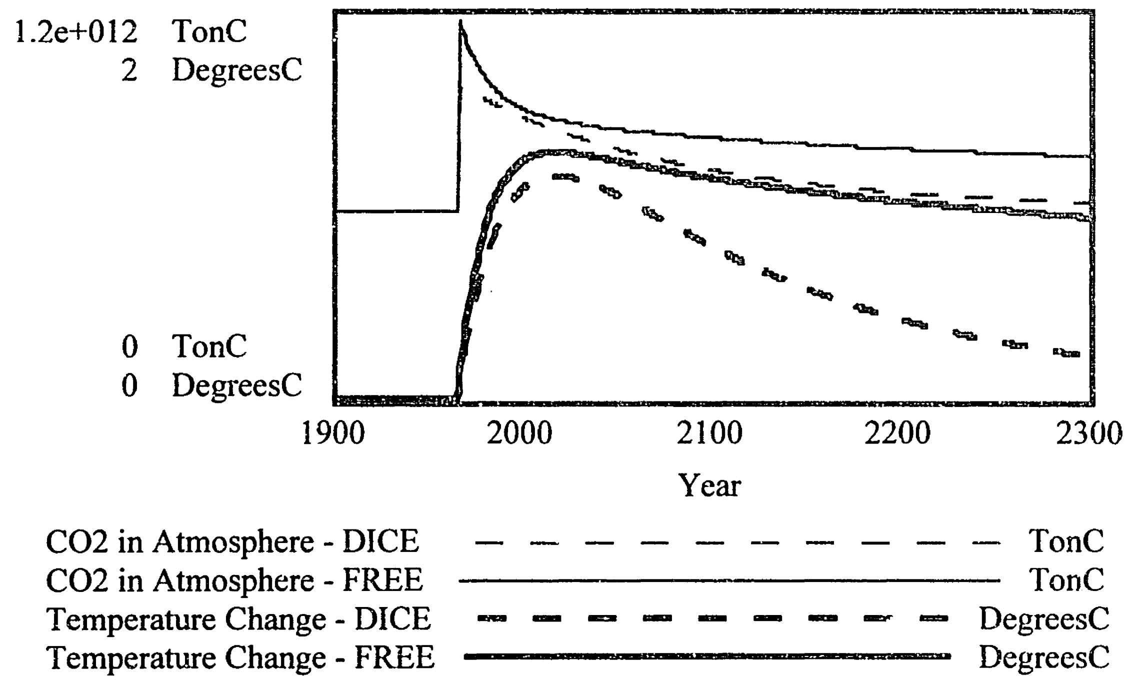


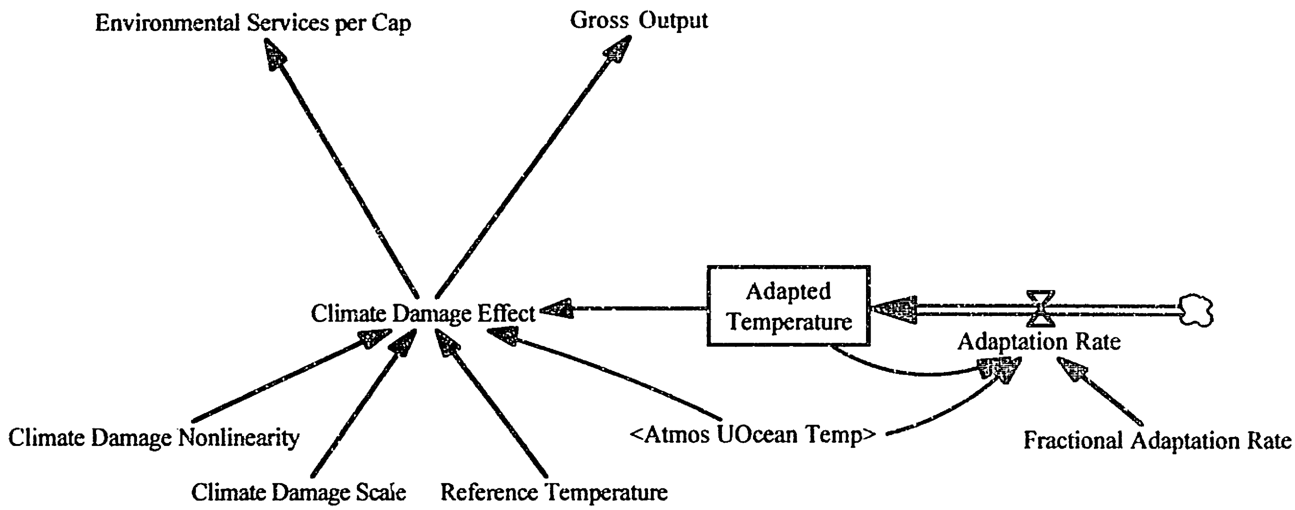
Table 25: Climate Parameters

Parameter	Alias	Value	Units	Notes
Climate Sensitivity	κ/λ	2.908	DegreesC	(Nordhaus 1994)
Radiative Forcing Coefficient	κ	4.1	watt/meter^2	(Nordhaus 1994)

Impacts

Climate impacts on the economy are the final output of the carbon cycle and climate subsystems. Climate damages in the FREE model are based on the DICE, with extensions that allow separate treatment of tangible damages (loss of economic output) and intangible damages (loss of non-market environmental services) and provide for adaptation to changing climate conditions (Hatlebakk and Moxnes 1992; Tol 1994).

Figure 74: Impact Sector



The impact of damages on output is roughly a quadratic function of the absolute deviation of the temperature of the atmosphere and upper ocean from adapted levels, as in the DICE model (Eq. 77-Eq. 79). The structure of the damage function for intangibles like environmental services is identical, but may use different parameters.

$$D(\Delta) = 1 - \frac{1}{1 + \theta_1 \left(\frac{\Delta}{\Delta_r}\right)^{\theta_2}} \qquad \text{Eq. 77}$$

D = *climate damage effect*
Δ = *deviation from adapted temperature*
Δ_r = *reference deviation from adapted temperature*

θ_1 = *climate damage scale*
θ_2 = *climate damage nonlinearity*

$$\Delta = \left| T - T_a \right| \qquad \text{Eq. 78}$$

T = *temperature of atmosphere and upper ocean*

T_a = *adapted temperature*

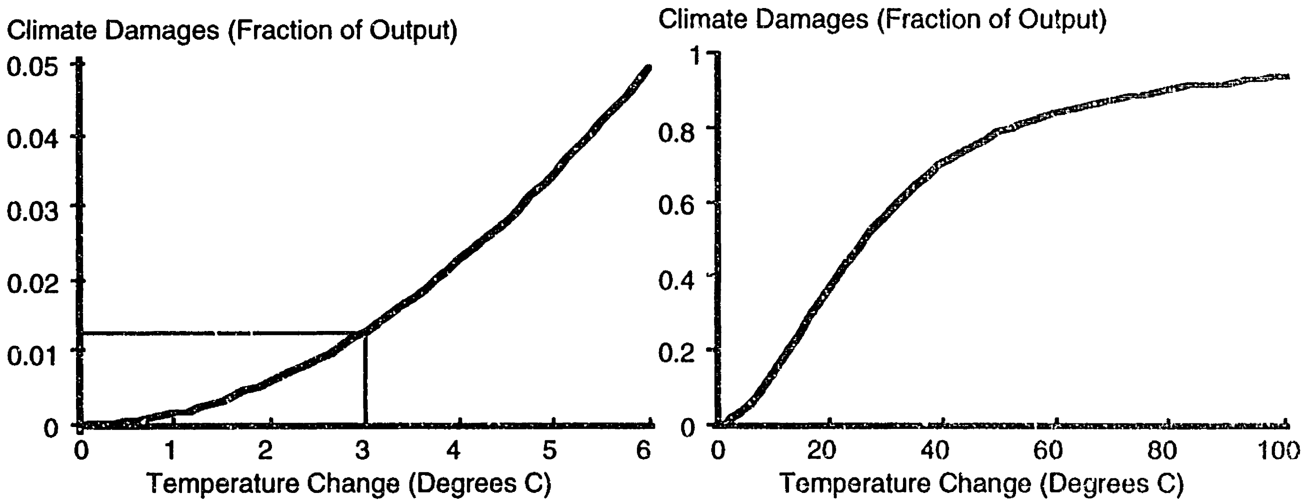
$$T_a(t) = \int \frac{T(t) - T_a(t)}{\tau_a} dt \qquad \text{Eq. 79}$$

τ_a = *adaptation time*

The adapted temperature adjusts to the prevailing temperature with a delay. The time constant of the adjustment process (the inverse of the fractional adjustment rate, α) represents the time required for built capital and natural systems to adapt to changing climatic conditions. Normally, $\alpha = 0$ and there is no adaptation, so damages depend on the absolute deviation of temperature from preindustrial levels.

For small temperature changes, damages increase quadratically with the change in temperature (Figure 75). For large temperature changes, losses of output and environmental services approach 100%.

Figure 75: Damage Response to Small and Large Temperature Changes



Because radiative forcing is logarithmic, and damages are roughly quadratic, the equilibrium damage response to a given concentration of CO_2 is relatively linear (Figure 76).

Figure 76: Equilibrium Damage Response

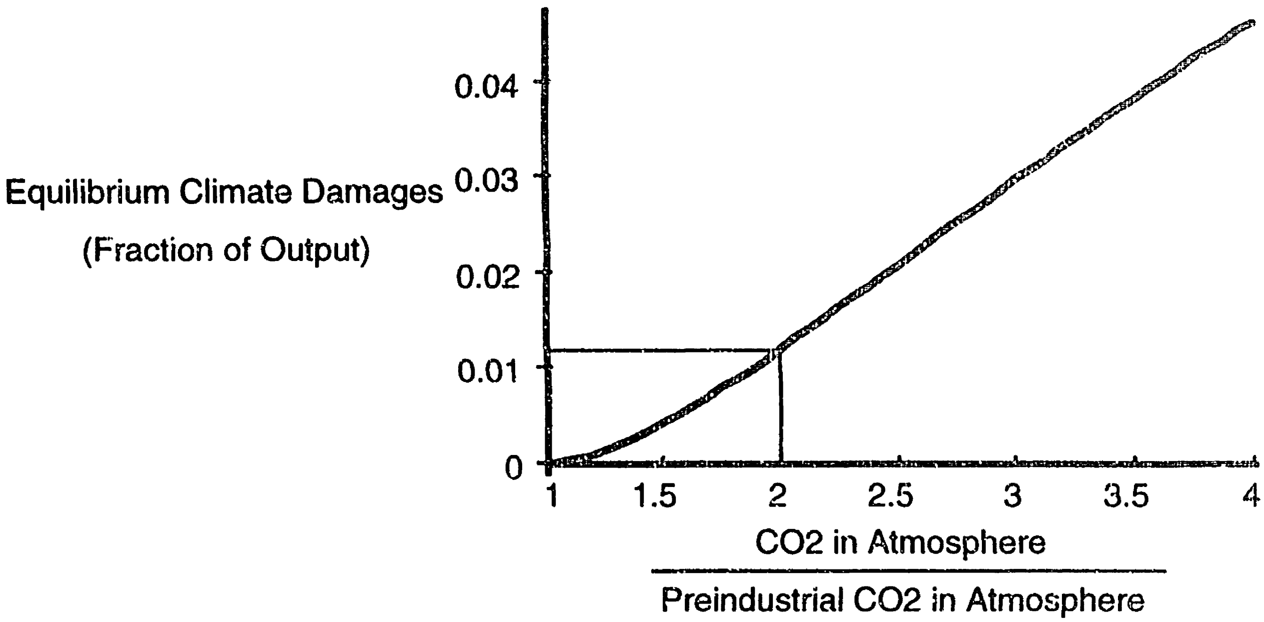


Figure 77 shows the temporal distribution of damages following a pulse doubling of atmospheric CO_2. The response is roughly second-order. Since damages are a monotonic function of temperature, they peak at the same time as temperature - about 50 years after the pulse. Because it has more rapid carbon uptake, damages have a lower peak and decay more quickly with the DICE carbon cycle.

Figure 77: Response of Temperature and Damages to 2x CO_2 Pulse

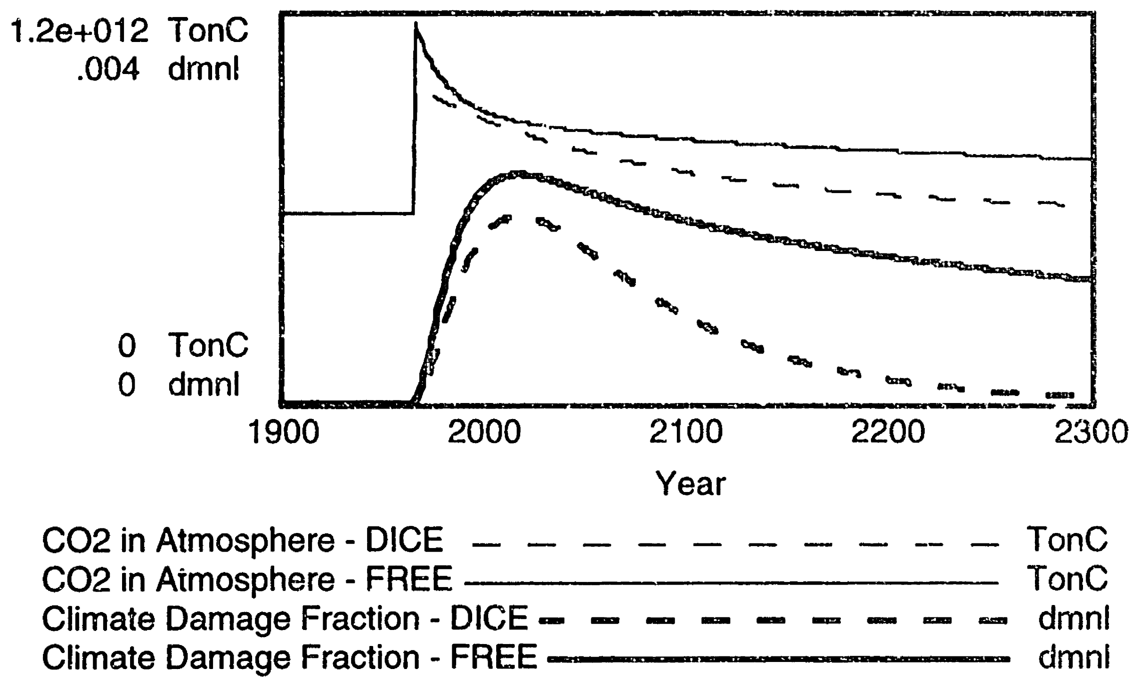


Table 26: Impact Parameters

Parameter	Alias	Value	Units	Notes
Climate Damage Scale	θ_1			
(tangible)		.013	dmnl	(Nordhaus 1994)
(intangible)		0	dmnl	
Climate Damage Nonlinearity	θ_2	2	dmnl	(Nordhaus 1994)
Fractional Adaptation Rate	$1/\tau_a$	0	1/year	No adaptation in base case.

Building on DICE

This chapter develops the parameterization of the model, building from a scenario that is much like the DICE model to a scenario that incorporates a more complex production structure, behavioral dynamics, depletion, endogenous technology, and a realistic carbon cycle. These features are added sequentially, so that the implications of each for model behavior may be explored. Table 27 contrasts the assumptions of the beginning and ending scenarios in this exploration. Parameter changes for each scenario are documented in the appendix (page 294).

Table 27: 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.

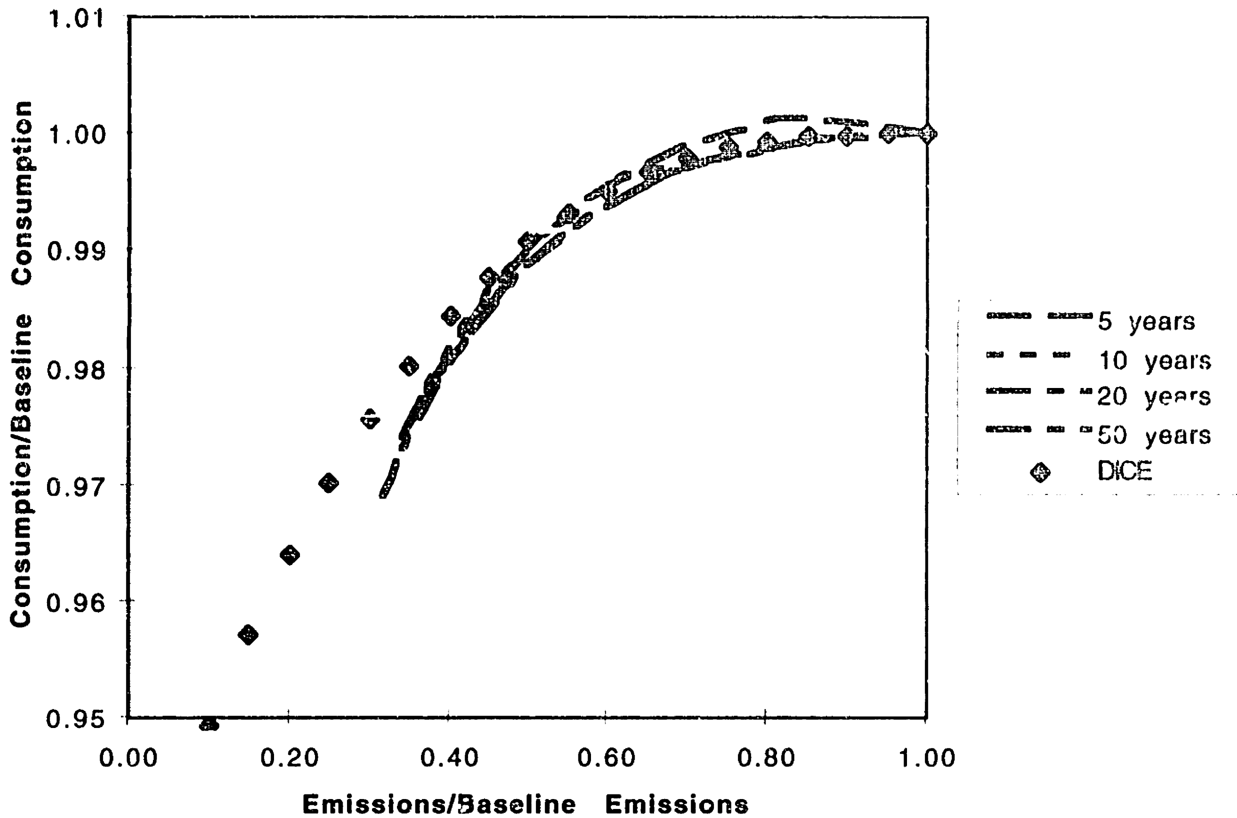
A. DICE Scenario

In the first scenario, the model is parameterized in order to behave much like Nordhaus' DICE model. The energy sector has static prices, and energy supply and demand equilibrate very rapidly. Autonomous energy efficiency improvements gradually reduce emissions. Population and factor productivity growth eventually cease, limiting pressure on the climate system.

The static energy sector functions much like the DICE model's emissions abatement cost curve. A carbon tax induces rapid interfuel and energy-capital substitution, which leads to lower capital productivity and higher energy production costs. These losses can be compared to the DICE abatement cost curve by testing the equilibrium response of the model to a carbon tax, and plotting the resulting welfare losses and emissions reductions.

To do this, all exogenous drivers, such as technology and population growth, are switched off, and investment is held constant, so that capital stocks and prices are in equilibrium. Carbon taxes between 0 and 400 $/TonC are imposed as step inputs. The cost of reducing emissions closely approximates that of the DICE model on both short and long time scales and for a wide range of emissions reductions. This flexible short run behavior has important policy implications. It reduces the incentive for near-term abatement under uncertainty, as it is easy to adjust emissions if needed later.

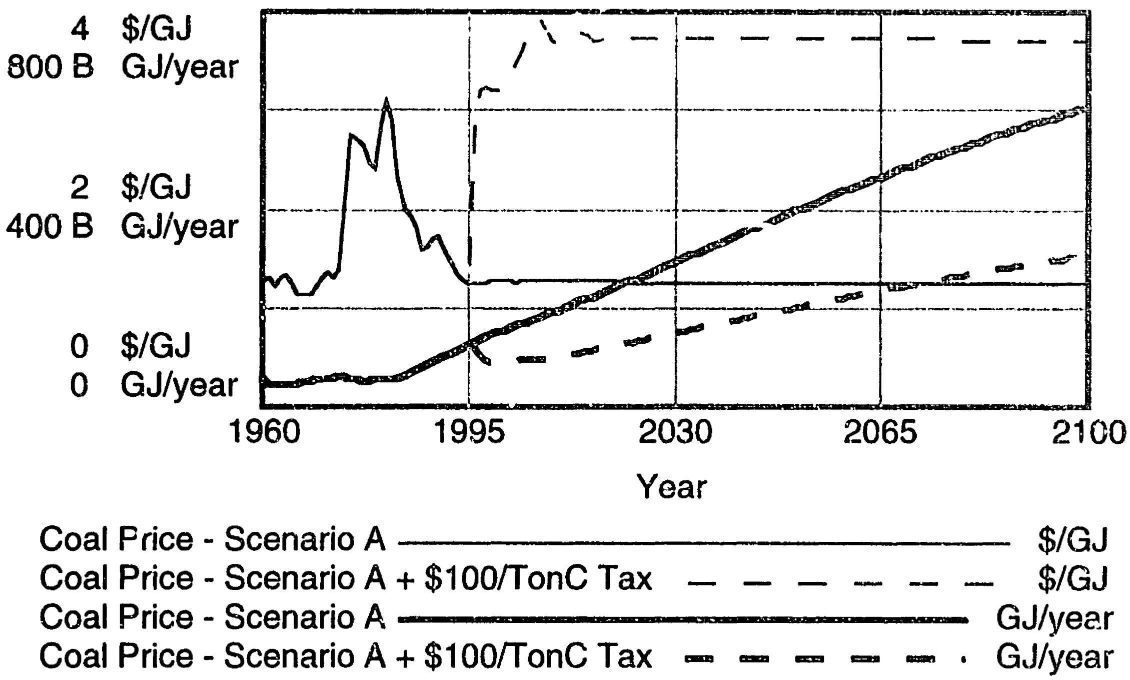
Figure 78: Emissions Reduction Costs vs. DICE



Emissions and consumption are shown as a fraction of baseline (no tax) values. Note that for the DICE model, losses are normally expressed as a fraction of output rather than consumption, so this figure assumes a constant savings rate—ordinarily a good approximation. Compare with Figure 95.

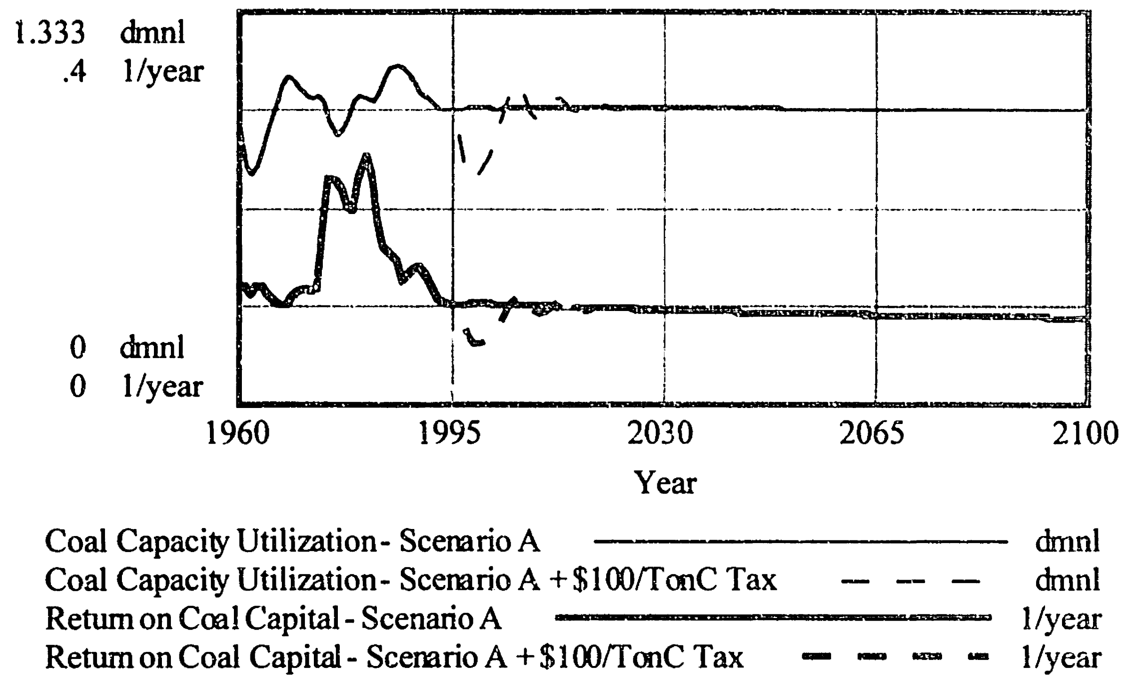
Returning to the disequilibrium case, a tax of $100 per ton carbon propagates rapidly through the energy-economy system (Figure 79). The delay in implementation of the carbon tax is short, so prices are immediately affected. The price of coal, for example, nearly triples in one year. This leads to immediate short-run substitution among fuels and between capital and energy. As a result, coal demand falls off dramatically, reaching its new equilibrium share within a few years.

Figure 79: Coal Price and Production



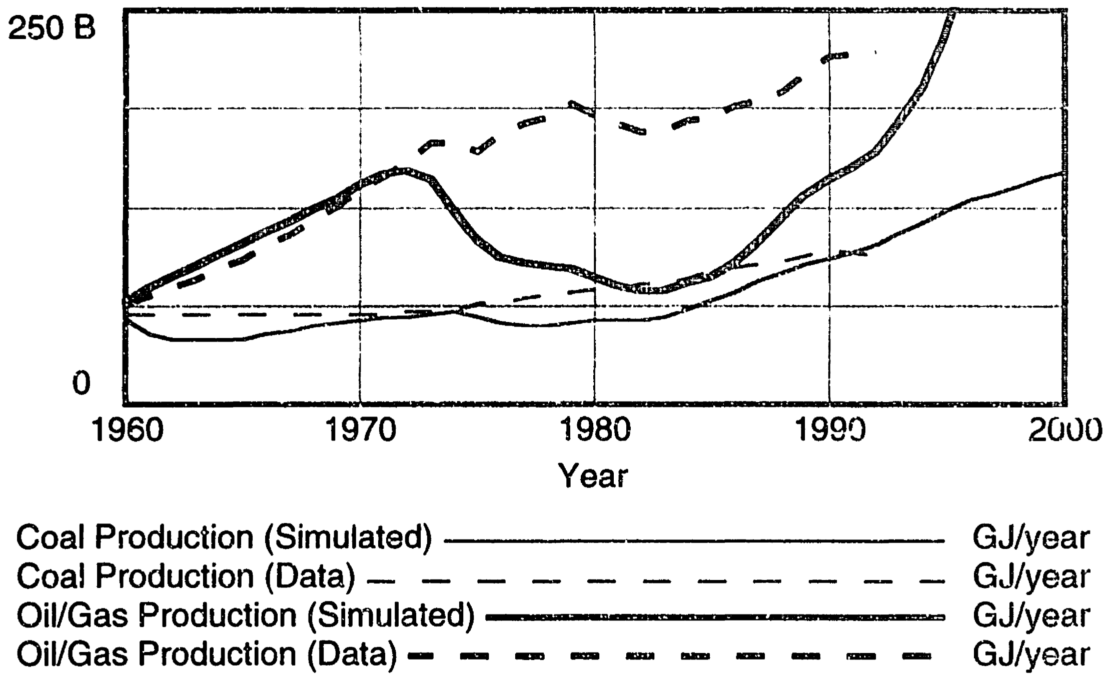
The energy system responds rapidly to the shift in demand. Beginning in 1995, there is a brief period of reduced capacity utilization in coal production, but this is essentially over within five years, as the lead times for adjusting capital stocks are short. Since the costs of energy production are mostly variable, this period of low utilization has almost no impact on the coal price.

Figure 80: Coal Capacity Utilization



Comparing this scenario to data, it is evident that the flexible short-run emissions response is not consistent with historic energy demand patterns. When subjected to exogenous energy prices from the OPEC era, the response of fuel shares and total energy demand to price changes is excessive. One possible explanation for this is that the substitution elasticities selected are too high. Scenarios G and H (page 142) explore another possibility, though—that structural and behavioral features account for the difference.

Figure 81: Simulated vs. Historical Energy Production

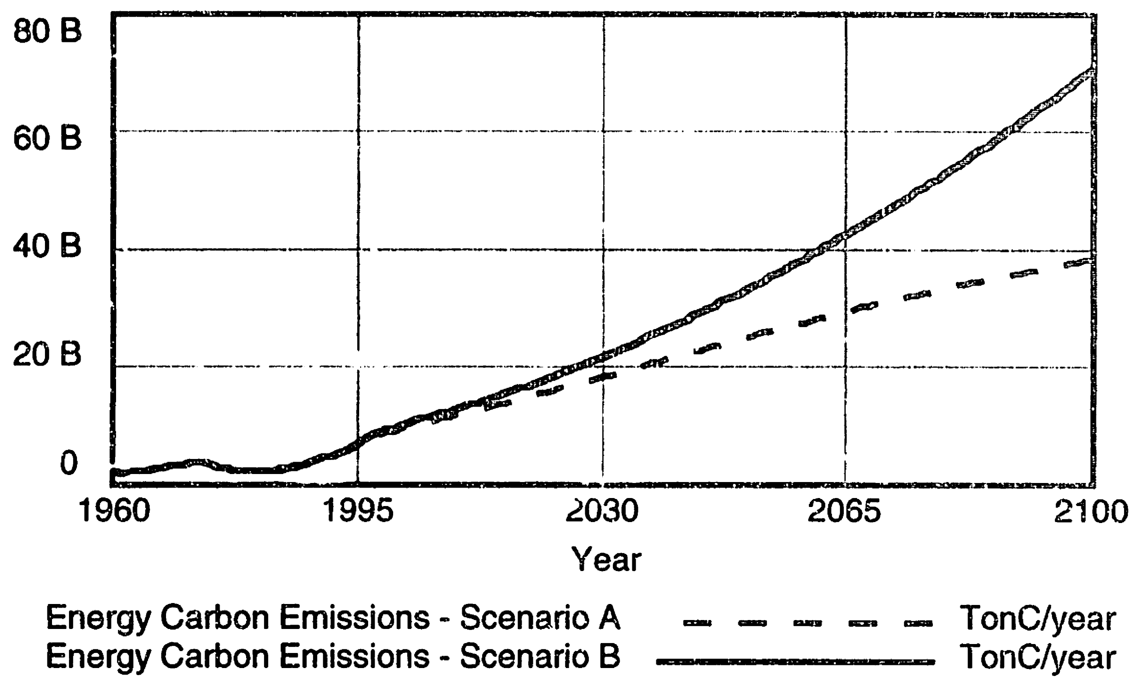


With flexible production in the short and long term, the simulated response of energy production and consumption to exogenous coal and oil/gas prices is excessive, especially for oil and gas.

B. Continuing Growth

One problem with the DICE scenario is that economic growth ceases late in the 21st century. This assumption is technically convenient for optimization, but is hardly consistent with recent technological history. The assumptions of declining technology and population growth reduce economic output and emissions, so that there is less pressure on fossil fuel resources and the climate system and less need for abatement. This is evident when one assumes that the rate of factor productivity growth declines, not to zero, but to some significant positive level. In this case, emissions rise to much higher levels. In a similar vein, Kolstad (1996) explores the consequences of population growth assumptions in detail.

Figure 82: Continuing Technological Progress

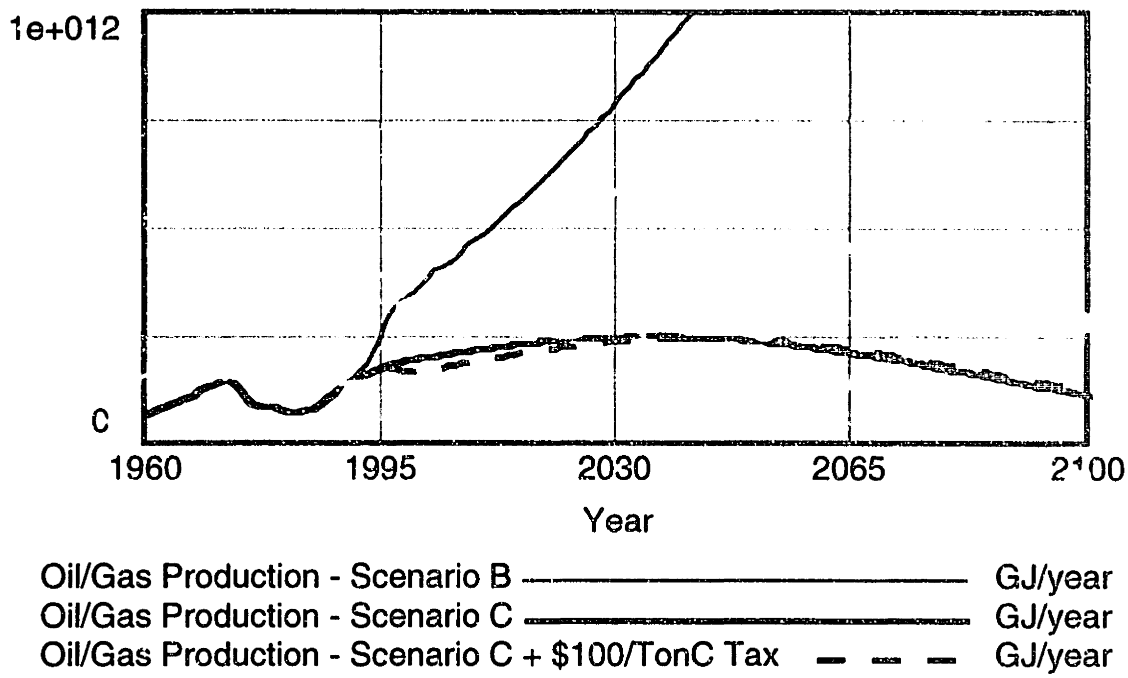


A nonzero asymptotic growth rate of factor productivity leads to substantially greater emissions in Scenario B.

C. Depletion

So far, the energy sector has been static, with constant energy supply costs. Unlike DICE, most climate-economy models incorporate an explicit energy system, with technological evolution and depletion. In this scenario, adding depletion of nonrenewable fuels introduces resource life cycle dynamics for oil and gas. Adding upper limits to the production of renewable energy limits the potential for backstop energy sources.

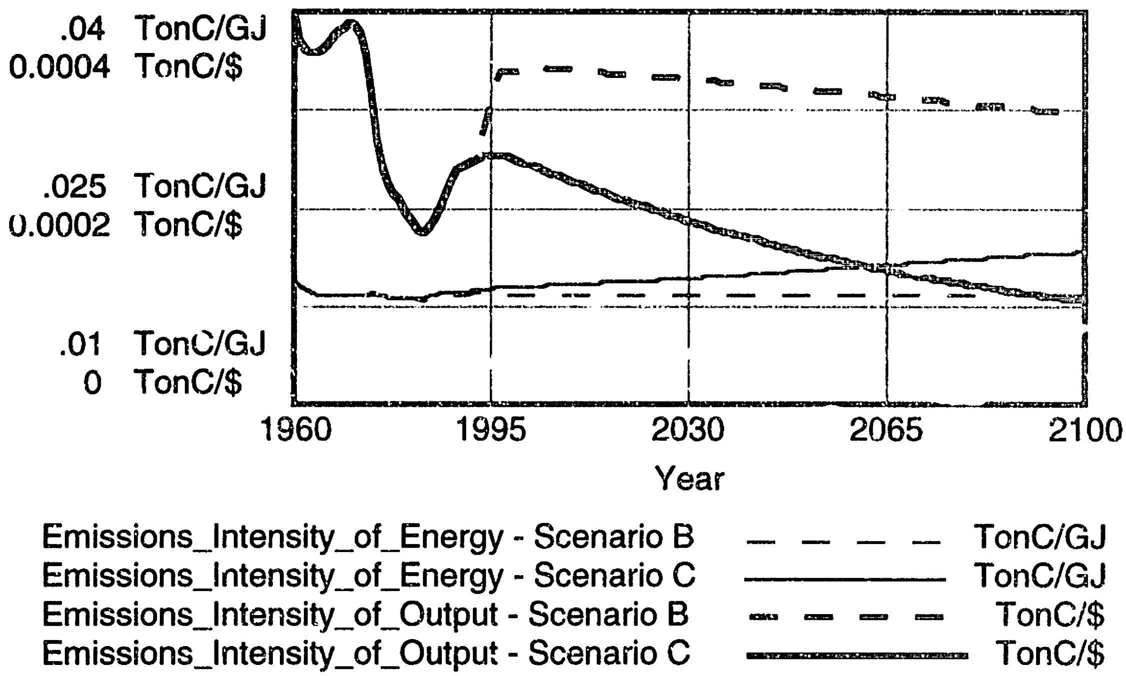
Figure 83: Oil & Gas Depletion Cycle



Over the historical period, oil and gas production is the same as in scenarios A and B. With the introduction of depletion, oil and gas production now peaks within 40 years. A carbon tax delays the peak by shifting demand to noncarbon fuels and promoting substitution of capital for energy, but the effect is limited because the tax falls more heavily on coal.

One important consequence of depletion is that the trend in decarbonization of energy assumed by Nordhaus (1994) and others may eventually reverse, as oil and gas are depleted and energy demand shifts to high-carbon solid and synthetic fuels. In this simulation, the carbon intensity of energy production does rise significantly, as coal replaces depleted oil and gas (Figure 84). However, the rising cost of energy leads to substitution of capital for energy inputs in production. This decrease in energy intensity more than offsets the increasing carbon intensity of energy. As a result, the overall ratio of carbon emissions to economic output falls. With a lower capital-energy substitution potential and higher interfuel substitution, the opposite could easily occur.

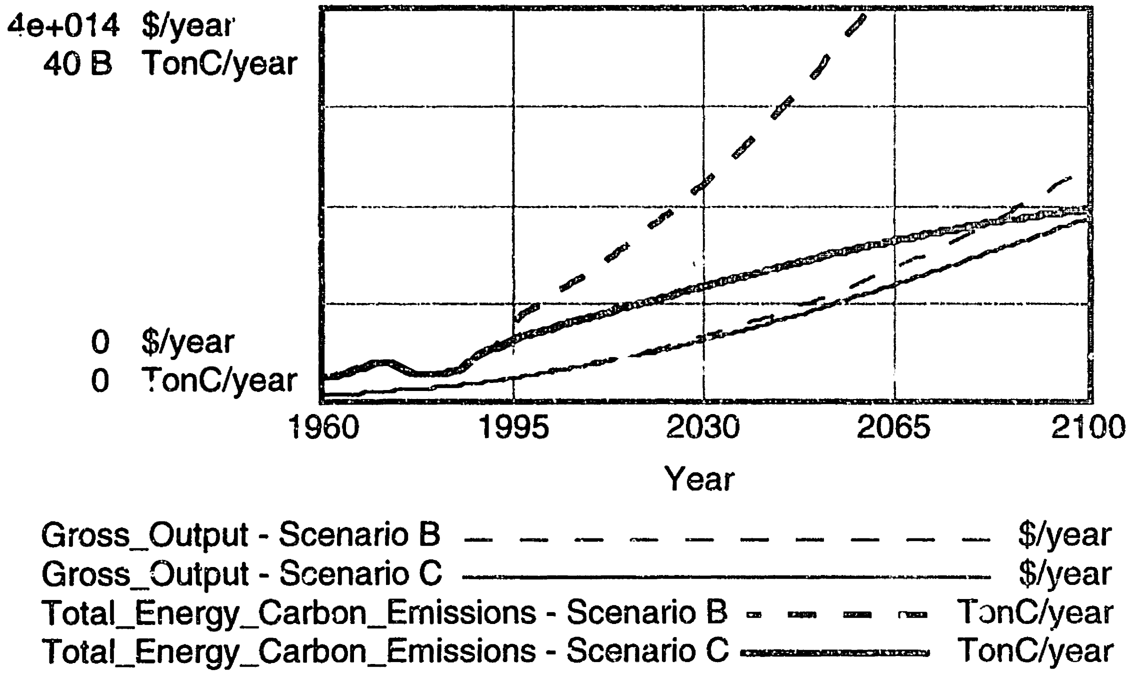
Figure 84: Carbon Emissions Intensity of Energy and Output



The emissions intensity of energy equals total energy carbon emissions divided by total physical energy production in primary equivalent terms. The emissions intensity of output equals total energy carbon emissions divided by gross output of goods and services.

Total carbon emissions thus are lower in Scenario C than in Scenario B, largely because of the decreasing carbon intensity of output. This reduction in emissions comes at a price, though. The carbon intensity of output falls because energy becomes very expensive. The rising cost of depletable energy sources reduces economic growth substantially (Figure 85).

Figure 85: Depletion's Impact on Output and Emissions

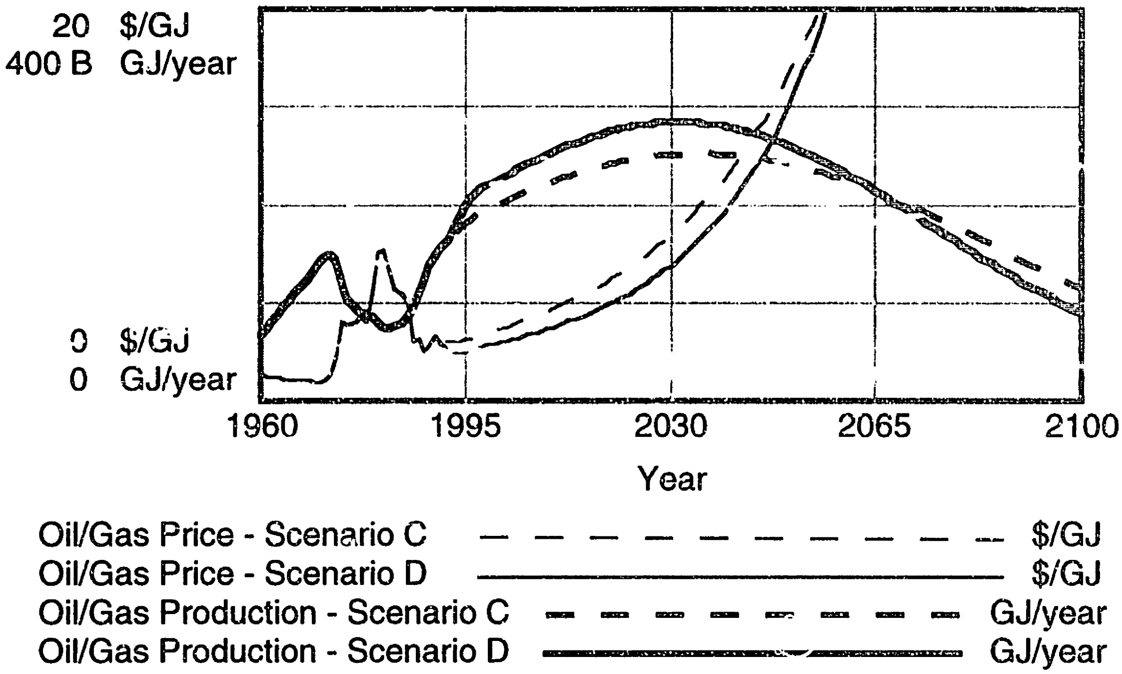


Depletion significantly reduces carbon emissions in scenario C, because economic output falls and energy efficiency increases.

D. Autonomous Energy Technology

Depletion is not the only process affecting energy production costs. Technological improvement reduces the cost of energy production. Historically, improvements in technology have offset the effects of depletion, though this can not continue forever. Adding autonomous cost-reducing technology in energy production to the model offsets some of the effects of depletion. As a result, the price of oil and gas is lower in the near term. However, this leads to more rapid depletion of the oil and gas resource. By 2030, rising costs from depletion outstrip continuing technological progress, and the price of oil and gas actually exceeds the price without technological change.

Figure 86: Oil and Gas Depletion with Autonomous Technology

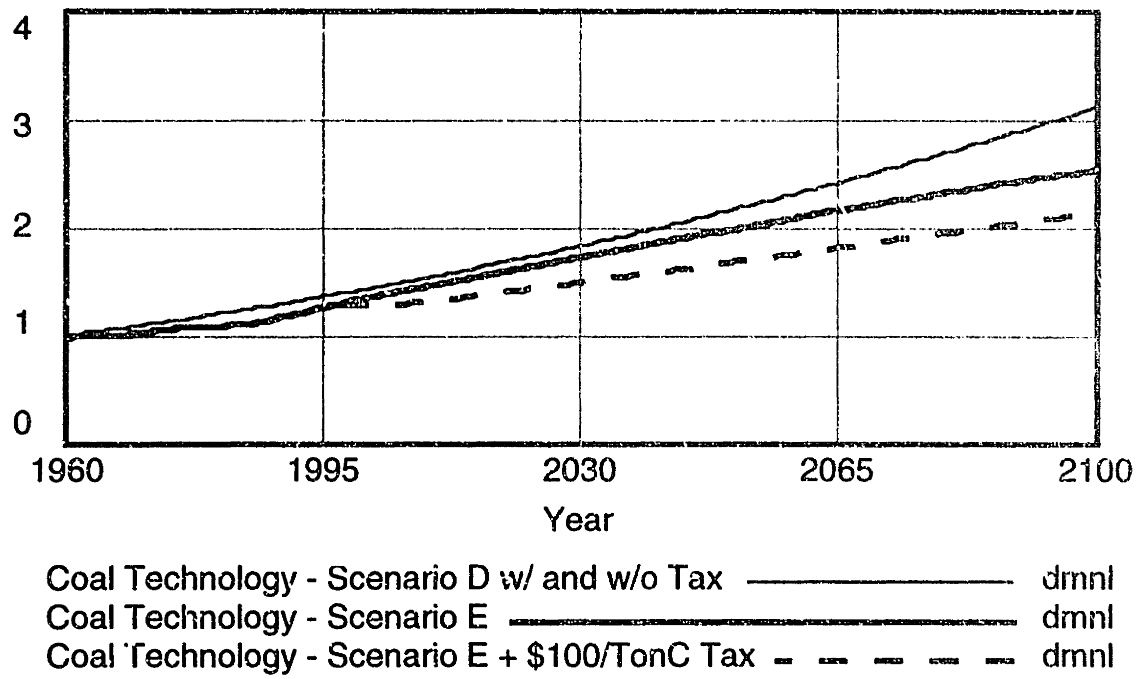


Autonomous technology reduces the cost of alternative energy technologies as well. This creates an incentive to wait before abating emissions, as it is cheaper to do so later, when technology drives down the cost of noncarbon energy.

E. Endogenous Energy Technology

In reality, technological evolution in the energy sector is at best only partly autonomous. Technological improvement in energy production also depends on intentional research and development and accumulation of production experience. Here, technology is made endogenous by substituting a standard learning curve for the autonomous technology driver. Technology improves as a function of cumulative investment. Each doubling of cumulative investment yields a 20% reduction in energy production costs.

Figure 87: Autonomous vs. Endogenous Technology



With autonomous technology, the technological trajectory is the same with and without a tax. With endogenous technology, technological progress slows when demand slows—is in the OPEC period and following the imposition of a tax in 1995.

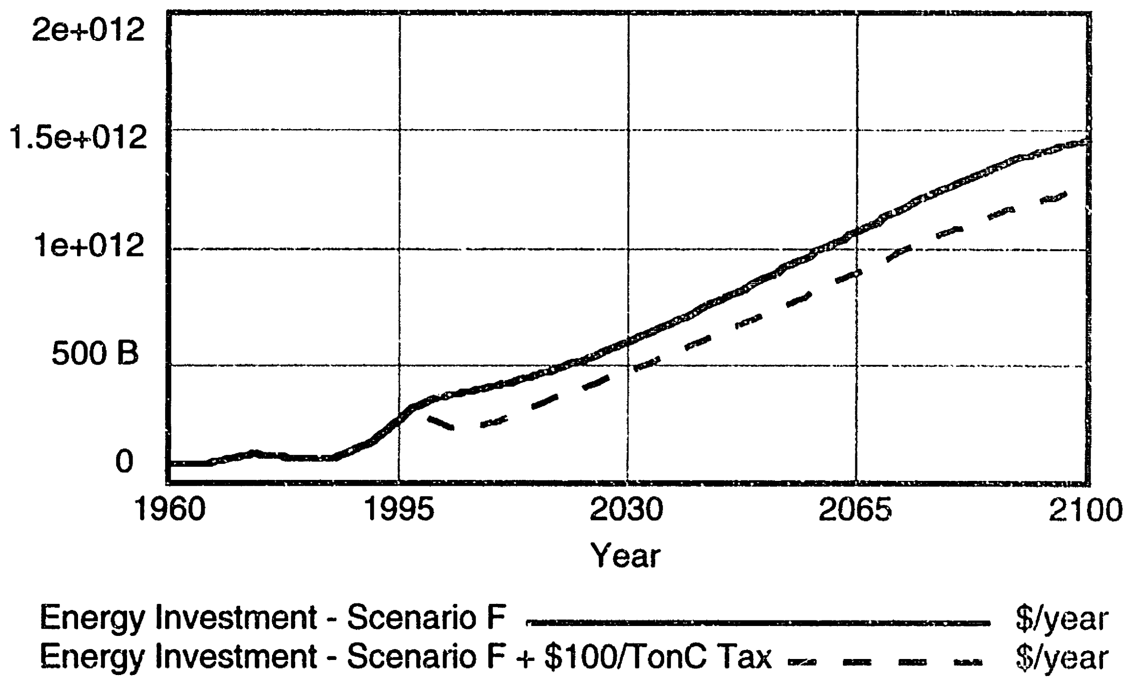
In the previous scenario, the implementation of a tax had no influence on the technological trajectory of the four energy sources. With endogenous technology, this is not the case. Imposition of a carbon tax reduces demand for coal, slowing investment and thus reducing technological progress (Figure 87). For noncarbon fuels, technological progress is accelerated.

F. Energy Capacitation

In many models the energy sector is treated as a flexible producer with a constant marginal cost of supply. While energy prices may vary due to depletion and technology effects, the costs of energy production are entirely variable. This means that a rapid transition from one energy source to another is smooth, even when it is unanticipated. In reality, the energy sector—especially electric power generation—is highly capital intensive, with long construction lead times and capital lifetimes. This means that transitions between energy sources require advance planning and may involve significant up-front costs.

One possible consequence of this is that a transition to a less carbon intensive energy system based on more expensive, capital intensive energy sources will require a substantial pulse of investment during the transition period, because of the necessity of rapidly building up capital stocks. This could be disruptive to overall economic activity. In this case, though, the disruption does not materialize, because the reduction in investment in fossil fuel technologies more than offsets the increase required in alternative technologies. Still, this would be a difficult period in the renewable energy sector, which would be required to grow rapidly. Expansion constraints not represented in the model, such as delays in acquiring labor or financing, would play an important role.

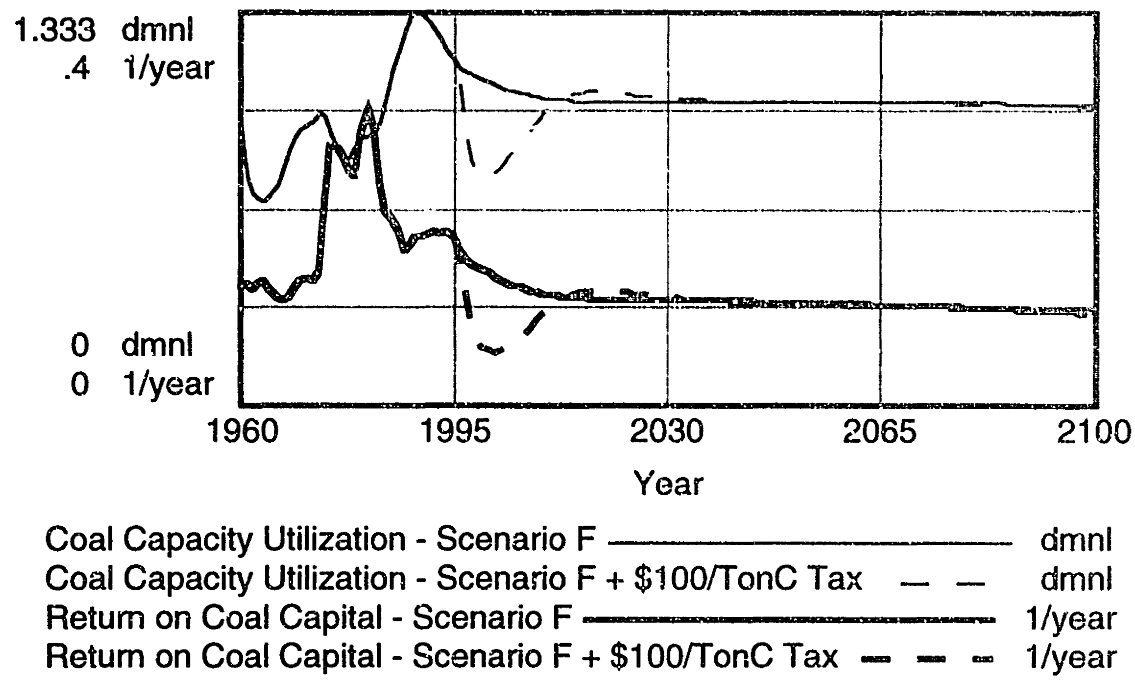
Figure 88: Energy Investment Costs



With the imposition of a tax, total energy investment falls in this scenario, because the effect of energy conservation exceeds the effect of increased demand in the noncarbon energy sectors.

There is significant disruption of another sort in the carbon energy sectors. Because the imposition of the tax is unanticipated by fossil fuel producers, the sudden reduction in demand causes significant underutilization of capital for coal and oil/gas production. This depresses returns in these industries; the marginal product of coal producing capital declines by half, and requires more than 15 years to return to normal levels. One could expect producers in these industries to fiercely resist the imposition of such a tax.

Figure 89: Coal Sector Returns



When energy sector capital stocks are taken into account, imposition of a carbon tax causes significant losses in the coal sector, as demand shifts to low-carbon fuels faster than capacity can adjust.

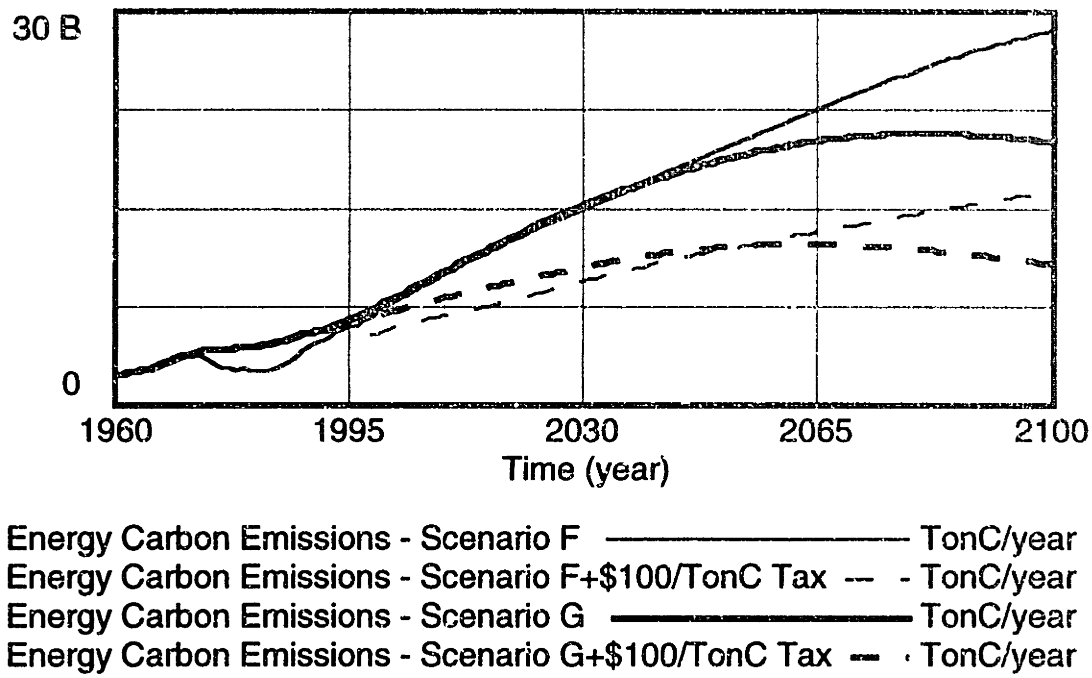
G. Putty-clay Production

Up to this point, the short and long run substitution potentials between capital and energy and among energy sources have been identical. Just as the energy sector cannot instantly adjust its production capacity, the energy requirements of goods and services production cannot be changed overnight. Energy requirements are embodied in capital at the time of construction; thereafter there is much less flexibility in the reallocation of factor intensities. To represent this in the model, a putty-clay production structure is added by reducing the short-term substitution potentials.

After 2030, the normal intensity of coal and oil/gas use embodied in the capital stock is far from equilibrium, because the energy intensity of new capital is based on myopic price expectations, and oil/gas prices are rising rapidly. With flexible short- and long-run substitution, as in the previous scenarios, coal demand rises well above normal requirements embodied in the capital stock in order to replace depleted oil and gas. However, with inflexible short-term demand, coal consumption is not able to immediately compensate for declining oil and gas production.

As a result of this inflexibility, welfare is significantly reduced. The slower transition away from oil and gas means that energy production costs consume an excessive fraction of output for a longer period of time. The putty-clay specification also implies that emissions are almost two-thirds less sensitive to a carbon tax in the short run (Figure 90 and Table 28). Over 30 years, twice the normal capital lifetime, emissions reductions are comparable.

Figure 90: Impact of Flexibility on Emissions



Switching to the putty-clay specification has little impact on gross output and consumption, until the economy is thrown into severe disequilibrium by the depletion of oil and gas.

Table 28: Emissions Reductions, with Putty-putty and Putty-clay Structures

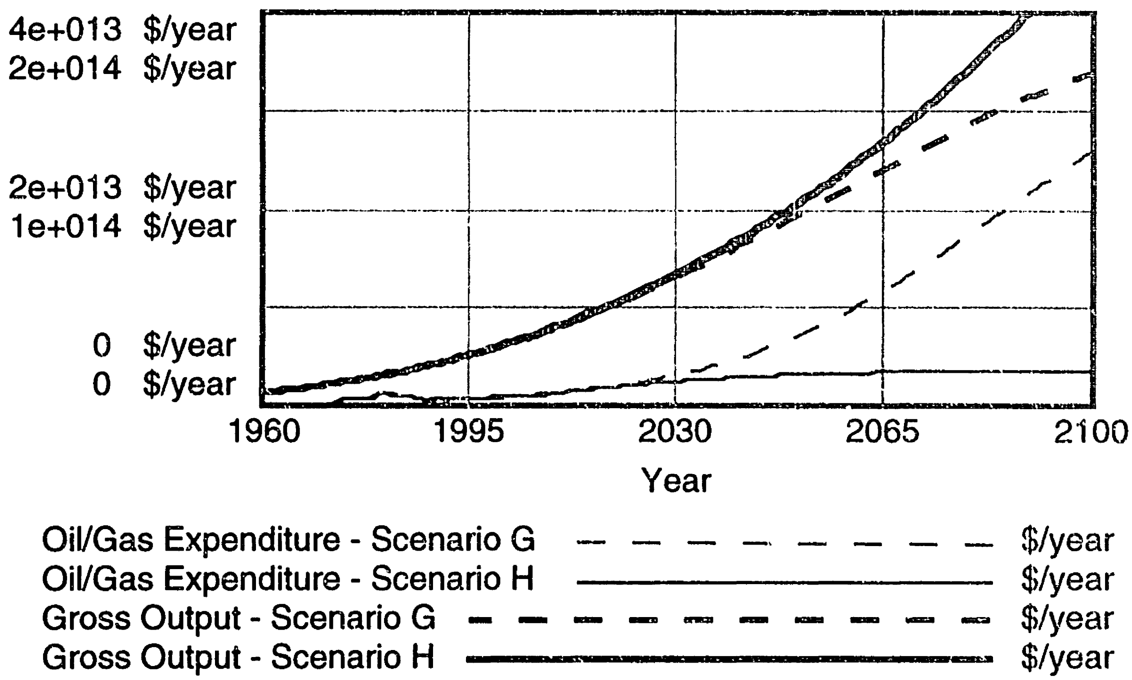
	Emissions Reduction (vs. Baseline)	
Year	2000	2025
Scenario F	24%	37%
Scenario G	10%	39%

Emissions reductions are expressed as a percentage of baseline (no tax) emissions. In both scenarios, a 100 $/TonC tax is imposed in 1995.

H. Behavior

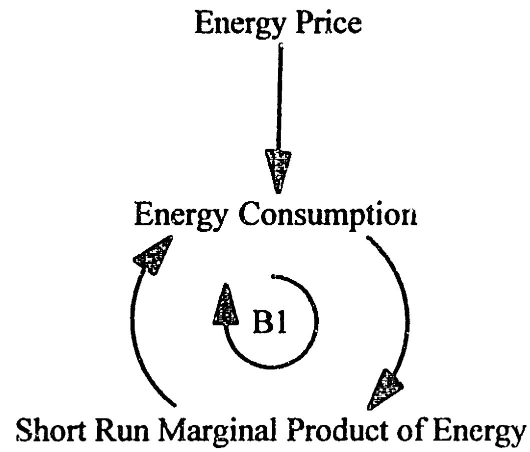
While the putty-clay structure above is already a great improvement over the baseline scenario, there are still several troubling problems. First, in order to obtain reasonable correspondence with historical data, the interfuel elasticity of substitution must be significantly less than 1 (.7 in this case). In the CES formulation, this means that there is a lower bound to the intensity of use of any particular fuel in the aggregate energy mix. Expenditures on oil and gas thus become an increasing drag on the economy as resources are depleted. By contrast, with a higher elasticity of substitution, oil and gas can be completely replaced in the energy mix, and after a transitional period, expenditures fall accordingly. Economic growth proceeds with little interruption.

Figure 91: Oil and Gas Expenditures and Economic Output



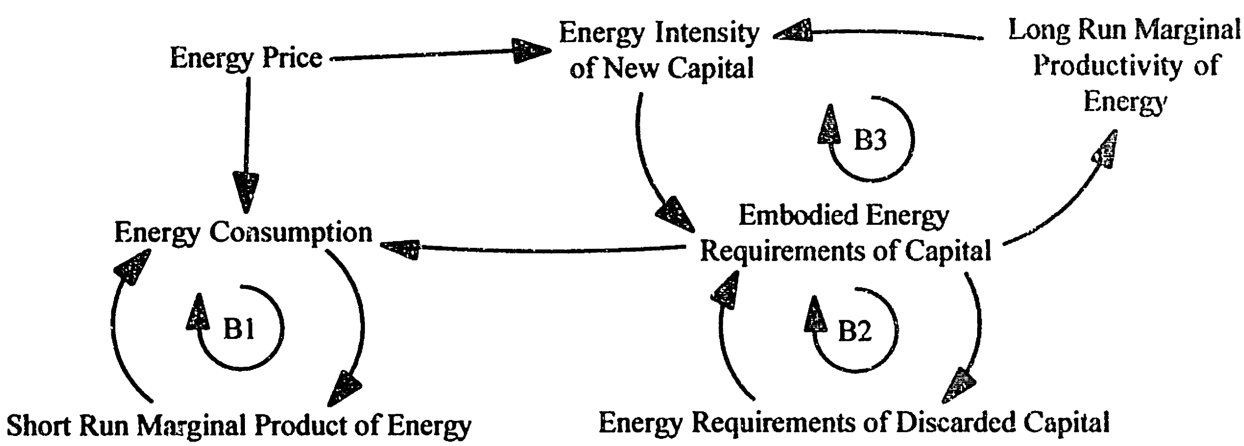
However, a high elasticity of interfuel substitution by itself is inconsistent with historical behavior; it leads to excessive adjustment in response to price shocks, as in Figure 81. The simplest elasticity estimates account only for short-run variation in energy demand due to price shocks. The elasticity then measures the change in the equilibrium of loop B1 in response to a change in price. B1 is assumed to reach this equilibrium very quickly.

Figure 92: Short-run Energy Demand Adjustment



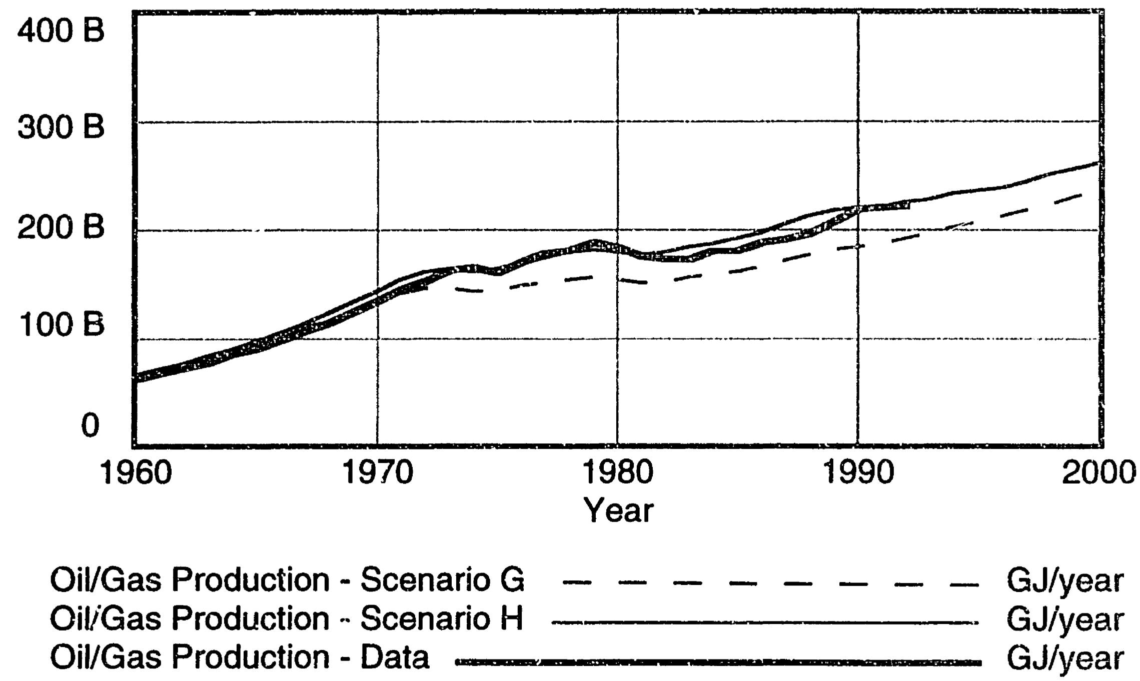
Long-run elasticity estimates used in models with putty-clay structures recognize that there are two components to the price response—short run changes in utilization, and long run changes in the energy requirements embodied in the capital stock. The capital stock reaches equilibrium more slowly, as capital is discarded (B2) and replaced by new investment. However, these models still assume that loop B3, which adjusts the energy intensity of new capital, reaches equilibrium instantly.

Figure 93: Putty-clay Energy Demand Adjustment



In reality, though, the adjustment to the energy intensity of new capital is likely to be gradual as well, as it takes time to recognize price changes and incorporate them in new plans or products. Since energy costs are a small component of most products, the profit gradient driving changes in energy intensity is weak. Neglecting these behavioral and structural factors affecting the gain and delay around loop B3 causes the long-run elasticity to be underestimated. Adding behavioral constraints to energy intensity adjustment allows interfuel substitution elasticities to be revised upward to more plausible values without losing correspondence with historical behavior.

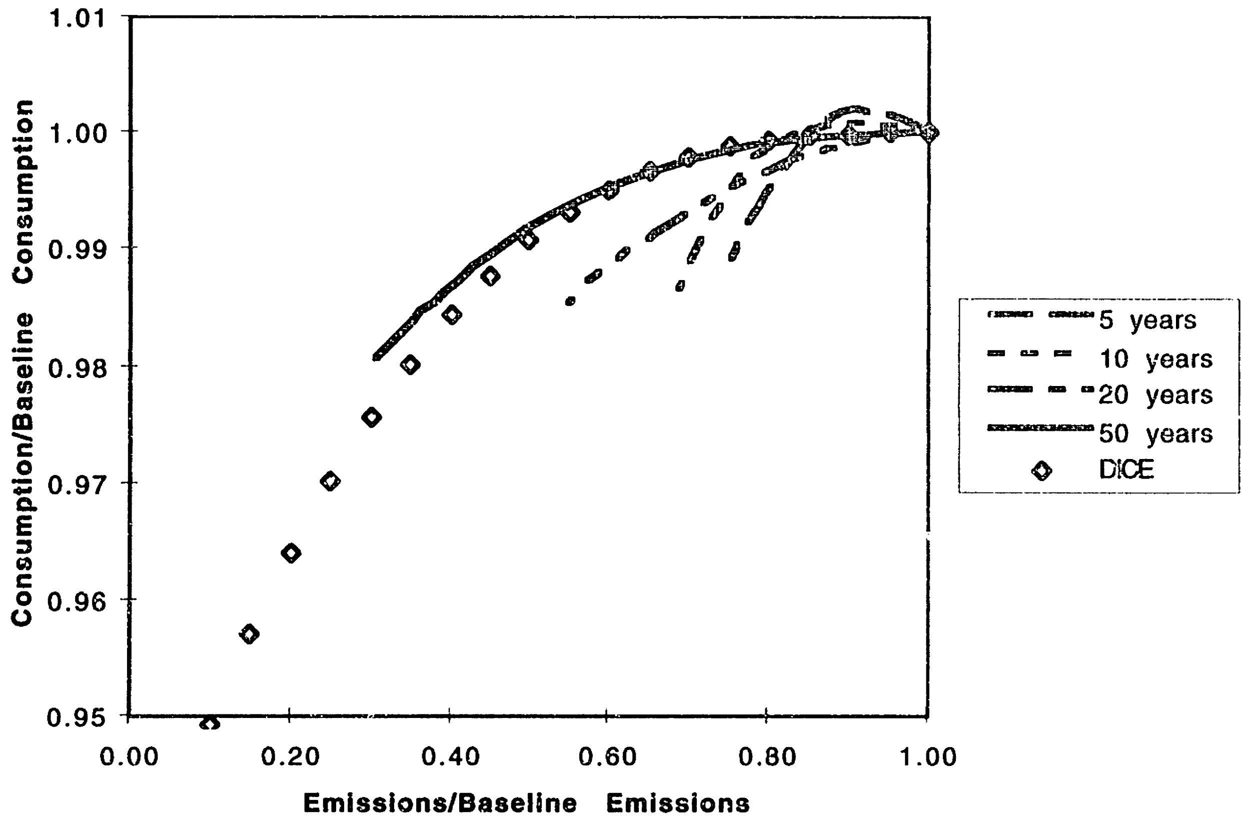
Figure 94: Oil and Gas Production vs. Data



Because of behavioral constraints to adjustment of energy intensity, scenario H displays a more moderate response to price shocks than scenario G, in spite of the fact that the long-run capital-energy and interfuel substitution potentials are higher.

Scenario H completes the changes to the energy-economy system. The long run response to a carbon tax is now slower but less costly than in Scenario A. This can be seen be reexamining the cost of emissions abatement on different time scales (Figure 95). It is now impossible to achieve large short-run emissions reductions without high carbon taxes that significantly reduce welfare. In the long run (50 years or more), emissions reductions are actually less costly than in DICE. Note that this is an equilibrium test, and ignores intertemporal effects of depletion and endogenous technology, which will be explored in the Policy Analysis chapter.

Figure 95: Equilibrium Tax Response in Scenario H



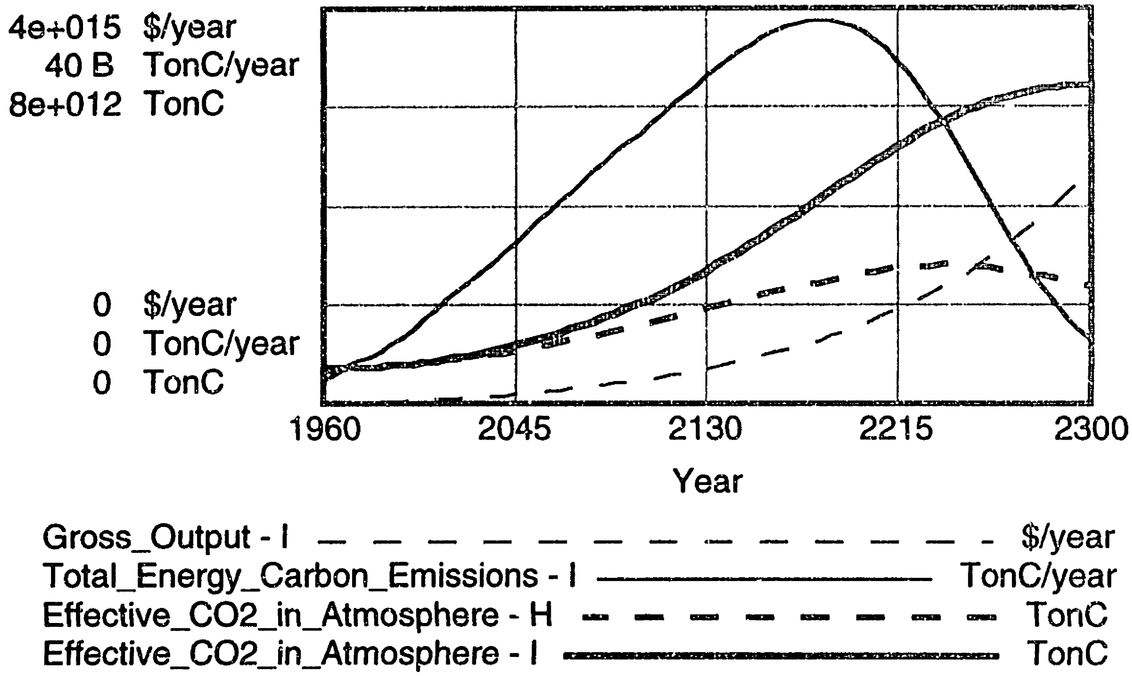
Compare to Figure 78.

I. Realistic Carbon Cycle

In the prior scenarios, the roles of the carbon cycle and climate have been ignored. It is useful to reexamine them now. If uncontrolled, emissions rise to extremely high levels in Scenario H, as energy demand shifts to coal. Because economic output continues to grow, eventually outstripping autonomous energy efficiency improvements, emissions increase dramatically, until coal resources are depleted in late in the 22nd century.

The resulting atmospheric concentrations of CO_2 projected by the DICE and FREE carbon cycle models differ by a factor of two. The lower of the two trajectories, from the DICE carbon cycle, is likely to be a significant underestimate of the true concentration (see Carbon Cycle section, page 114). Even though radiative forcing from CO_2 is only a logarithmic function of atmospheric CO_2 concentration, the difference between the two carbon cycles has a large impact on the climate.

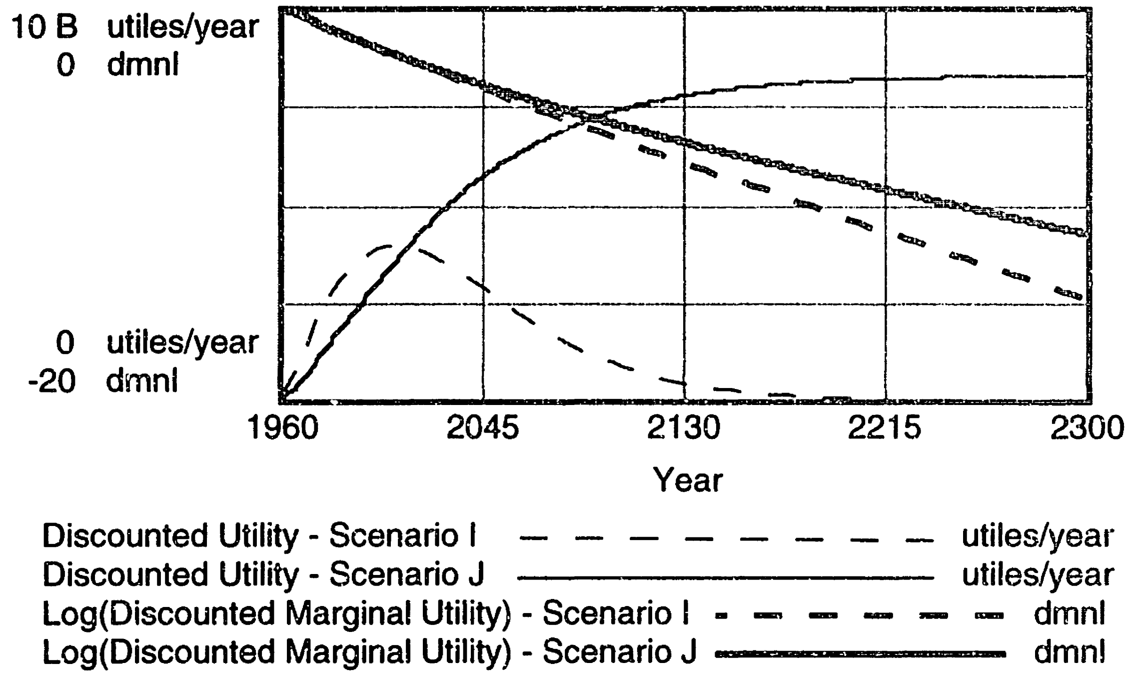
Figure 96: Carbon Cycle Comparison



J. Fair Discounting

The final scenario contrasts the typical assumption of time discounting of welfare with an intergenerationally fair scheme. Since social welfare does not feed back to other variables in the model, this has no impact on the behavior of the energy-economy-climate system. The key difference is that, with significant time discounting, the importance of the welfare of future generations eventually diminishes to zero, whereas with a zero discount rate, the flow of discounted utility continues to increase. For climate policy, this means that the welfare of future generations receives greater weight, and present abatement efforts should be greater.

Figure 97: Social Welfare



Policy Analysis

This chapter uses the FREE model to explore 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 to the implications of depletion, endogenous energy technology, adjustment constraints, externalities and non-optimizing behavior, and discounting.

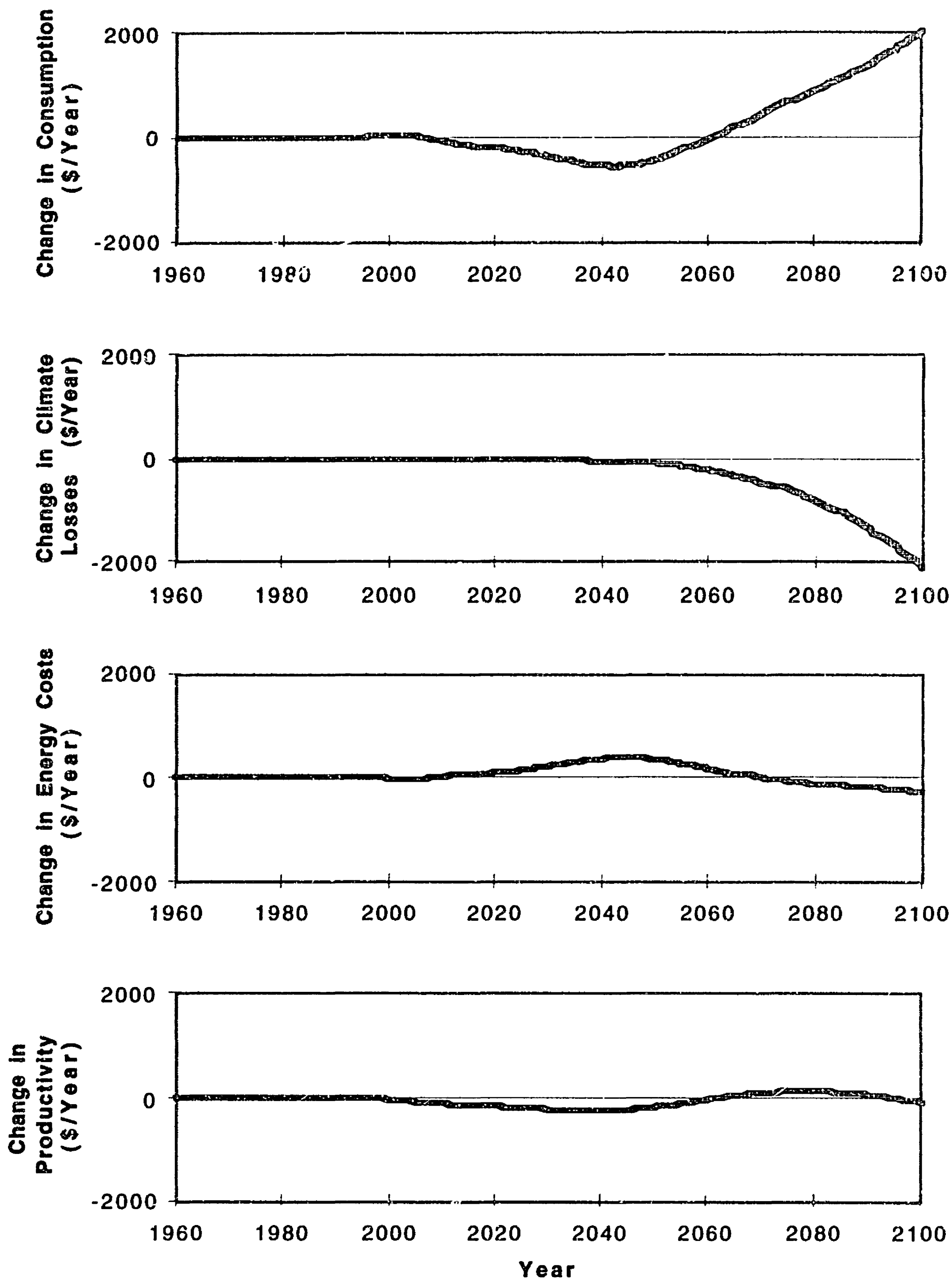
Impact of a Carbon Tax

The impact of a carbon tax can be very complex in the FREE model. Figure 98 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.

Figure 98: 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.

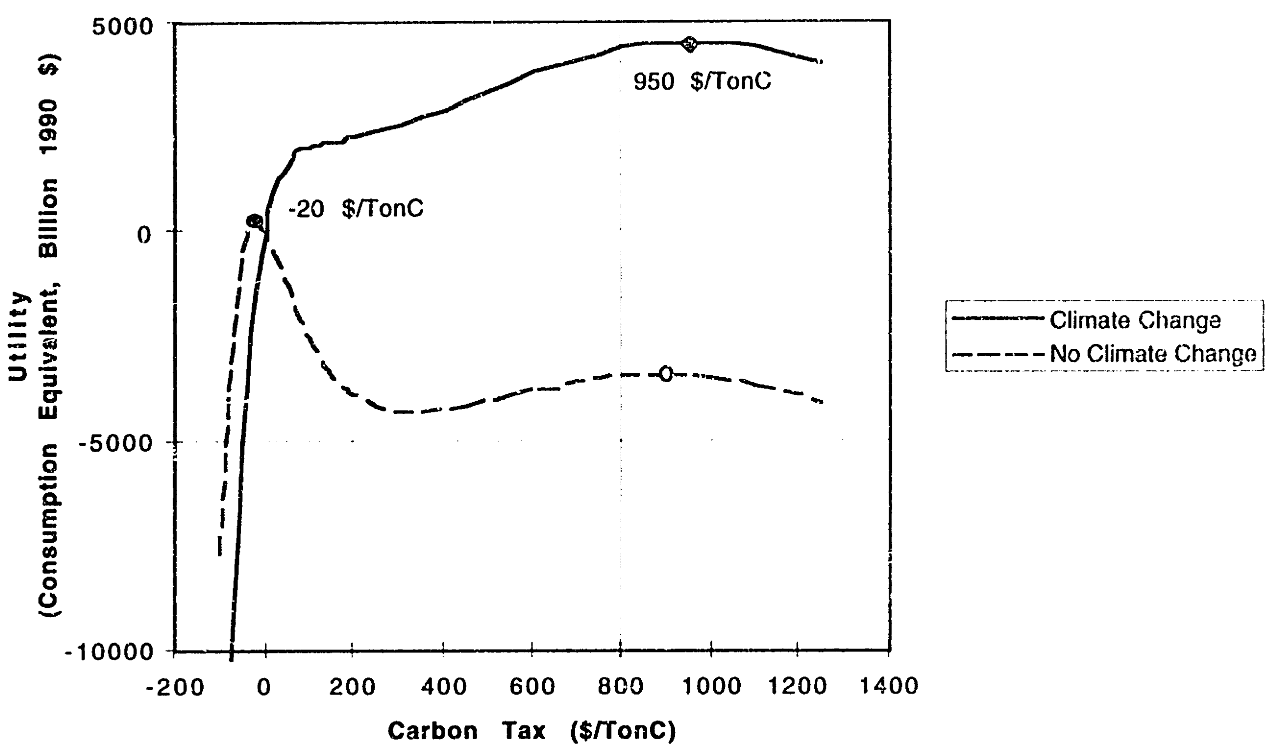
Optimal Carbon Tax

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 controller (see page 109) that responds to the CO_2 emissions rate and atmospheric concentration. For simplicity, a constant tax (implemented gradually) is used in most tests. The criteria for policy evaluation is maximization of cumulative discounted utility over the simulation period (see page 69). 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 99). 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 99: 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.

The Connecticut/YOHE model (Yohe and Wallace 1996) incorporates an explicit energy system, with carbon and noncarbon sources. The carbon resource aggregates coal, oil, and gas. It is subject to increasing extraction costs as the resource is exhausted. However, because the resource is so large (with respect to cumulative production over the model time horizon), depletion is not very important, and only a small tax is required to restore intertemporal efficiency. This tax or depletion rent is calculated separately from the carbon tax, so the baseline from which climate policy is evaluated is already intertemporally optimal. Because oil and gas are aggregated with coal, there is implicitly a high substitution potential among the resources, and there are no difficult dynamics of a transition from one fuel to another. Transitional dynamics are also eased by the lack of a short-run production structure with embodied energy requirements.

ICAM separates oil, gas, and coal resources (Dowlatabadi and Ball 1994). However, the depletion mechanism in ICAM suffers from several problems that make its dynamic behavior unrealistic (see page 51). These problems prevent a serious evaluation of the implications of depletion.The EPPA model (Yang, Eckaus et al. 1996) incorporates a putty-clay production structure that can make the transition to an alternate energy system more challenging. In addition, factor allocation decisions are made myopically, so it is possible for intertemporal inefficiencies to arise. However, the rate of resource conversion to reserves follows an exogenously specified depletion profile, reducing the sensitivity of the depletion process to intervention. Fossil resources have readily available, highly substitutable backstops.

The Global 2100 model (Manne and Richels 1992) has a similar structure to EPPA, but the model employs 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.

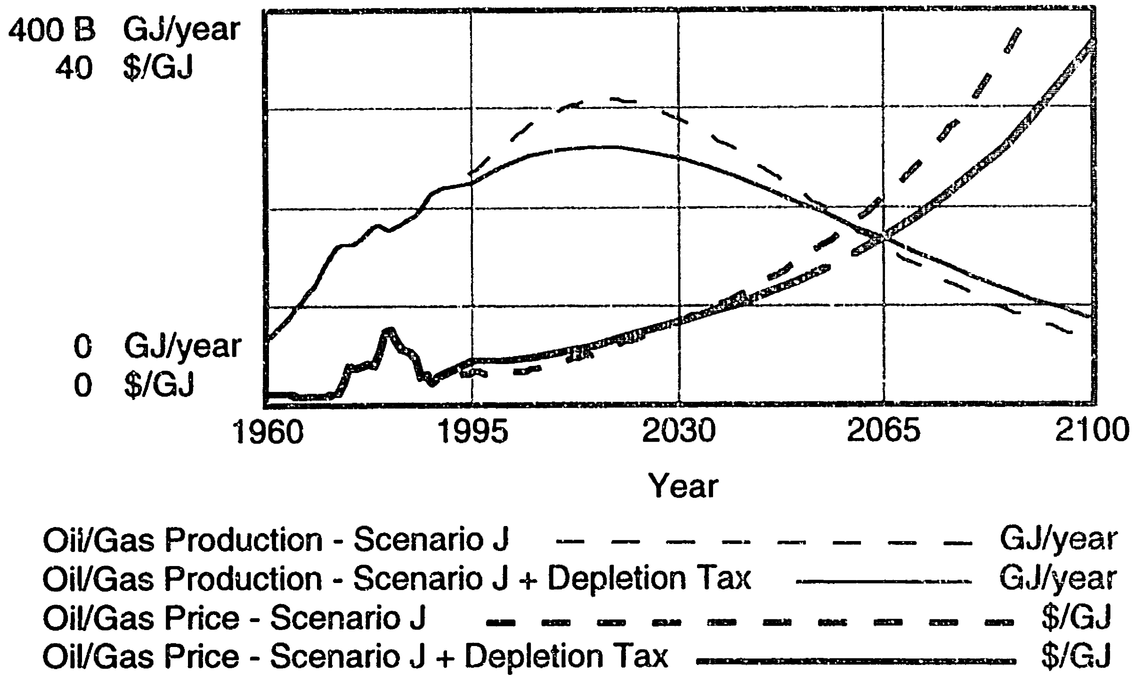
The transition from oil and gas to other fuels is difficult for several reasons. First, the increase in oil and gas prices with cumulative production is super-exponential, because the effect of depletion on extraction costs has a vertical asymptote at the ultimate recoverable resource limit (as in most depletion models). This means that any linear or exponential extrapolation strategy will underforecast future energy prices. In the model, this effect is slightly augmented by the fact that energy pricing does not include extrapolative anticipation of future costs.

At the same time, because of the assumption of perfect mixing of capital from all vintages, the requirements for a given fuel embodied in the capital stock decay only exponentially, even if the intensity of use of that fuel in new capital is zero. A nonzero embodied energy requirements for an energy source implies a lower limit to the input of that fuel in production, since the short-run elasticity of substitution among fuels is low (<<1).

Together, these effects lead to subobtimal capacity utilization in the goods producing sector when oil and gas are depleted, 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. See page 111 for details of the tax implementation.

Figure 100: Impact of Depletion Tax



The imposition of a depletion tax increases the price of oil and gas from 1995 to about 2030, but after that time, the price of oil and gas is actually lower, because depletion is delayed, reducing extraction costs.

The depletion tax initially increases oil and gas prices by a modest amount—it adds a 56% premium above extraction costs. This causes the peak in oil and gas production to occur slightly earlier and at a lower rate. After about 2030, oil and gas prices after tax remain lower than without the tax, as the rising costs from depletion have been postponed. As a consequence, production remains at higher rates. The impact of the depletion tax on total carbon emissions is small, as oil and gas production rates change modestly and coal production adjusts to compensate (Figure 100).

Table 29: Effect of Depletion Tax on Oil/Gas Prices

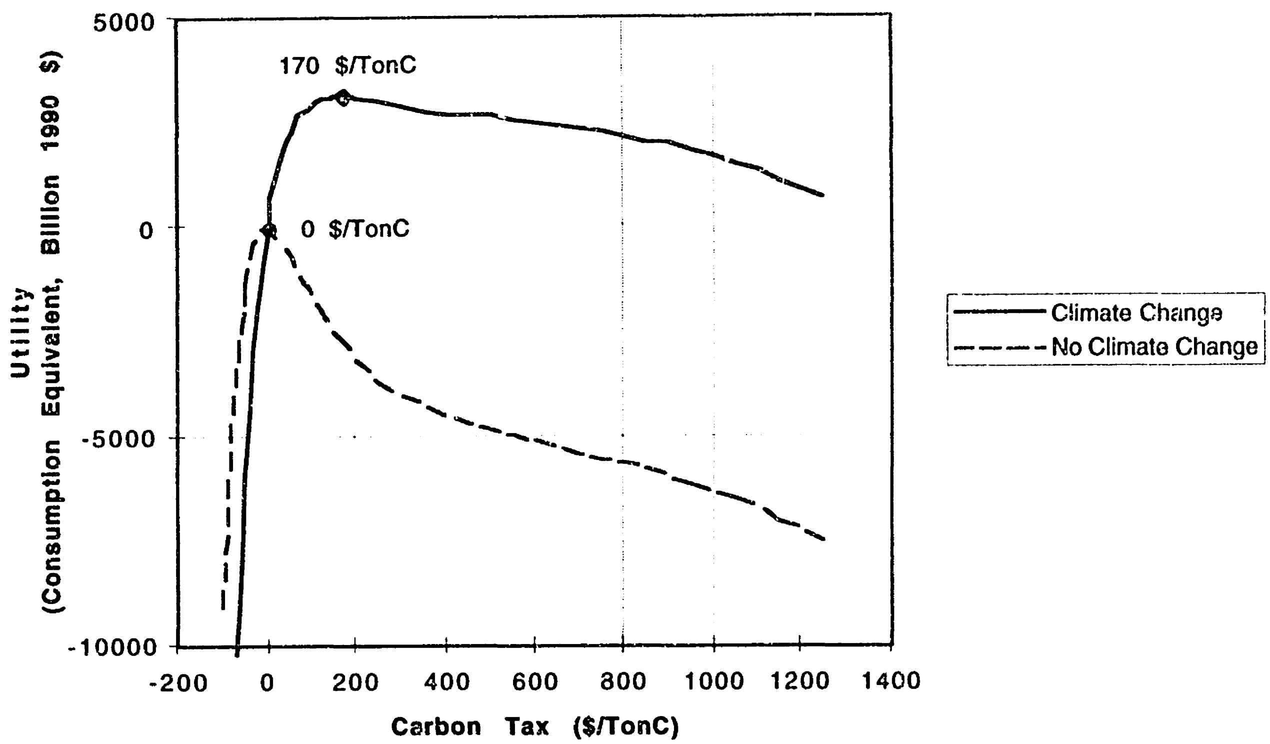
	Price ($/GJ)	
	2000	2050
No Depletion Tax		
Producer Price	3.35	14.52
Depletion Tax	0.00	0.00
Total Price	3.35	14.52
With Depletion Tax		
Producer Price	3.02	6.55
Depletion Tax	1.70	6.05
Total Price	4.72	12.60

In the year 2000, the depletion tax comprises about one-third of the total price of oil and gas. The price charged by oil and gas producers is actually reduced by about 10% below the base case (no tax), as the depletion tax leads to lower capacity utilization in the short run. By 2050, the depletion tax is half the total price, but the total price is actually lower than in the base case. No carbon tax is in effect.

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 101). 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 101 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 101: Welfare Implications of a Constant Tax, with Depletion Tax



Compare with Figure 99. 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.

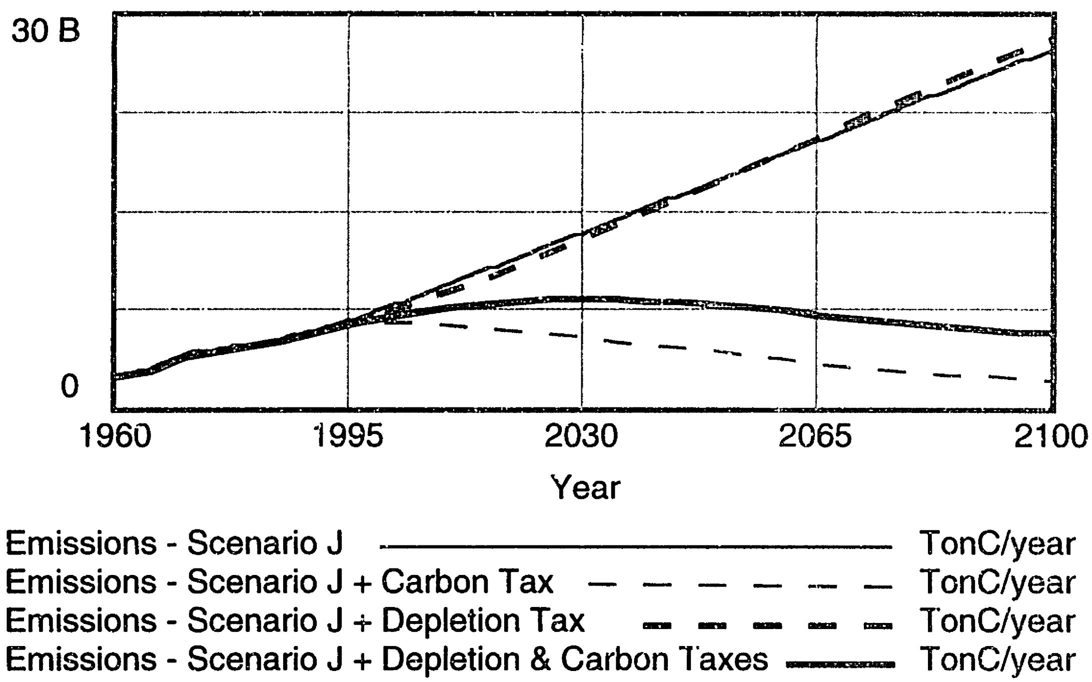
Table 30: Effect of Optimal Carbon Tax, with and without Depletion Tax

	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.

The depletion tax has an ambiguous effect on emissions (see Figure 102). 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.

Figure 102: Effect of Carbon and Depletion Taxes on Emissions



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

Externalities and Non-optimizing Behavior

> *"A majority of the available studies start from an optimized baseline projection; they then compute the shift induced by a taxation policy, and consequently cannot but conclude that there will be net macroeconomic costs."*
>
> *(Hourcade and Chapuis 1994)*

Undervalued depletion is not the only potential cause of suboptimal fossil fuel utilization. Negative social externalities to fossil fuel use may also create opportunities for costless abatement (England 1994). These include the cost of acid rain and other pollutants as well as the cost of maintaining political stability in oil-producing regions. Hohmeyer (1990) identifies externalities of -.0284 to -.0769 DM/kWh for fossil fuel electricity generation in Germany, and +.051 to +.168 DM/kWh for solar and photovoltaic electricity. Hall (1990) identifies zero external costs for conservation, wind, and solar energy, and significant external costs of coal, gas, oil, and nuclear energy. Distortionary subsidies on fossil fuel use, particularly in the developing world, may create additional potential for zero or negative-cost emissions reductions (Burniaux, Martin et al. 1992).

In addition, there is a major debate over the availability of negative cost emissions reductions from corrections to failures in energy markets or consumer behavior. The discussion has organized itself around a family of related puzzles. Analyses of consumer purchases of energy-using appliances reveal high discount rates—as much as 800% in one case (Gately 1979; Hausman 1979). A high discount rate indicates that the stream of energy costs generated by a device receives less weight in the purchase decision than its up-front capital cost, and thus that the device is more energy-intensive than it otherwise would be. Similarly, detailed studies of technological options for energy conservation suggest that there are many profitable energy-conserving opportunities that go unexploited (Lovins 1977; Lovins and Lovins 1991). This manifests itself in the gap between the assumptions of top-down macroeconomic models and bottom-up engineering models (Wilson and Swisher 1993).

There are many alternate explanations for high consumer discount rates and inertia in energy markets. Imperfections in capital markets may make high discount rates realistic for some consumers (Stern 1986; Ruderman, Levine et al. 1987; Sutherland 1991; Koomey and Sanstad 1994). Hidden costs of adoption, like installation or maintenance requirements, or qualitative differences in the energy services provided by products may offset apparent technical opportunities for energy savings (Joskow 1991; Huntington 1994; Jaffe and Stavins 1994; Jaffe and Stavins 1994; Lutzenhiser 1994; Nichols 1994). Heterogeneity of users or circumstances may similarly cause real savings to fall short of technical potential (Hausman 1979; Hassett and Metcalf 1993; Howarth and Anderson 1993; Jaffe and Stavins 1994; Jaffe and Stavins 1994; Koomey and Sanstad 1994).

Similarly, real costs of acquiring information reduce the potential for a free lunch (Gates 1983; Stern 1986; Sutherland 1991; Jaffe and Stavins 1994; Koomey and Sanstad 1994; Sanstad and Howarth 1994). Principal/agent problems may not be solved by information alone, as there are costs involved in reaching or enforcing agreements (Sanstad and Howarth 1994), particularly for marginally involved third parties like lenders (Lutzenhiser 1994).

Finally, the irreversible nature of many energy efficiency investments suggests that there may be an option value to delaying the implementation of conservation measures (Hassett and Metcalf 1993; Huntington 1994; Jaffe and Stavins 1994; Metcalf 1994; Nichols 1994). Producers as well as consumers may delay action to reduce risk, augmenting the delays inherent in product restocking and manufacturing ramp-up

(Ruderman, Levine et al. 1987). However, risk alone is insufficient to explain high discount rates on energy costs, both for the technical reason that households are well diversified against energy price fluctuations (Sutherland 1991; Metcalf 1994) and the more practical reason that few decision makers have the skills or time to make decisions on the basis of CAPM models.

While the above costs are real, proponents of intervention to realize low-cost abatement opportunities note a variety of market and behavioral failures that create opportunities for costless abatement. Consumers are often poorly informed about energy prices (Sanstad and Howarth 1994), utility rate structures (Friedman and Hausker 1988; Kempton and Layne 1994), and the energy requirements or operating costs of energy consuming devices (Howarth and Anderson 1993; Nichols 1994). It is often difficult for consumers to become well informed, due to the high cost (in time and effort) of discerning the performance of devices in the face of limited experience (Metcalf 1994), poor feedback, and confounding factors (Stern 1986; Friedman and Hausker 1988; Kempton and Layne 1994).

Information is often asymmetric, as it is easier for producers than for consumers to evaluate .product performance (Sanstad and Howarth 1994). At the same time, it may be hard for producers to convey the benefits of efficiency credibly (Jaffe and Stavins 1994). This contributes to a variety of commonly-cited principal/agent problems, as between a landlord and tenant or a home buyer and builder (Gates 1983; Stern 1986; Ruderman, Levine et al. 1987; DeCanio 1993; Howarth and Anderson 1993; Jaffe and Stavins 1994; Jaffe and Stavins 1994; Lutzenhiser 1994; Nichols 1994; Sanstad and Howarth 1994), which may lead to excessive energy use.

Energy performance information has public good attributes. It is often generated through collective experience (Jaffe and Stavins 1994), and may be much cheaper to collect centrally. This suggests that there may be substantial benefits to low-cost policies that improve the dissemination of energy-related information. The credibility of information sources is critical, particularly in the resolution of asymmetries or principal/agent problems (Gates 1983; Stern 1986). This suggests a role for government or neutral third parties. On the other hand, information measures like appliance labeling do not appear to have much effect, so provision of information alone may not be sufficient (Stern 1986; Ruderman, Levine et al. 1987).

Even properly informed consumers may have difficulty making decisions. There is a great deal of evidence for bounded rationality and cognitive failures in energy-related decision making. Rather than optimizing—which may be costly in terms of effort (Sanstad and Howarth 1994)—consumers may pursue simpler satisficing or procedurally rational strategies (Stern 1986; Friedman and Hausker 1988; Lutzenhiser 1994). This may cause significant inertia in decision making, with symptoms like asymmetric responses to losses and gains (Stern 1986) or endowment and separation effects (Huntington 1994).

Inertia in energy decision making may be reinforced by established social norms or institutional structures (Stern 1986; Lutzenhiser 1994). Markets may exhibit inertia as well. Producers may be complacent until their dominance is threatened (Ruderman, Levine et al. 1987; Lutzenhiser 1994). Changing energy prices may lead to appropriate changes in energy consuming products, but also to anti-competitive behavior by existing inefficient producers (Lutzenhiser 1994).

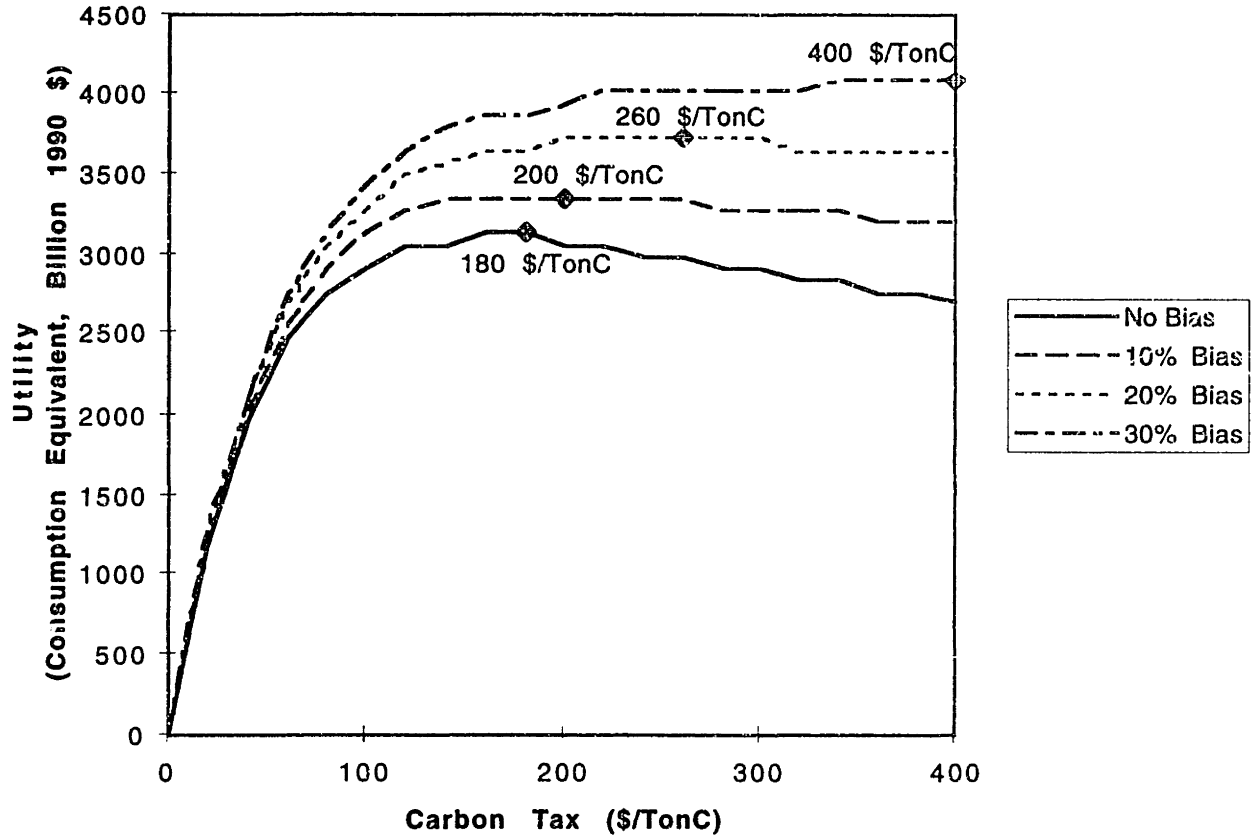
In addition, consumers make outright mistakes. Various authors note errors in forecasting (Sutherland 1991), in the attribution of changes in energy bills to particular causes (Kempton and Layne 1994), misperceptions of the physics of energy systems (Lutzenhiser 1994), overestimation of energy use by salient devices (Stern 1986; Kempton and Layne 1994), and the use of nominal (instead of real) prices in the face of inflation and rising energy costs (Stern 1986).

Errors may plague other aspects of decision making, not just energy use (Huntington 1994). They create opportunities for negative cost emissions only if they create a bias toward excessive energy consumption, rather than near-optimal behavior or a bias toward overinvestment in energy conservation (Sutherland 1991; Metcalf 1994). However, improvements in energy information processing may be amenable to the same types of low-cost interventions as improvements in information dissemination.

It is extremely unlikely that all of the above externalities, market barriers, market failures, and behavioral limitations sum to zero. It is much more credible to assume that, while real costs account for some of the top-down/bottom-up gap, there is some potential for costless energy savings. While most of the issues above are below the level of aggregation of the model, it is worthwhile to investigate the policy implications of costless or negative-cost emissions reductions.

This can be implemented in the model by adjusting the energy price perception bias parameter. Figure 103 illustrates the effects of varying this bias term. Opportunities for costless energy efficiency improvements in the range of 10 to 30 percent are commonly cited (Lovins and Lovins 1991; National Academy of Sciences 1991; Wilson and Swisher 1993). If these opportunities are attributed entirely to externalities, distortionary taxes, and misperceptions, they are consistent with a bias in energy price perception of 13 to 40 percent, given the long-run substitution elasticity (.75) between capital and energy in the model.

Figure 103: Effect of Bias in Energy Price Perception



See notes for Figure 99. Taxes are evaluated at intervals of 20 $/TonC; markers indicate the optimal tax levels. The stair-steps evident in the curves are due to roundoff error. 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 biases in energy price perception, but not depletion.

As the bias in energy price perception increases, the optimal carbon tax increases. A positive bias implies that consumers discount energy costs excessively when making purchase decisions, and thus overuse energy. A carbon tax raises the price of fossil fuels, so that the discounted cost perceived by consumers is closer to the true cost of energy. As in the case of depletion, a carbon tax is a poorly designed instrument for eliminating externalities and biases in energy pricing, for two reasons. First, the impact of the tax is not distributed in the same way as the externalities, subsidies, or biases in price perception.

Second, in the model, all consumers exhibit a uniform bias in energy price perception, and thus all benefit equally from an offsetting tax. In reality, some consumers probably take full account of energy costs when making decisions, while others err significantly. A tax-based policy needlessly punishes those who are already making efficient energy choices. However, even those consumers making effective decisions are not properly valuing energy if prices are distorted by subsidies or externalities.

It may be more effective to correct for biases in energy decision making through non-tax policies and to correct for externalities directly, reserving a carbon tax specifically for the purpose of suppressing carbon emissions. Still, if climate change is a concern, the pain of a carbon tax can be mitigated by the benefits of improved resource allocation. The substantial impact of biases on the optimal tax level suggests that further investigation, at a lower level of aggregation, is worthwhile.

Lock-in

Arguments for intervention to offset externalities and correct market or behavioral failures are essentially static. There are more interesting dynamic issues that affect the cost of abatement. 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:

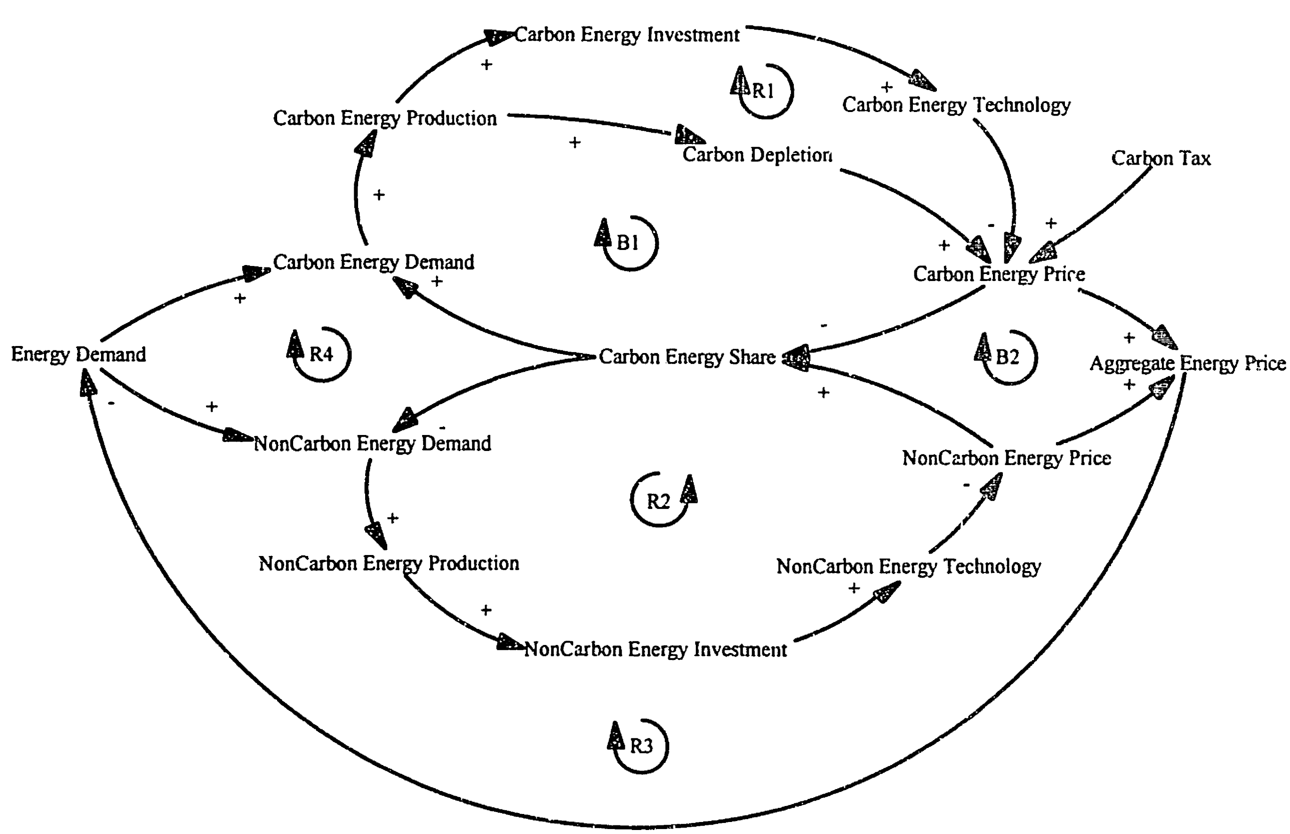
> *"Finally, exogenizing technology in energy models implies that when the learning process is finished and the system has turned into a mature technology, it can be employed without previous investment in the learning process." (Messner 1996)*

In intertemporal optimization models, the differences between exogenous and endogenous technological change are not so important, as the economy is assumed to always discover the globally optimal technology trajectory.

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 selected, 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 104: Reinforcing Loops Introduced by Learning Curve



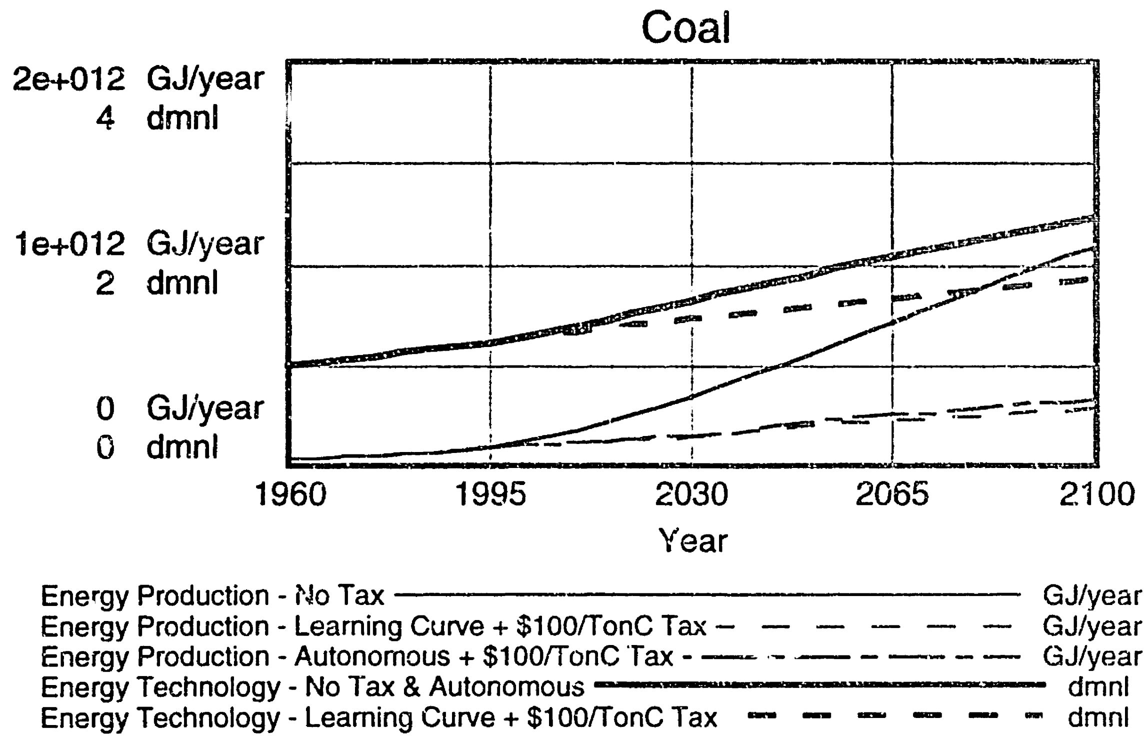
The key loops added to the model are R1 and R2, which represent the learning curve effect. Associated with these are R3 and R4, which represent increasing energy demand with falling prices, but these loops are dominated by the impact of efficiency technology. Loops B1 and B2 represent the effects of 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.

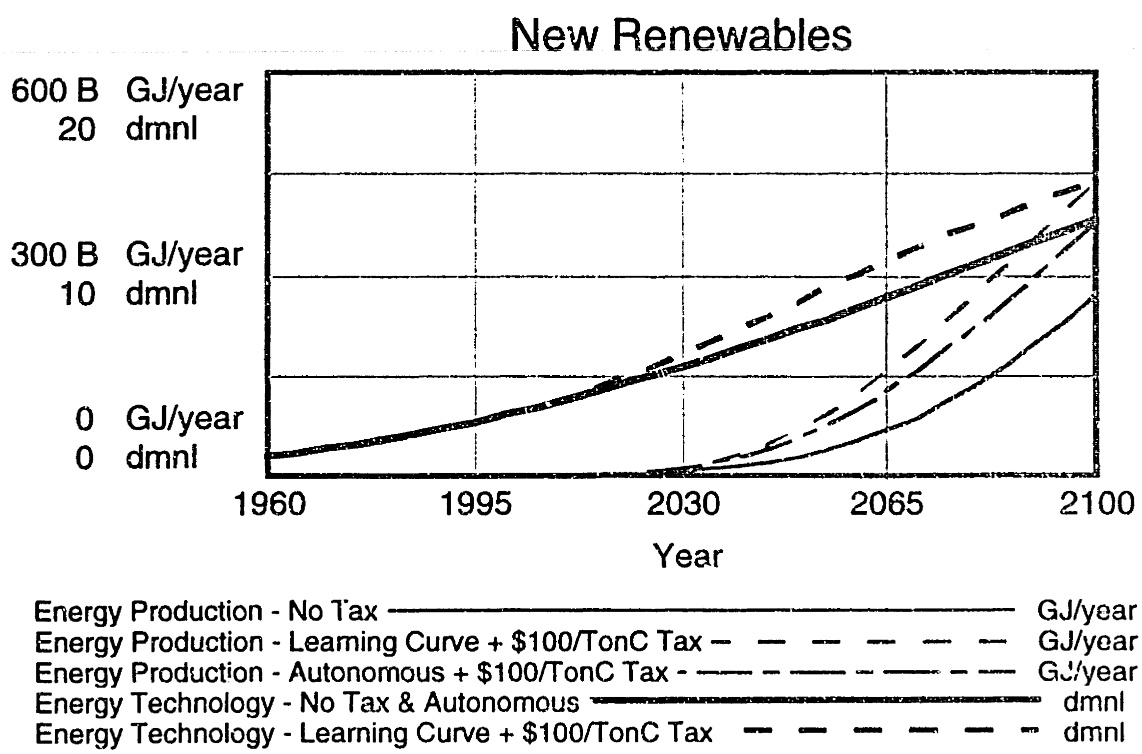
Learning is one of several mechanisms that make the energy system path dependent. Path dependence means that the attractiveness of various energy technologies depends on their prior history of use, rather than on exogenous technological change. Path dependence allows dominant technologies to become "locked in", as initial differences between competing technologies are amplified by self-reinforcing processes (Arthur 1989). 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 104 are effectively switched off and replaced by the exogenous technology forecast. The omission of these feedback loops has serious implications for model behavior.

Figure 105 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.

Figure 105: Energy Technology—Learning Curve vs. Autonomous





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 31: 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

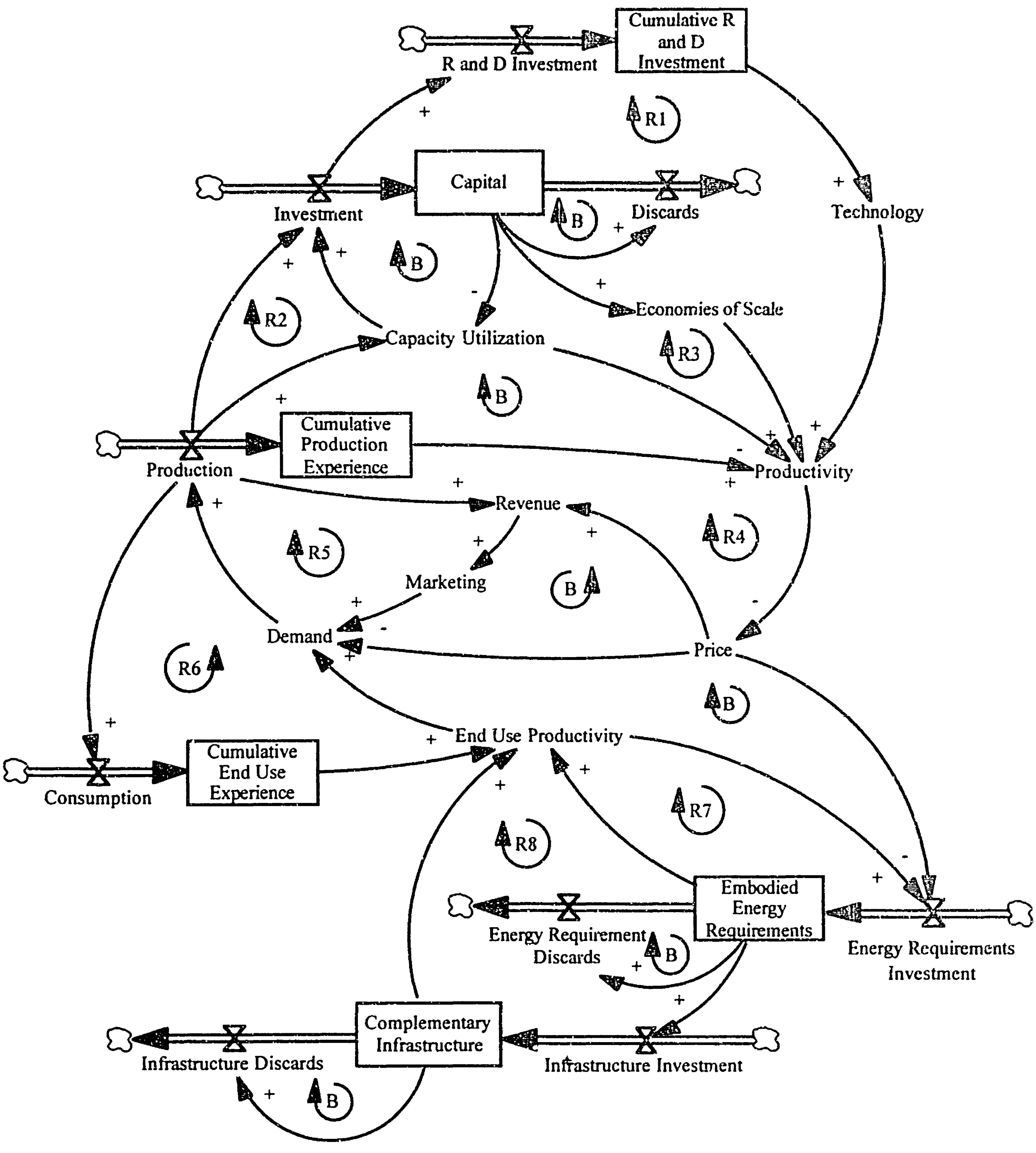
Optimal taxes listed are constant (see notes to Figure 99). The depletion tax from the previous section is applied prior to the carbon tax, so the taxes here reflect the effects of climate change and technology specification, and not depletion.

The differences in Figure 105 and Table 31 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 106 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).

Figure 106: 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.

The strength of many of the reinforcing loops in Figure 106 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.

Adjustment Constraints

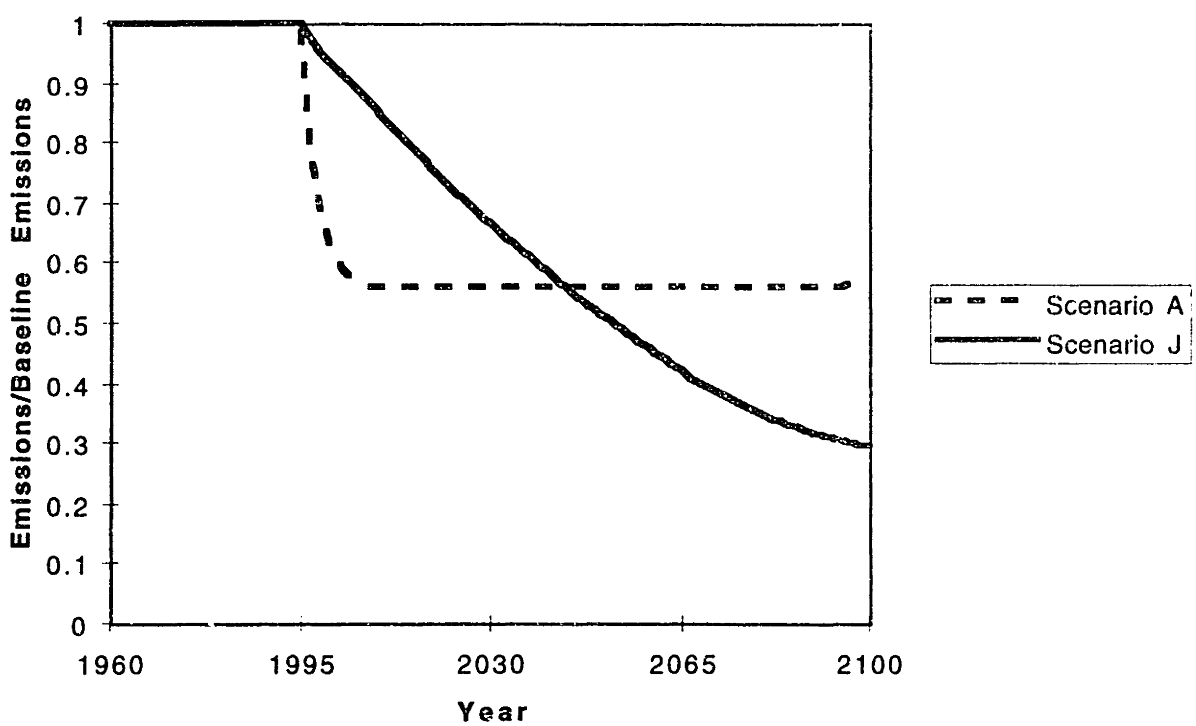
Another major dynamic issue is the cost of adjusting to changing climate policies. In DICE and most other simple models, the cost of reducing emissions is based on the absolute level of emissions reductions, rather than on the rate of change of emissions reductions (for an exception, see Grubb, Chapuis et al. 1995). This means that rapid changes in carbon intensity may be achieved at the same cost as gradual changes. Even in models which employ a putty-clay production structure, the situation is similar if intertemporal optimization is assumed:

> *"Delaying action by 10 years in intertemporal energy economy models does not mean business as usual continued for 10 years. Non-myopic models will anticipate the imposition of a carbon constraint in the future and start adding new technologies that are necessary for an optimal preparation for the carbon constraint to be imposed." (Toth 1995)*

In reality, a number of long delays impose important constraints on the energy-economy system. Energy requirements embodied in the capital stock can be adjusted only as the stock turns over. While the average capital lifetime in the model is relatively short, 15 years, a substantial portion of energy demand is determined by capital stocks with much longer lifetimes, like the building stock, transportation infrastructure, and the land use patterns that influence them. Capital stocks in energy production and conversion, like electric power plants, have long lifetimes. Technology development and institutional change also involve long delays. In the shorter term, changes in energy patterns require time for the mobility of labor, acquisition of financing, and perception of changing prices and consumption patterns. Tax and other policies are subject to delay from the time required to develop and implement agreements.

With the exception of labor mobility and long-lived infrastructure effects, these delays are captured by the model. This means that the time constant for full realization of the impact of a carbon tax is as much as 60 years—which is still short compared to the time scale of changes in settlement patterns or the relative positions of nations in the world economy. Figure 107 contrasts this delayed impact with the impact of a tax in Scenario A, in which most of the adjustment constraints have been removed.

Figure 107: Time Required for Tax Impacts



Emissions fall in response to a 100 $/TonC carbon tax implemented in 1995. When the model is parameterized to behave similarly to the DICE model (Scenario A), the response to a carbon tax is rapid, reaching equilibrium within a decade. In the standard run of the model, structural and behavioral factors slow the response, but the eventual change in emissions is greater.

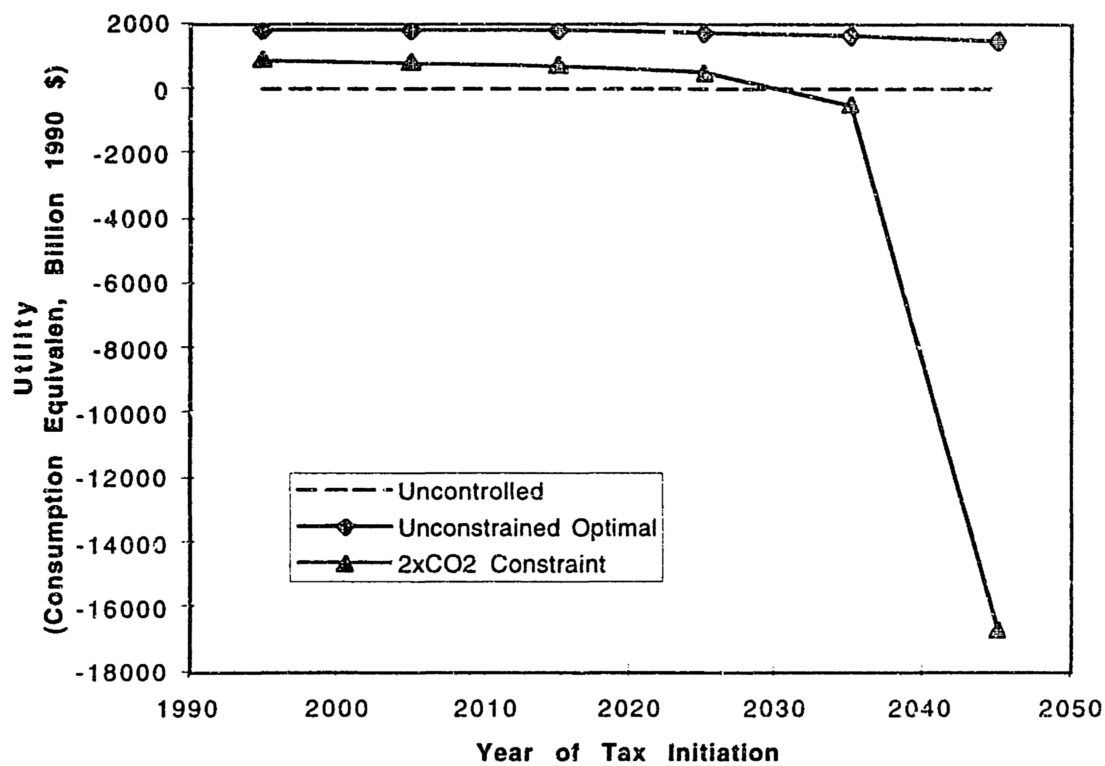
Adjustment constraints create irreversible effects of policies that must be balanced against the irreversible effects of emissions on the climate. On one hand, costly adaptation motivates one to wait until better information about climate change is available, in order to avoid regretting the implementation of unnecessary policies that are costly to undo later. On the other hand, if climate change turns out to be a serious problem, the sooner one takes action, the better.

Yohe investigates the near-term action required to anticipate the future imposition of constraints on atmospheric CO_2 (Yohe and Wallace 1996). He concludes that the best short term policy is to anticipate a high constraint—that is, to take little action at present. There are several reasons for this conclusion. A trend-following error in Yohe's energy allocation decision creates a bias towards low (or negative) taxes (see Discrete Time Models, page 22). No scenario examined by Yohe implies an optimal solution meeting a carbon constraint of less than 700 ppm CO2—two and a half times preindustrial levels.

As in the DICE model, the Connecticut/YOHE production structure is extremely flexible, so that emissions may be greatly reduced in a short time with no adjustment costs. Because a constrained optimal solution is always less attractive than its unconstrained counterpart (compare the two trajectories in Figure 108 for an example of this), with discounting and uncertainty, it is therefore attractive to delay the costs of meeting the constraint as long as possible.

While a full replication of Yohe's analysis will be left for future work, preliminary exploration suggests at least one way in which the conclusions would be different with the FREE model. It is difficult to rapidly reduce emissions in the FREE model, due to adjustment constraints from embodied energy requirements, capacitation of the energy system, and delays in perception and action. If action is delayed until the constraint approaches, there is a large loss of welfare—as much as 17 trillion dollars in present value terms (roughly a year of world consumption; see Figure 108). Losses become pronounced at least 15 to 25 years before the constraint is actually violated.

Figure 108: Meeting a $2xCO_2$ Constraint



Utility scale shows the change in welfare over the uncontrolled (no tax) case for an optimal carbon tax policy initiated in the indicated year. The unconstrained optimal tax maximizes social welfare (cumulative discounted utility), while the constrained tax maximizes welfare, subject to the limitation that the atmospheric CO2 concentration not exceed twice the preindustrial level. With no tax, the 2xCO2 constraint is exceeded in 2050. The time horizon for these simulations is 1960-2200.

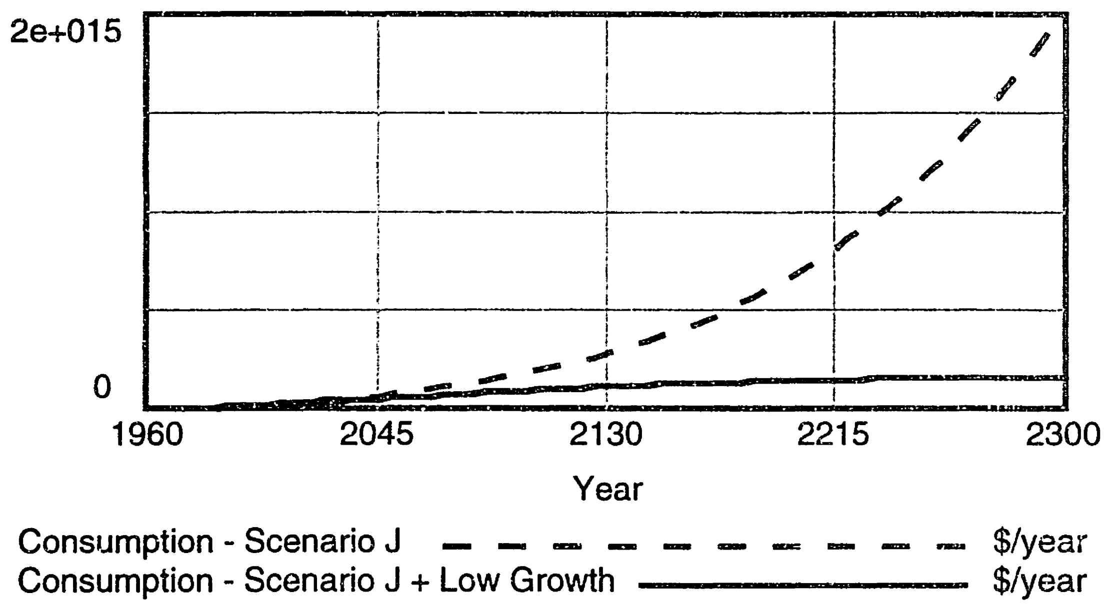
Discounting and Welfare

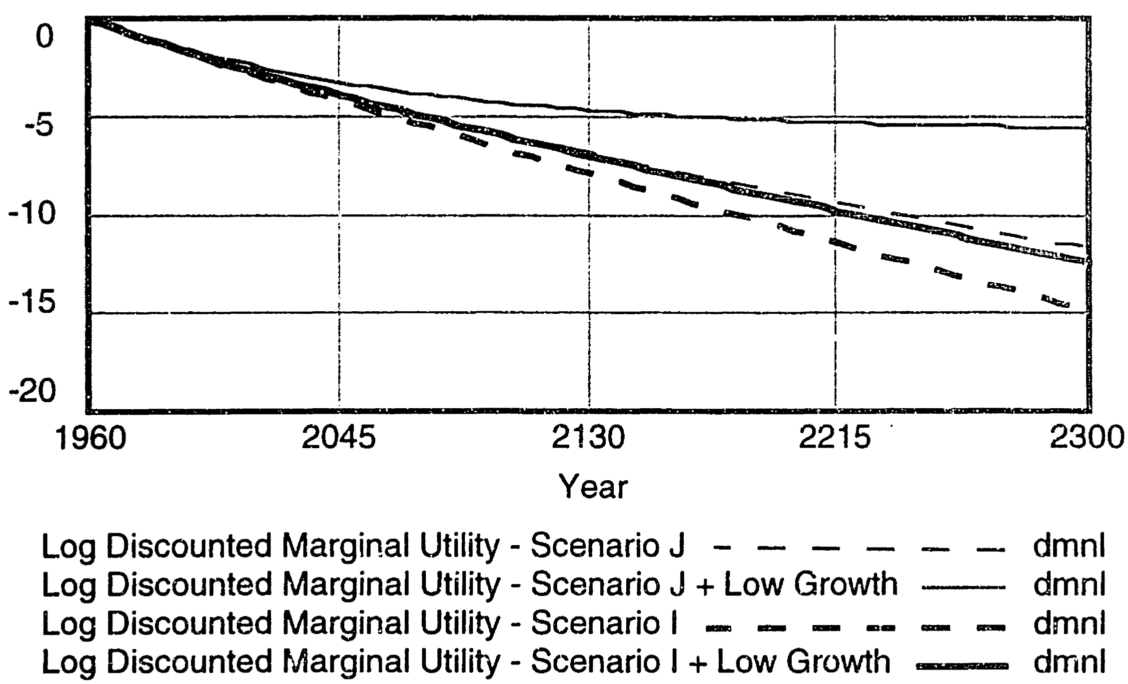
A final concern in the evaluation of climate policies is the criteria used for evaluation. There are really two issues here—the extent to which tangible (consumption of goods) vs. intangible (environmental services or health) factors contribute to welfare, and the relative weight assigned to the welfare of generations distant from one another in time.

The FREE model deviates from standard practice in that no discount is applied to welfare for pure time preference. In other words, all generations are treated equally. This has a potentially large impact on policy. However, it turns out in practice that the impact is not so important, due to the offsetting assumptions of high inequality aversion and continuing economic growth. Because future generations become much richer than current generations, the impact of climate change on their welfare is relatively unimportant, even though no discount for time preference is applied.

Though the two discounting methods yield relatively similar results in the standard run of the model (see Table 32), it is worth considering when they might differ. The major difference arises when the wealth of future generations changes, perhaps due to technological progress that is greater or less than anticipated. If income rises, it is probably reasonable to be less concerned about climate impacts, all other things being equal. Both discounting approaches work similarly under these conditions.

Figure 109: Impact of Utility and Growth Assumptions





The key difference arises if income growth is low or, worse, negative. Then a positive discount rate for pure time preference leads to an extremely low weight to the welfare of future generations, exactly when they would be most sensitive to climate impacts. By contrast, the approach to discounting in the FREE model weights welfare more heavily as income falls. This is demonstrated in Table 32. With discounting for time preference, a low growth scenario results in reduced abatement efforts. Low growth in the FREE model instead results in very high abatement efforts, because climate impacts on future generations, who are not much wealthier than ourselves, are given greater weight.

Table 32: Impact of Discounting and Growth Assumptions on Optimal Carbon Tax

	Standard Run Rate of Time Preference = 0%/year Rate of Inequality Aversion = 2.5	Discounting for Time Preference Rate of Time Preference = 3%/year Rate of Inequality Aversion = 1
Standard Run Asymptotic Rate of Growth of Factor Productivity = 0.75%/year	\$170/TonC	\$38/TonC
Low Growth Asymptotic Rate of Growth of Factor Productivity = 0%/year	\$888/TonC	\$28/TonC

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 discounting alone.

One feature common to both approaches is the diminishing marginal utility of a unit of consumption as wealth increases. In reality, diminishing returns arise at least in part because welfare does not consist entirely of consumption. Other factors available in limited quantities, like environmental amenities, also play a role. If this is the case, then the importance of these other, intangible factors will rise as wealth rises. One reflection of this is the apparent increase in willingness to pay for a variety of environmental and health services in the developed countries (Fankhauser 1995). If environmental services or intrinsic valuation of the environment are a significant component of welfare, and are impaired by climate change, then rising income will increase the incentive for abatement (Tol 1994).

Table 33 summarizes the outcome when consumption and environmental services (in fixed supply per capita) each contribute half of total welfare, and climate damages affect both tangible and intangible factors. This is an optimistic assumption, as the supply of environmental services per capita is in reality likely to fall as population increases. In addition, when there is no carbon tax, the total tangible and intangible damages in 2100, 1.93% of output, are actually less than in the standard scenario, where tangible damages cause a 2.20% loss of output in 2100.

In spite of the optimistic assumptions about the supply of intangibles and the reduced total damages in the no-tax case, the optimal carbon tax is dramatically higher—877 $/TonC. This is because future citizens value the environment more, since it is in more restricted supply than consumption, and because, at the margin, environmental damages have a much greater impact on utility than lost consumption.

Table 33: Impact of Welfare Criteria

		Tangible Climate Damages in 2100	Intangible Climate Damages in 2100	Optimal Carbon Tax	Emissions in 2100
		% of output	% of output	$/TonC	TonC/year
Standard Run	No Tax	2.20	0.00	-	28.4
	Optimal Tax	1.16	0.00	170	5.8
Intangibles	No Tax	0.93	1.00	-	28.7
	Optimal Tax	0.34	0.37	877	2.2

Intangible damages are converted to equivalent output according to the increase in consumption that would be required to offset their effect on welfare. The depletion tax from the previous sections is applied prior to the carbon tax, so the taxes here reflect the effects of climate change and damage specification alone.

Sensitivity Analysis

Parametric Sensitivity

The FREE model includes 213 parameters of functional forms and initial conditions of state variables. Almost half of these are redundant coefficients (used to normalize production function inputs, for example), trivial switches for test inputs, or definitional. The remaining parameters, though, are subject to significant uncertainty, so it is important to assess their impact. Ideally, one would identify the parameters which contribute most to variation in the optimal climate policy over the full parameter space of the model. However, this is computationally infeasible.

Another approach is to evaluate the relative sensitivity of key model variables to variation in individual parameters. If the model output is linear in all of the parameters, this approach would provide full understanding, but this is extremely unlikely. The best that this method can provide is a sense of the local gradient of the model's response to each parameter.

For this analysis, each parameter was varied ±10%. A few parameters with initial values of zero were varied by an absolute value of ±0.1. The results were then ranked according to the variation induced in four target variables: the energy CO_2 emissions rate, the temperature of the atmosphere and upper ocean, gross output, and discounted utility. The measure of variance was the sum of squares difference between the perturbed and baseline trajectories, $\Sigma\ [X_p(t) - X_b(t)]^2$.

For each target variable, the results were then ranked in descending order. Since each variable's gradient was tested in two directions, the direction with the greater absolute value was used for the ranking. Trivial or redundant parameters were omitted from the rankings. This univariate sensitivity test was performed at two points in the parameter space, corresponding to the initializations for scenario A (similar to the DICE model) and scenario J (the standard run of the FREE model).

Table 34 shows the 25 parameters with the steepest gradients around the initial conditions for scenario A. As in the DICE model, the parameters governing the exogenous population and factor productivity trajectories are among the most sensitive (Nordhaus 1994). This suggests that making these variables endogenous could have particularly significant impacts on model behavior. Also of considerable importance in the ranking are the time preference and inequality aversion parameters describing investment behavior and the prices and value shares of energy sources in production.

While the rate of autonomous energy efficiency improvement and the capital-energy and interfuel elasticities of substitution make the top 25, they are by no means dominant in the rankings. None of the behavioral parameters describing equilibration processes in the economy make the list. This is reassuring, since the scenario was deliberately constructed to exhibit rapid, flexible adjustment.

Table 34: Scenario A Parameter Sensitivity

	Rank			
	Emissions	Output	Temperature	Utility
Asymptotic Frac Factor Prod Gr Rt	1	1	1	1
Value Share Of Labor	2	2	2	2
Init Frac Factor Prod Gr Rt	3	3	4	4
Frac Factor Prod Gr Rt Decline Rt	4	4	8	7
Forecast Pop Growth Rt Decline Rt	6	5	9	8
Capital Lifetime	8	7	10	6
Frac Depletion Recovered	5	13	5	10
Fractional Adaptation Rate[Tangible]	7	6	13	13
Consumer Discount Rate	13	9	21	11
Capital Energy Subst Elast	9	16	14	18
Initial Producer Price[Oilgas]	11	25	15	15
Preindustrial CO2	24	12	6	25
Climate Sensitivity	21	10	3	36
Energy Price Discount	20	15	26	12
Initial Producer Price[HN]	18	21	25	17
Initial Producer Price[Coal]	14	26	20	22
Ref Energy Value Share[Coal]	16	22	23	23
Marginal Atmos Retention	26	14	7	42
Consumer Inequal Aversion	28	23	31	9
Frac Auton Energy Eff Improvement Rate	10	18	17	47
Low Lim Energy Tech[Oilgas]	12	32	18	31
Climate Damage Nonlinearity[Tangible]	19	8	30	38
Ref Energy Value Share[NH]	17	27	24	27
Climate Damage Scale[Tangible]	25	11	32	41
Rate Of CO2 Transfer	27	17	11	58

Variables are sorted by their mean rank. The appearance of the lower limit to oil/gas technology and the fraction of depletion rent recovered is somewhat spurious here, as the lower limits are used to switch off technology in this scenario and there is no depletion.

Many of the same parameters appear in the ranking for scenario J, the standard run of the model. Exogenous forcings from population and factor productivity again play an important role. New to the ranking are the learning curve parameters describing the strength of the endogenous energy technology feedback loops. Similarly, the depletion profile for oil and gas resources is of great importance. Capital-energy and interfuel substitution elasticities are still important, but they are joined by other parameters, like the retrofit rate, describing the gain and delay of the long-run energy intensity adjustment process.

Table 35: Scenario J Parameter Sensitivity

	Emissions	Rank Output	Temperature	Utility
Value Share Of Labor	2	1	4	4
Init Frac Factor Prod Gr Rt	5	3	9	5
Resource Elasticity[Coal]	1	9	1	23
Retrofit Rate	4	15	6	11
Energy Subst Elast	7	8	13	17
Asymptotic Frac Factor Prod Gr Rt	12	2	26	8
Capital Energy Subst Elast	6	7	12	27
Forecast Pop Growth Rt Decline Rt	14	6	34	3
Energy Learning Rate	9	24	19	10
Capital Lifetime	20	11	28	6
Energy Scale Effect	11	27	16	14
Frac Factor Prod Gr Rt Decline Rt	18	5	41	9
Preind CO2 In Mixed Layer	39	13	2	19
Fractional Adaptation Rate[Tangible]	17	4	44	12
Mixed Depth	40	14	3	22
Initial Producer Price[Coal]	10	29	15	39
Resource Elasticity[Oilgas]	13	45	31	7
Ref Energy Value Share[Coal]	8	34	11	49
Endogenous Tech Fraction	15	23	39	29
Consumer Discount Rate	27	19	48	13
Climate Sensitivity	46	12	5	44
Ref Energy Value Share[New]	19	21	40	37
Initial Resource[Coal]	3	22	10	82
Min Depletion Time	16	33	38	31
Preindustrial CO2	54	20	7	43

Variables are sorted by their mean rank.

The results for scenario A and scenario J agree to a large extent. There are, however, a few dramatic differences. Table 36 summarizes variables for which the difference in rankings between the two scenarios is greatest. Variables like energy learning rates, carbon cycle parameters, and resource endowments that affect feedback loops that are switched off in one of the two parameterizations are excluded. Most of the remaining entries appear on the list because of differences between the putty-putty and putty-clay production structures of the two models.

Parameters like the energy delivery delay and short-run energy price perception time play a more important role in Scenario A because short term substitution processes have greater scope. In Scenario J, short-term substitution plays only a limited role in the model outcome due to low short run elasticities, so these delays have little impact. Similarly, the retrofit rate is unimportant in Scenario A because there is so much short run flexibility that retrofits are unnecessary, while the putty-clay structure in Scenario J makes retrofits potentially important.

Table 36: Sensitivity Rank Differences

	Mean Rank - Scenario A	Mean Rank - Scenario J
Energy Delivery Delay	40.25	106.5
Energy Order Adj Coeff	36.75	97.75
SR Energy Price Perc Time	49	109
Capital Share[Oilgas]	42.25	89.5
Output Trend Establishment Time	35.5	80.5
Price Adjustment Time	60.5	109.25
Init Atmos Uocean Temp	59.25	108
LR Order Trend Time	64.5	110.75
LR Output Trend Time	55.75	98.75
Initial Producer Price[Oilgas]	16.5	56.75
Energy Capital Lifetime[Oilgas]	48.75	87
Output Perc Time	51.5	89.75
Capital Share[HN]	51	89.25
Return Perc Time	46.5	87.75
Energy Construction Delay[Oilgas]	59.25	101.75
Heat Trans Coeff	44.25	80.25
Labor Force Fraction	80	117.5
Retrofit Rate	45.25	9
SR Elasticity	34.75	68.5
Weight To Average Cost	53.25	87.75

Interestingly, few climate or carbon cycle parameters appear on either scenario's top 25 list. This can be attributed to both the model and the sensitivity criteria. Of the four target variables, only temperature is strongly influenced by the climate parameters. Emissions and gross output are only affected weakly by climate. While utility is significantly affected by climate damages, economic variables still dominate.

Multivariate Sensitivity

The preceding parametric sensitivity analysis is unsatisfying for two reasons. First, the model behavior is highly nonlinear, and univariate sensitivity analysis neglects potentially critical interactions among variables. Second, the analysis makes no use of subjective information about the relative uncertainty of the various parameters; it merely identifies parameters which, if they were uncertain, might have a substantial impact.

While it is beyond the scope of this work to conduct a full uncertainty analysis on the model, a preliminary exploration of the multivariate parameter sensitivity of the model is presented here. Subjective probability distributions for key parameters were assigned, based largely on the work of other modelers. These distributions were then used to identify an effective carbon tax rule and to assess its performance under uncertainty. This work should be regarded more as an exploration of the properties of the model than as a definitive statement about the policy implications of uncertainty.

Identification of the uncertain distributions was not a focus of this research. Where possible, distributions were drawn from other modeler's work. For other parameters, distributions were created around the deterministic parameter value using the range of values in relevant literature. For a few parameters which have not been addressed in other studies—such as the fraction of depletion rents recovered—distributions were chosen ad hoc. The parameter distributions are summarized in Table 37.

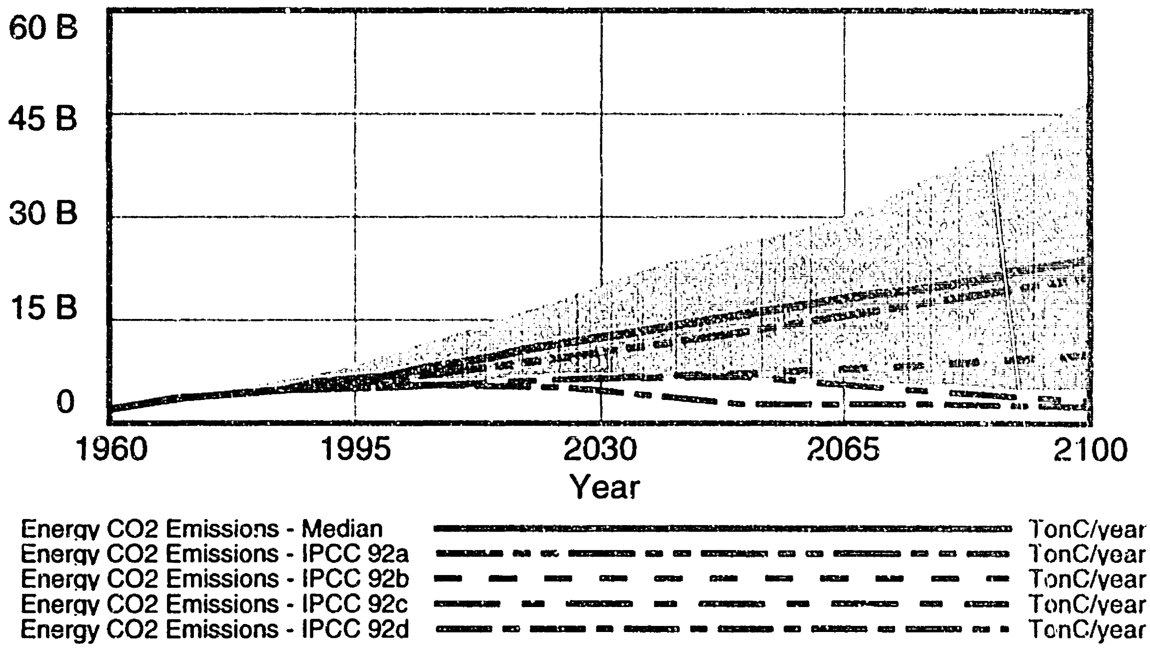
Table 37: Parameter Distributions

Parameter	Distr.	Min	Max	Mean	SD	Notes
Forecast Pop Growth Rt Decline Rt	Normal	.0027	.033	.019	.0106	Adapted from DICE (Nordhaus 1994)
Frac Tech Gr Rt Decline Rt	Normal	0.002	.024	.011	.0077	Adapted from DICE (Nordhaus 1994)
Climate Sensitivity	Normal					Adapted from DICE (Nordhaus 1994)
Biostim Coeff	Normal	0	.7	.4	.1	Range of values in literature (Goudriaan and Ketner 1984; Rotmans 1990)
Climate Damage Scale	Normal	0	.032	.013	.011	Adapted from DICE (Nordhaus 1994)
Initial Resource[OilGas]	Normal	2e13	4e13	3e13	3e12	
Eddy Diff Coeff	Normal	3300	5000	4000	300	(Oeschger, Siegenthaler et al. 1975)
Frac Auton Energy Eff Improvement Rate	Normal	.001	.023	.011	.0076	Adapted from DICE (Nordhaus 1994)
Capital Energy Subst Elast	Normal	.4	.95	.7	.1	
Energy Subst Elast	Normal	1.05	3	2	.33	
Frac Depletion Recovered	Uniform	0	1			

Normal distributions are truncated at minimum and maximum values, typically ±3 standard deviations.

Using these distributions leads to a wide range of model outcomes. Figure 110 compares the range of emissions in the model to the IPCC scenarios. The median trajectory is slightly higher than the 92a scenario, generally regarded as "business as usual." This is in accord with the interpretation of 92a as a middle-of-the-road scenario rather than an upper bound on emissions (IPCC 1994). Emissions are widely distributed above and below this path, but no trajectories encompass the IPCC low-emissions scenarios. This is sensible, as no deliberate emissions reductions are undertaken in this set of simulations.

Figure 110: Emissions Under Uncertainty



The shaded area indicates the range of outcomes in 100 simulations when no carbon tax is applied, while the solid line is the median outcome. Dashed lines indicate IPCC scenarios.

The wide range of emissions leads to substantial variance in atmospheric temperature as well (see Table 38). All simulations show significant climate change, though. Economic output varies greatly over the simulations, but this is attributable almost entirely to changes in population and technology rather than emissions and climate damages. For each variable, the median value from the Monte Carlo simulations is quite close to the value from a deterministic simulation using the median values of the uncertain inputs.

Table 38: Uncertainty of Key Variables

	Min	Max	Mean	Median	Norm. SD	Deterministic
Output in 2100 (trillion $/year)	108	762	271	239	0.427	236
Energy Carbon Emissions in 2100 (10^9 TonC/year)	4.5	46.3	23.4	22.3	0.422	24.8
Temperature in 2100 (DegreesC)	1.86	5.88	3.75	3.67	0.241	3.80

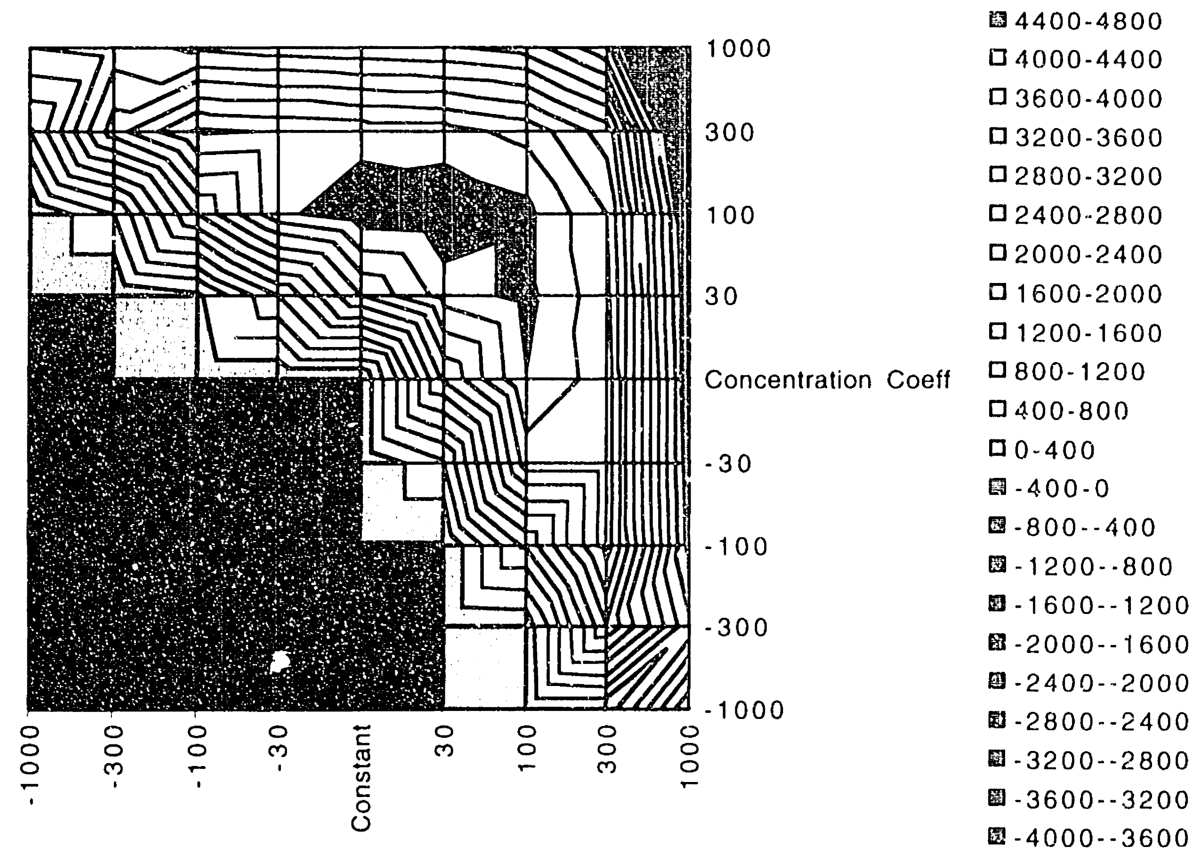
Values are reported for 100 simulations. The deterministic case uses the median value for each uncertain parameter.

Stochastic Optimization

It is natural to investigate the implications of uncertainty for the optimal carbon tax policy. In this case, to evaluate a policy, one must calculate its expected value over a wide variety of possible states of the world. The computational intensity of this process (and software limitations) make it unattractive to use the local-search hill climbing procedure that was used to discover optimal taxes in the deterministic case. Instead, a grid search strategy was employed to visualize the parameter space of an optimal carbon tax rule with two parameters (a constant term and an atmospheric concentration coefficient).

Figure 111 shows the results of this search. Each grid point describes a unique carbon tax strategy. Points in the upper right quadrant, for example, describe taxes that tend to rise over time, as the atmospheric CO_2 concentration rises, while taxes in the lower right quadrant tend to fall over time. At each point, the model was simulated 20 times, using Latin Hypercube sampling from the subjective probability distributions. While the sample of 20 simulations is small, repetition of the procedure with larger samples and different random number seeds indicates that it is sufficient to generate a reasonable sense about the payoff surface.

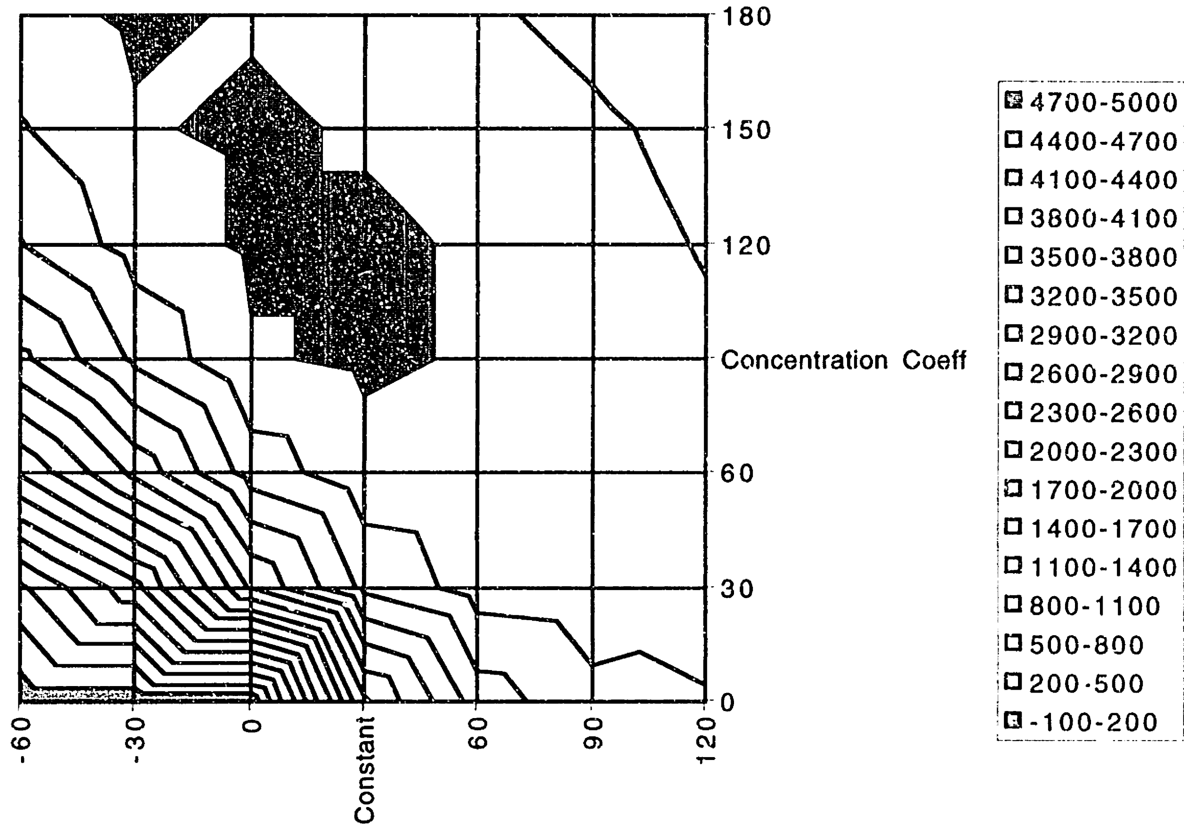
Figure 111: Expected Value of Tax Policies



The surface shows the expected value of the improvement in welfare (in billion $ consumption equivalent) of a carbon tax policy with the indicated constant and atmospheric concentration coefficients (which have units of $/TonC; see page 109). Each contour line represents a change of $200 billion. The lower left quadrant, which yields taxes that are always negative, was not explored. Note that only the grid points were evaluated; the contours are interpolated.

The outcome in Figure 111 is a flat-topped "hill" of policies that perform well, located in the upper right quadrant. In this region, carbon taxes have positive constant and atmospheric concentration coefficients, indicating that they are initiated in 1995 with a positive value and tend to rise over time. The best tax policies yield an improvement in welfare of more than $4 trillion. While most policies in the space explored perform at least marginally better than no tax, a few do not. Beyond a certain point, high taxes—particularly those with a high constant component, which implies rapid implementation of a large tax—perform poorly. The worst tax policies generate losses of nearly $4 trillion. This is probably mainly an issue of adjustment costs. Rapid implementation of a high tax creates considerable economic disruption.

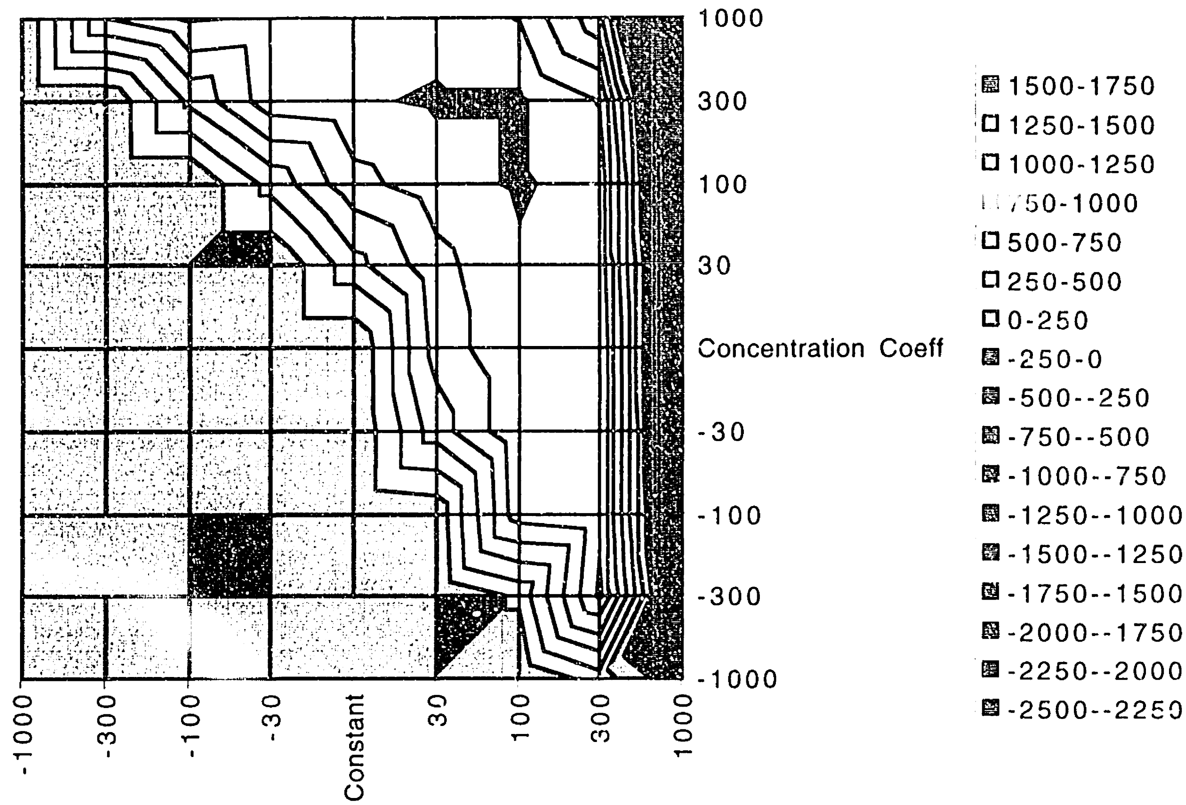
Figure 112: Expected Value of Tax Policies



This surface examines a region around the best point in Figure 111. Each contour line represents a change of $300 billion. No point performs worse than the no tax case.

Examining the top of the hill in Figure 111 at higher resolution yields Figure 112. The best tax policies are located around a point with a constant of 30 $/TonC and an atmospheric concentration coefficient of 120 $/TonC. The best tax in the deterministic case, which has a constant term of -28 $/TonC and an atmospheric concentration coefficient of 198 $/TonC, lies just outside this figure, in a region which appears likely to be near-optimal under uncertainty.

Figure 113: Worst Outcomes of Tax Policies

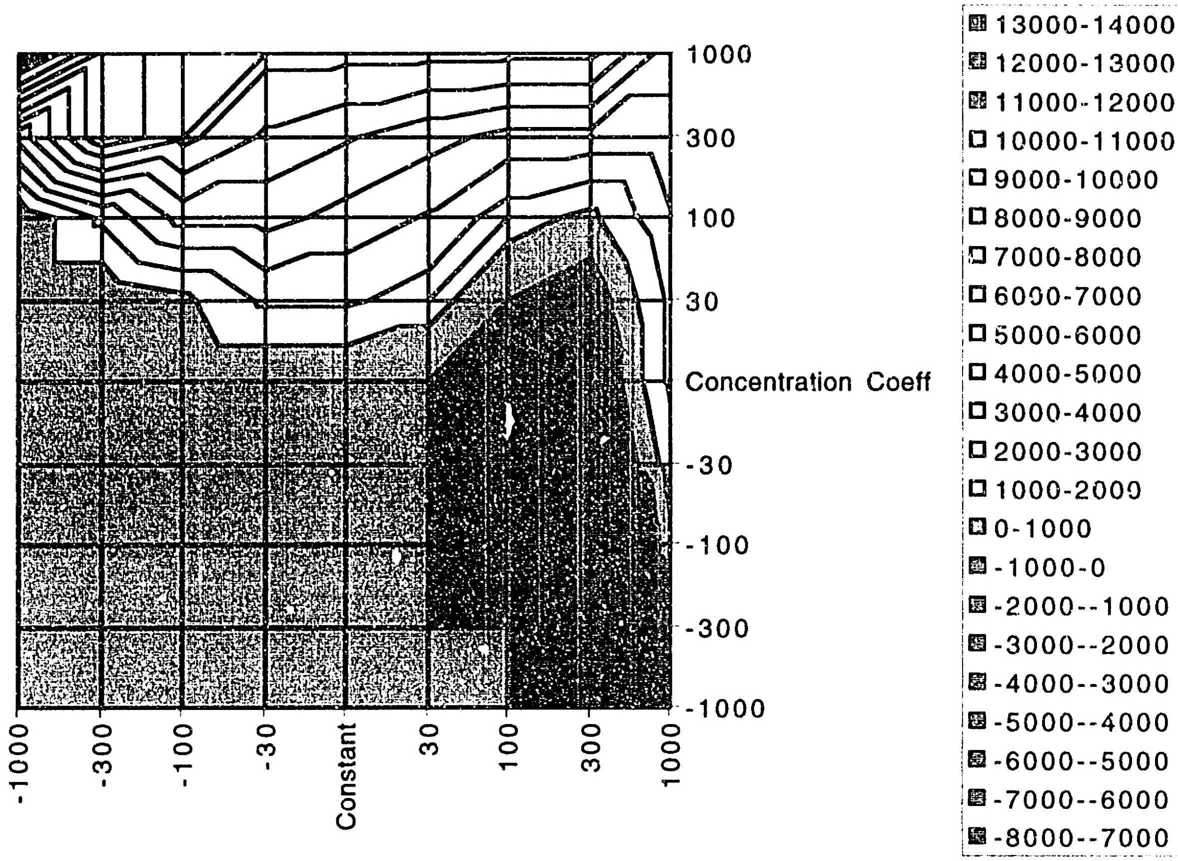


The surface shows the improvement in welfare from a carbon tax policy in the scenario with the worst outcome. Each contour line represents a change of $250 billion. The lower left quadrant, which yields taxes that are always negative, was not explored. Note that only the grid points were evaluated; the contours are interpolated.

Evaluating policies on the basis of the expected value of outcomes implies risk-neutrality. In reality, policy makers may be more interested in minimizing losses in the case of a bad outcome. Figure 113 illustrates the impact of tax policies on the worst outcome in each sample. The absolute difference between the best and worst policies is smaller than before, roughly ± $2 trillion, because the base value of cumulative discounted utility is much lower. Maximizing welfare in the worst-case scenario implies higher carbon taxes than maximizing the expected value of welfare. The best maximin policies still lie within the region of good performance in expected value terms, though.

The opposite criteria—maximizing welfare in the best case—results in a very different payoff surface (Figure 114). The best policy is now located in the extreme upper left corner of the space—a region in which taxes start near zero, but rise to high levels as the atmospheric CO_2 concentration rises. Policies in the opposite quadrant, which start high and decline, perform very poorly. The best maximin or expected value policies perform indifferently.

Figure 114: Best Outcomes of Tax Policies

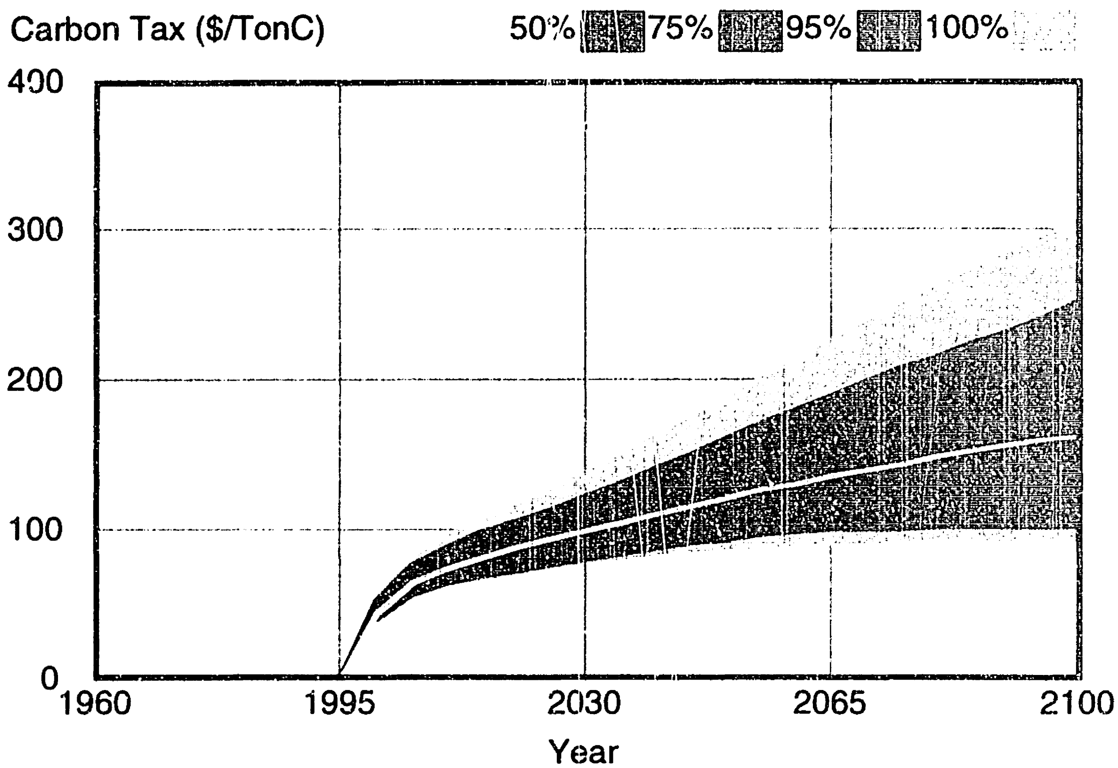


The surface shows the improvement in welfare from a carbon tax policy in the scenario with the best outcome. Each contour line represents a change of $1000 billion. The best policy is in the upper left corner of the grid. The lower left quadrant, which yields taxes that are always negative, was not explored. Note that only the grid points were evaluated; the contours are interpolated.

Impact of the Optimal Tax

Using the expected value criterion, the best tax policy under uncertainty yields carbon taxes in the range of 100-300 $/TonC (Figure 115). The actual magnitude of the tax varies adaptively in response to changing atmospheric CO_2 concentrations, so high emissions rates that are resistant to policy intervention result in progressively higher taxes.

Figure 115: Optimal Carbon Taxes



Shading indicates the distribution of tax trajectories for 100 simulations.

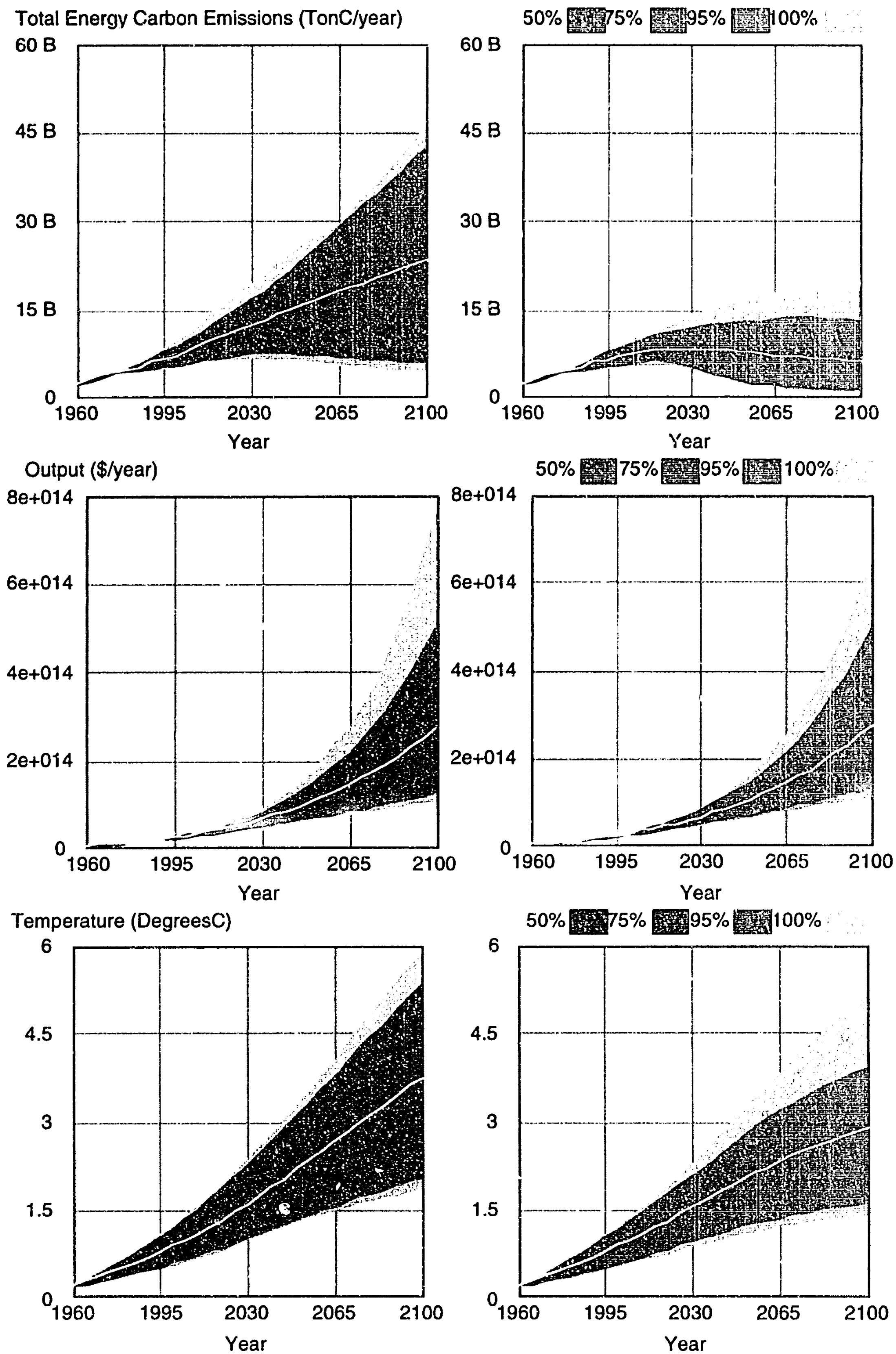
Controlling emissions with this policy results in substantial improvement in welfare (Table 39). Emissions are reduced dramatically, by roughly 70%, in all cases. As a result, climate change is reduced by about one degree in 2100. Figure 116 illustrates these changes graphically. The major tradeoff for these emissions reductions and welfare improvements is apparently a loss of welfare in scenarios which have very high welfare anyway.

Table 39: Multivariate Sensitivity of Key Variables with Carbon Tax

	Min	Max	Mean	Median	Norm. SD
Output in 2100 (trillion $/year)	114	650	273	255	0.369
	(+5%)	(-15%)	(+1%)	(+7%)	(-13%)
Energy Carbon Emissions in 2100 (10^9 TonC/year)	1.2	18.3	6.3	5.2	0.588
	(-73%)	(-60%)	(-73%)	(-77%)	(+39%)
Temperature in 2100 (DegreesC)	1.42	5.11	2.89	2.91	0.234
	(-23%)	(-13%)	(-23%)	(-21%)	(-3%)

Statistics are reported for 100 simulations. Values in parentheses are percentage variations from the no-tax case.

Figure 116: Emissions, Output, and Temperature under Uncertainty



Shading indicates the distribution of outcomes for 100 simulations.

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.

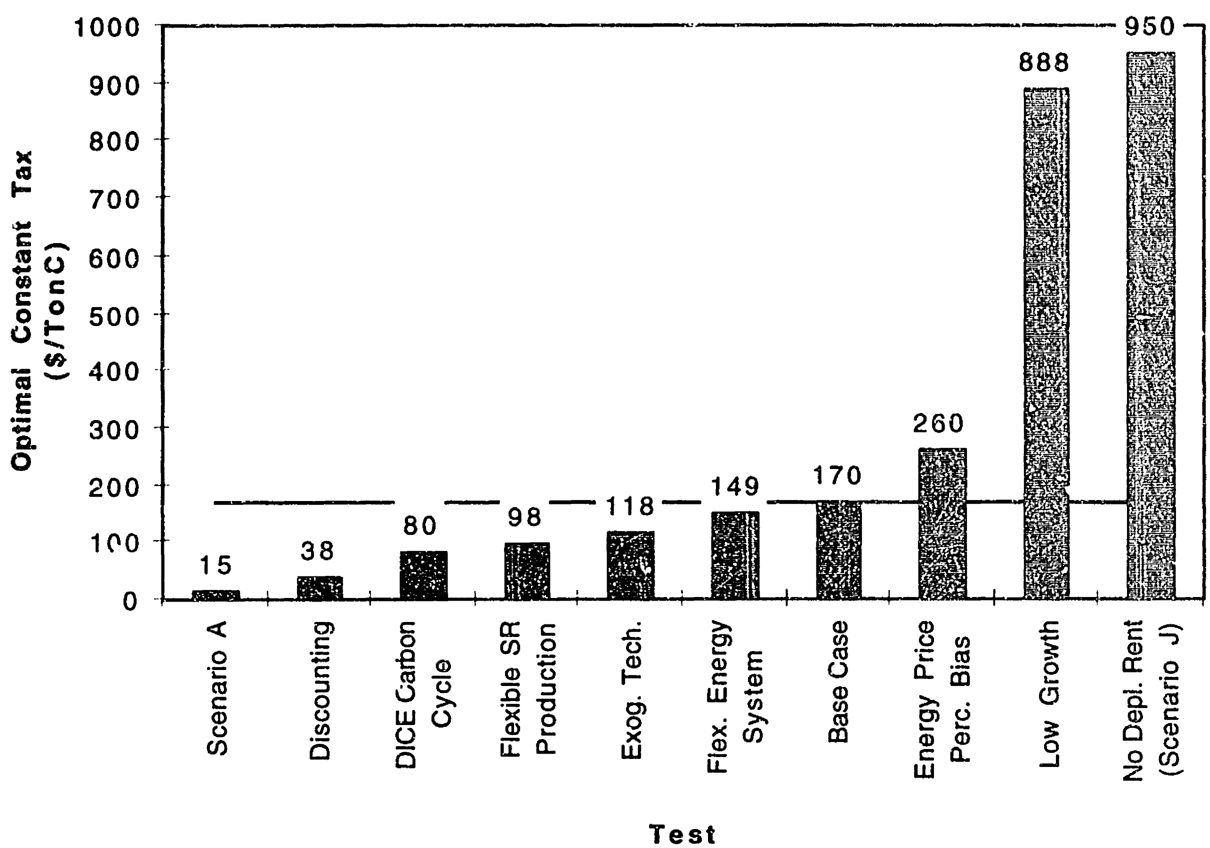
The FREE model can be parameterized to behave much like the DICE model (Scenario A, page 129). In this case, the optimal carbon tax is 15 $/TonC, a level that causes small increases in energy prices. Yet in the standard model run, Scenario J, the optimal tax is 950 $/TonC, a very high tax with strong 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.

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 117 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 (see also Table 32).

The choice of discounting method is essentially ethical, and most models can support a variety of perspective 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.

Figure 117: 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.

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 31). 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 (see Table 32), illustrating the necessity of exploring parameter and structural changes together rather than piecemeal.

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. These are outlined in detail in the Feedback Structure in Integrated Models chapter. To summarize, 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 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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FREE Model Equations

This appendix documents the FREE model. The model listing is cross-referenced for easy perusal of the equations. The listing was generated by the Vensim documentation tool. For details of the Vensim language, refer to (Ventana Systems 1994). The format is as follows:

```
(###) Variable = equation
```
units
Comment
(###) Causes (inputs to this variable)
(###) Uses (dependent variables)

The model is normally simulated using Euler integration, but some parameter changes (such as energy pricing according to true short-run marginal cost) require a higher-order integration method and/or a shorter time step (see .Control, page 220).

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```
:MACRO: INIT(input)

INIT = INITIAL(input)
```
input
Same as INITIAL function, but useable anywhere in an expression.

```
:END OF MACRO:
```

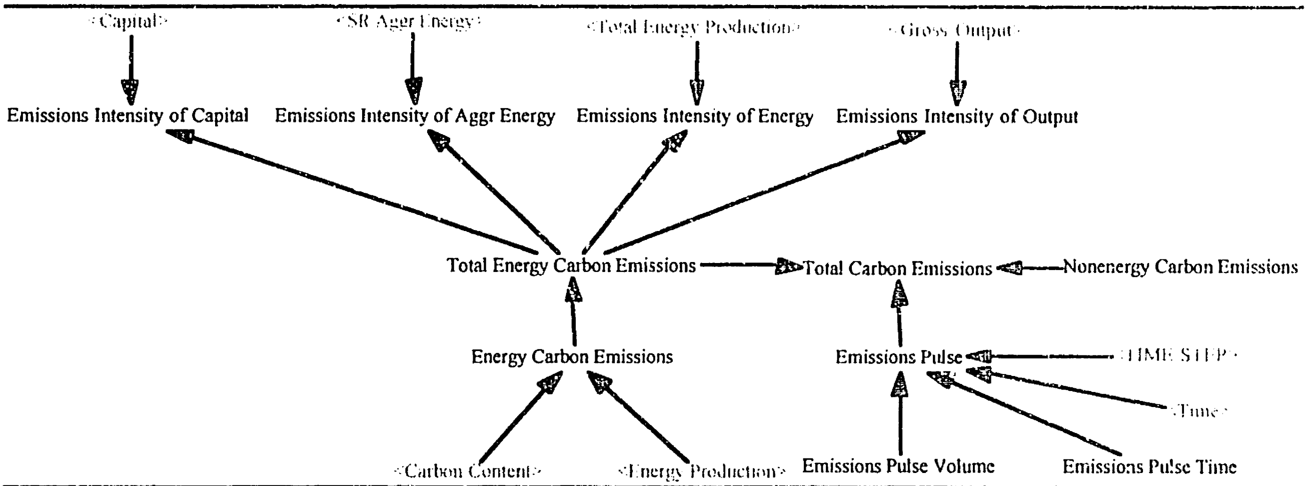
.Carbon.Control

```
(001) Carbon_Cycle_Switch = 1
```
dmnl
0 = simple (Nordhaus' DICE), 1 = complex.
(002)Effective_CO2_in_Atmosphere

```
(002) Effective_CO2_in_Atmosphere = IF_THEN_ELSE(Carbon_Cycle_Switch = 0,
        CO2_in_Atmos, CO2_in_Atmosphere)
```
TonC
Switches between simple (DICE) and complex carbon cycles.
(053)CO2_in_Atmos

(020)CO2_in_Atmosphere
(001)Carbon_Cycle_Switch
(065)CO2_Rad_Forcing
(482)Constraint_Violation_Penalty
(439)Indicated_Carbon_Tax

.Carbon.Emissions



(003) Emissions_Intensity_of_Aggr_Energy = Total_Energy_Carbon_Emissions / SR_Aggr_Energy
TonC/GJequiv
Average emissions intensity of aggregate energy product (neglecting nonenergy emissions).
(177)SR_Aggr_Energy
(013)Total_Energy_Carbon_Emissions

(004) Emissions_Intensity_of_Capital = Total_Energy_Carbon_Emissions / Capital
TonC/year/$
Average emissions intensity of capital stock (neglecting nonenergy emissions).
(157)Capital
(013)Total_Energy_Carbon_Emissions

(005) Emissions_Intensity_of_Energy = Total_Energy_Carbon_Emissions / Total_Energy_Production
TonC/GJ
Average emissions intensity of energy in physical terms (neglecting nonenergy emissions).
(013)Total_Energy_Carbon_Emissions
(400)Total_Energy_Production

(006) Emissions_Intensity_of_Output = Total_Energy_Carbon_Emissions / Gross_Output
TonC/$
Average emissions intensity of gross output of goods and services (neglecting nonenergy emissions).
(262)Gross_Output
(013)Total_Energy_Carbon_Emissions

(007) Emissions_Pulse = IF_THEN_ELSE(Time > = Emissions_Pulse_Time :AND: Time < Emissions_Pulse_Time + TIME_STEP, Emissions_Pulse_Volume / TIME_STEP, 0)
TonC/year

Rate of emissions from test pulse of given volume.
(000)Time
(008)Emissions_Pulse_Time
(009)Emissions_Pulse_Volume
(079)TIME_STEP
(012)Total_Carbon_Emissions

(008) Emissions_Pulse_Time = 2000
year
Year of emissions test pulse.
(007)Emissions_Pulse

(009) Emissions_Pulse_Volume = 0
TonC
Volume of test carbon pulse to atmosphere.
(007)Emissions_Pulse

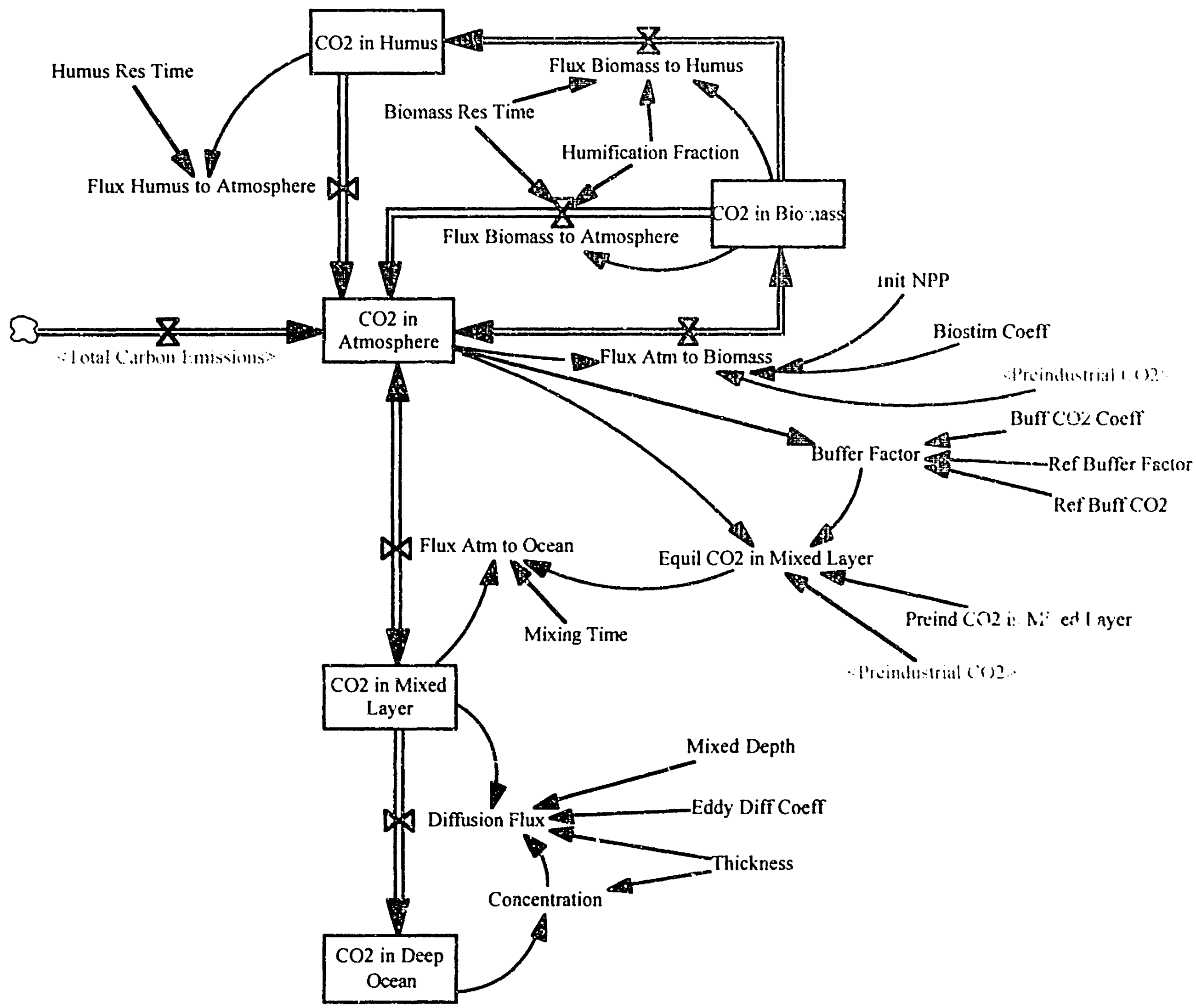
(010) Energy_Carbon_Emissions[nonrenewable] = Energy_Production[nonrenewable]
* Carbon_Content[nonrenewable]
TonC/year
Carbon emissions rate from energy production.
(429)Carbon_Content
(390)Energy_Production
(013)Total_Energy_Carbon_Emissions

(011) Nonenergy_Carbon_Emissions
TonC/year
Nonenergy carbon emissions.
(012)Total_Carbon_Emissions

(012) Total_Carbon_Emissions = Total_Energy_Carbon_Emissions +
Nonenergy_Carbon_Emissions + Emissions_Pulse
TonC/year
Emissions of carbon from energy use and other sources.
(007)Emissions_Pulse
(011)Nonenergy_Carbon_Emissions
(013)Total_Energy_Carbon_Emissions
(020)CO2_in_Atmosphere
(014)Atmospheric_Retention
(052)Average_Atmos_Retention
(054)CO2_Net_Emiss

(013) Total_Energy_Carbon_Emissions =
SUM(Energy_Carbon_Emissions[nonrenewable!])
TonC/year
Total carbon emissions from all energy sources
(010)Energy_Carbon_Emissions
(003)Emissions_Intensity_of_Aggr_Energy
(004)Emissions_Intensity_of_Capital
(005)Emissions_Intensity_of_Energy
(006)Emissions_Intensity_of_Output
(442)Perceived_Emissions_Rate
(012)Total_Carbon_Emissions

.Carbon.FREE



<Atmospheric Retention>

```
(014) Atmospheric_Retention = ZIDZ(Total_Carbon_Emissions-Flux_Atm_to_Ocean-
          Flux_Atm_to_Biomass + Flux_Biomass_to_Atmosphere +
          Flux_Humus_to_Atmosphere , Total_Carbon_Emissions )
```

dmnl

Atmospheric retention of emissions.

(029)Flux_Atm_to_Biomass
(030)Flux_Atm_to_Ocean
(031)Flux_Biomass_to_Atmosphere
(033)Flux_Humus_to_Atmosphere
(012)Total_Carbon_Emissions

```
(015) Biomass_Res_Time = 10.6
```

year

Average residence time of carbon in biomass.

(031)Flux_Biomass_to_Atmosphere

(032)Flux_Biomass_to_Humus

```
(016) Biostim_Coeff = 0.4
```
dmnl
Coefficient for response of primary production to CO2 concentration.
(029)Flux_Atm_to_Biomass

```
(017) bottom5 : (layer6-layer10)
```
Bottom 5 (thick) ocean layers.

```
(018) Buff_CO2_Coeff = 4.05
```
dmnl
Coefficient of CO2 concentration influence on buffer factor.
(019)Buffer_Factor

```
(019) Buffer_Factor = Ref_Buffer_Factor + Buff_CO2_Coeff *
        LN(CO2_in_Atmosphere / Ref_Buff_CO2)
```
dmnl
Buffer factor for atmosphere / mixed ocean carbon equilibration.
(020)CO2_in_Atmosphere
(018)Buff_CO2_Coeff
(047)Ref_Buff_CO2
(048)Ref_Buffer_Factor
(028)Equil_CO2_in_Mixed_Layer

```
(020) CO2_in_Atmosphere = INTEG ( Total_Carbon_Emissions-Flux_Atm_to_Ocean-
        Flux_Atm_to_Biomass + Flux_Biomass_to_Atmosphere +
        Flux_Humus_to_Atmosphere, init_co2_in_atm)
```
TonC
Carbon in atmosphere
(029)Flux_Atm_to_Biomass
(030)Flux_Atm_to_Ocean
(031)Flux_Biomass_to_Atmosphere
(033)Flux_Humus_to_Atmosphere
(036)init_co2_in_atm
(012)Total_Carbon_Emissions
(019)Buffer_Factor
(002)Effective_CO2_in_Atmosphere
(028)Equil_CO2_in_Mixed_Layer
(029)Flux_Atm_to_Biomass

```
(021) CO2_in_Biomass = INTEG ( Flux_Atm_to_Biomass-Flux_Biomass_to_Atmosphere-
        Flux_Biomass_to_Humus, Init_CO2_in_Biomass)
```
TonC
Carbon in biosphere (biomass, litter, and humus)
(029)Flux_Atm_to_Biomass
(031)Flux_Biomass_to_Atmosphere
(032)Flux_Biomass_to_Humus
(037)Init_CO2_in_Biomass
(031)Flux_Biomass_to_Atmosphere
(032)Flux_Biomass_to_Humus

```
(022) CO2_in_Deep_Ocean[upper] = INTEG ( Diffusion_Flux[upper]-
        Diffusion_Flux[lower], Init_CO2_in_Deep_Ocean [upper])

      CO2_in_Deep_Ocean[layer10] = INTEG(Diffusion_Flux[layer10],
        Init_CO2_in_Deep_Ocean[layer10])
```
TonC

Carbon in deep ocean.

(026)Diffusion_Flux
(038)Init_CO2_in_Deep_Ocean
(025)Concentration

```
(023) CO2_in_Humus = INTEG ( Flux_Biomass_to_Humus-Flux_Humus_to_Atmosphere,
        Init_CO2_in_Humus)
```

TonC

Carbon in humus.

(032)Flux_Biomass_to_Humus
(033)Flux_Humus_to_Atmosphere
(039)Init_CO2_in_Humus
(033)Flux_Humus_to_Atmosphere

```
(024) CO2_in_Mixed_Layer = INTEG ( Flux_Atm_to_Ocean-Diffusion_Flux[layer1],
        Init_CO2_in_Mixed_Ocean)
```

TonC

Carbon in mixed layer.

(026)Diffusion_Flux
(030)Flux_Atm_to_Ocean
(040)Init_CO2_in_Mixed_Ocean
(026)Diffusion_Flux
(030)Flux_Atm_to_Ocean

```
(025) Concentration[layers] = CO2_in_Deep_Ocean[layers] / Thickness[layers]
```

TonC/meter

Concentration of carbon in ocean layers.

(022)CO2_in_Deep_Ocean
(049)Thickness
(026)Diffusion_Flux

```
(026) Diffusion_Flux[layer1] = (CO2_in_Mixed_Layer / Mixed_Depth-
        Concentration[layer1]) * Eddy_Diff_Coeff * 2 / (Mixed_Depth +
        Thickness[layer1])

      Diffusion_Flux[lower] = (Concentration[upper]-Concentration[lower]) *
        Eddy_Diff_Coeff * 2 / (Thickness[upper] + Thickness[lower])
```

TonC/year

Diffusion flux between ocean layers.

(024)CO2_in_Mixed_Layer
(025)Concentration
(027)Eddy_Diff_Coeff
(044)Mixed_Depth
(049)Thickness
(022)CO2_in_Deep_Ocean
(024)CO2_in_Mixed_Layer

```
(027) Eddy_Diff_Coeff = 4000
```

*meter*meter/year*

Eddy diffusion coefficient.

(026)Diffusion_Flux

```
(028) Equil_CO2_in_Mixed_Layer = Preind_CO2_in_Mixed_Layer *
        (CO2_in_Atmosphere / Preindustrial_CO2) ^ (1 / Buffer_Factor)
```

TonC

Equilibrium carbon content of mixed layer.

(020)CO2_in_Atmosphere

(019)Buffer_Factor
(046)Preind_CO2_in_Mixed_Layer
(073)Preindustrial_CO2
(030)Flux_Atm_to_Ocean

```
(029) Flux_Atm_to_Biomass = Init_NPP * (1 + Biostim_Coeff *
        LN(CO2_in_Atmosphere / Preindustrial_CO2))
```
TonC/year
Carbon flux from atmosphere to biosphere (from primary production)
(020)CO2_in_Atmosphere
(016)Biostim_Coeff
(041)Init_NPP
(073)Preindustrial_CO2
(020)CO2_in_Atmosphere
(021)CO2_in_Biomass
(014)Atmospheric_Retention

```
(030) Flux_Atm_to_Ocean = (Equil_CO2_in_Mixed_Layer-CO2_in_Mixed_Layer) /
        Mixing_Time
```
TonC/year
Carbon flux from atmosphere to mixed ocean layer.
(024)CO2_in_Mixed_Layer
(028)Equil_CO2_in_Mixed_Layer
(045)Mixing_Time
(020)CO2_in_Atmosphere
(024)CO2_in_Mixed_Layer
(014)Atmospheric_Retention

```
(031) Flux_Biomass_to_Atmosphere = CO2_in_Biomass / Biomass_Res_Time * (1-
        Humification_Fraction)
```
TonC/year
Carbon flux from biomass to atmosphere.
(021)CO2_in_Biomass
(015)Biomass_Res_Time
(034)Humification_Fraction
(020)CO2_in_Atmosphere
(021)CO2_in_Biomass
(014)Atmospheric_Retention

```
(032) Flux_Biomass_to_Humus = CO2_in_Biomass / Biomass_Res_Time *
        Humification_Fraction
```
TonC/year
Carbon flux from biomass to humus.
(021)CO2_in_Biomass
(015)Biomass_Res_Time
(034)Humification_Fraction
(021)CO2_in_Biomass
(023)CO2_in_Humus

```
(033) Flux_Humus_to_Atmosphere = CO2_in_Humus / Humus_Res_Time
```
TonC/year
Carbon flux from humus to atmosphere.
(023)CO2_in_Humus
(035)Humus_Res_Time
(020)CO2_in_Atmosphere
(023)CO2_in_Humus

(014)Atmospheric_Retention

(034) `Humification_Fraction = 0.428`
dmnl
Fraction of carbon outflow from biomass that enters humus stock.
(031)Flux_Biomass_to_Atmosphere
(032)Flux_Biomass_to_Humus

(035) `Humus_Res_Time = 27.8`
year
Average carbon residence time in humus.
(033)Flux_Humus_to_Atmosphere

(036) `init_co2_in_atm = 6.576e+011`
TonC
Initial carbon in atmosphere. From simulations with historical emissions, starting at equilibrium in 1775.
(020)CO2_in_Atmosphere

(037) `Init_CO2_in_Biomass = 6.566e+011`
TonC
Initial carbon in biomass. From simulations with historical emissions, starting at equilibrium in 1775.
(021)CO2_in_Biomass

(038) `Init_CO2_in_Deep_Ocean[layers] = 2.054e+012, 2.051e+012, 2.05e+012, 2.049e+012, 2.048e+012, 5.734e+012, 5.733e+012, 5.733e+012, 5.733e+012, 5.733e+012`
TonC
Initial carbon in deep ocean layers. From simulations with historical emissions, starting at equilibrium in 1775.
(022)CO2_in_Deep_Ocean

(039) `Init_CO2_in_Humus = 7.259e+011`
TonC
Inital carbon in humus. From simulations with historical emissions, starting at equilibrium in 1775.
(023)CO2_in_Humus

(040) `Init_CO2_in_Mixed_Ocean = 7.712e+011`
TonC
Initial carbon in mixed ocean layer. From simulations with historical emissions, starting at equilibrium in 1775.
(024)CO2_in_Mixed_Layer

(041) `Init_NPP = 6e+010`
TonC/year
Initial net primary production.
(029)Flux_Atm_to_Biomass

(042) `layers : (layer1-layer10)`
Deep ocean layers.

(043) `lower : (layer2-layer10) -> upper`
Lower 9 deep ocean layers.

(044) `Mixed_Depth = 75`
meter
Mixed ocean layer depth.

(026)Diffusion_Flux

(045) `Mixing_Time = 9.5`
year
Atmosphere - mixed ocean layer mixing time.

(030)Flux_Atm_to_Ocean

(046) `Preind_CO2_in_Mixed_Layer = 7.678e+011`
TonC
Initial carbon content of mixed ocean layer.

(028)Equil_CO2_in_Mixed_Layer

(047) `Ref_Buff_CO2 = 7.6e+011`
TonC
CO2 in atmosphere at normal buffer factor.

(019)Buffer_Factor

(048) `Ref_Buffer_Factor = 10`
dmnl
Normal buffer factor.

(019)Buffer_Factor

(049) `Thickness[top5] = 200`

`Thickness[bottom5] = 560`
meter
Deep ocean layer thicknesses.

(025)Concentration
(026)Diffusion_Flux

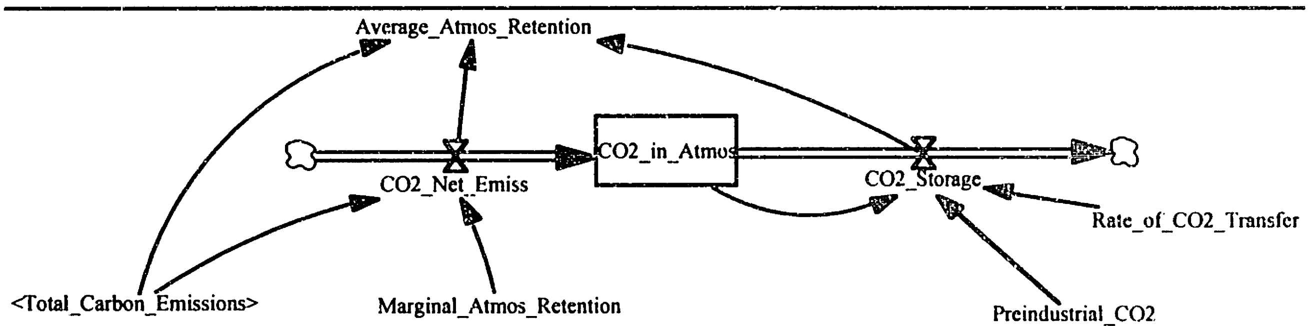
(050) `top5 : (layer1-layer5)`
Top 5 (thin) ocean layers.

(051) `upper : (layer1-layer9) -> lower`
Upper 9 deep ocean layers.

.Carbon.Nordhaus

Drawn exactly from Nordhaus' DICE model. See:

Nordhaus, W. D. 1994. Managing the Global Commons. Cambridge, MA: MIT Press.



(052) `Average_Atmos_Retention = (CO2_Net_Emiss-CO2_Storage) /`
`Total_Carbon_Emissions`
dmnl
Average atmospheric retention.

(054)CO2_Net_Emiss
(055)CO2_Storage

(012)Total_Carbon_Emissions

(053) `CO2_in_Atmos = INTEG(CO2_Net_Emiss - CO2_Storage, 6.77e+011)`
TonC
CO2 in atmosphere.
(054)CO2_Net_Emiss
(055)CO2_Storage
(055)CO2_Storage
(002)Effective_CO2_in_Atmosphere

(054) `CO2_Net_Emiss = Marginal_Atmos_Retention * Total_Carbon_Emissions`
TonC/year
CO2 emissions less short-run uptake (to mixed ocean layer).
(056)Marginal_Atmos_Retention
(012)Total_Carbon_Emissions
(053)CO2_in_Atmos
(052)Average_Atmos_Retention

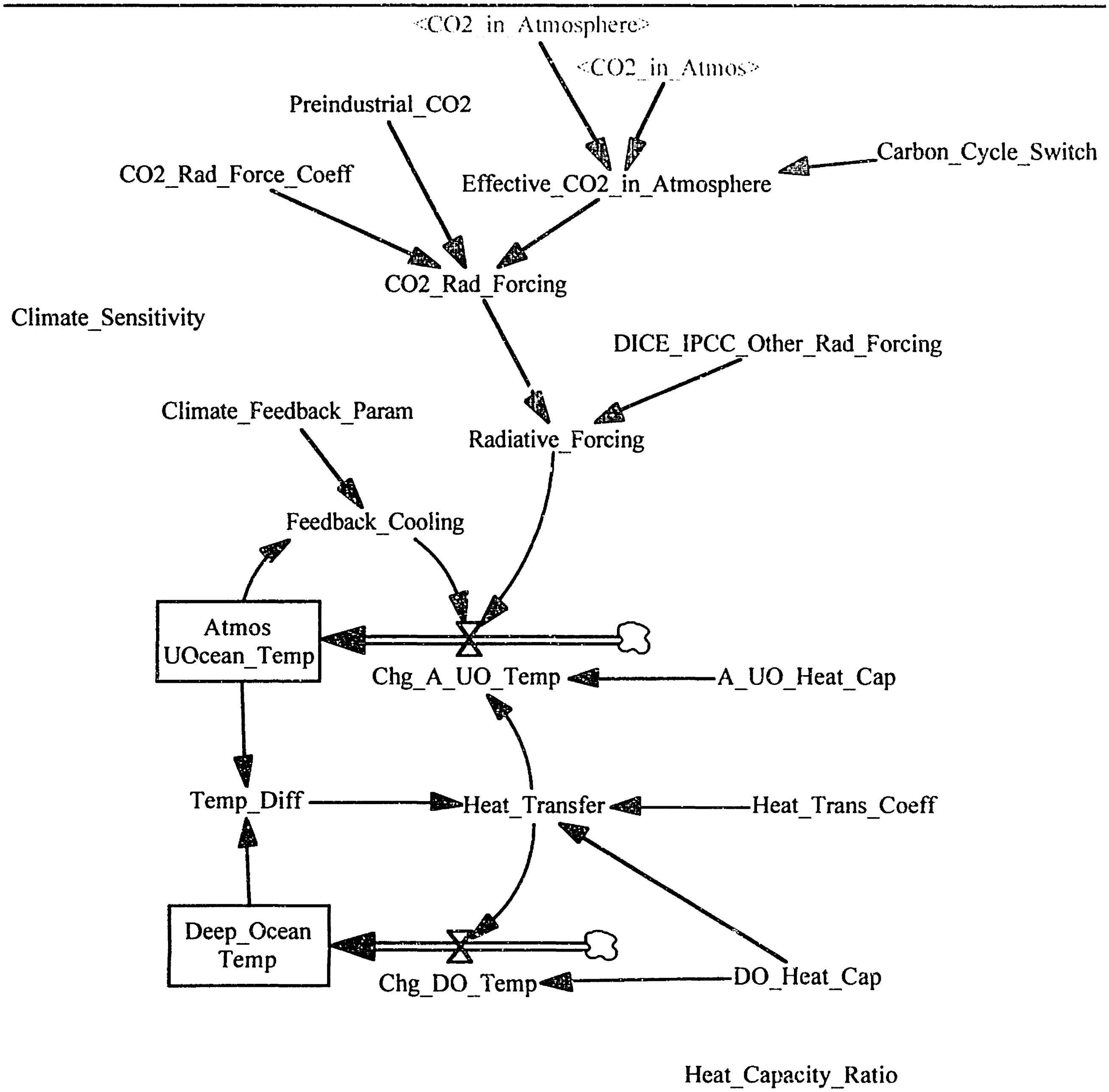
(055) `CO2_Storage = (CO2_in_Atmos-Preindustrial_CO2) * Rate_of_CO2_Transfer`
TonC/year
CO2 removal from the atmosphere and storage by long-term processes.
(053)CO2_in_Atmos
(073)Preindustrial_CO2
(057)Rate_of_CO2_Transfer
(053)CO2_in_Atmos
(052)Average_Atmos_Retention

(056) `Marginal_Atmos_Retention = 0.64`
dmnl
Marginal Atmospheric Retention Fraction. Fraction of Greenhouse Gas Emissions which accumulate in the atmosphere.
(054)CO2_Net_Emiss

(057) `Rate_of_CO2_Transfer = 0.008333`
1/year
Fractional rate of CO2 storage (corresponds to 120 year residence time)
(055)CO2_Storage

.Climate

Drawn from Nordhaus' DICE model. See: Nordhaus, W. D. 1994. Managing the Global Commons. Cambridge, MA: MIT Press.



(058) A_UO_Heat_Cap = 44.248
*watt*year/DegreesC/(meter*meter)*
Atmosphere & Upper Ocean Heat Capacity per Unit Area
(060)Chg_A_UO_Temp

(059) Atmos_UOcean_Temp = INTEG(Chg_A_UO_Temp, Init_Atmos_UOcean_Temp)
DegreesC
Temperature of the Atmosphere and Upper Ocean
(060)Chg_A_UO_Temp
(072)Init_Atmos_UOcean_Temp
(402)Adaptation_Rate
(404)Climate_Damage_Effect
(068)Feedback_Cooling
(075)Temp_Diff

```
(060) Chg_A_UO_Temp = (Radiative_Forcing-Feedback_Cooling-Heat_Transfer) /
        A_UO_Heat_Cap
```
DegreesC/year
Rate of Change in the Atmosphere & Upper Ocean Temperature.
(058)A_UO_Heat_Cap
(068)Feedback_Cooling
(071)Heat_Transfer
(074)Radiative_Forcing
(059)Atmos_UOcean_Temp

```
(061) Chg_DO_Temp = Heat_Transfer / DO_Heat_Cap
```
DegreesC/year
Rate of Change in the Deep Ocean Temperature
(067)DO_Heat_Cap
(071)Heat_Transfer
(066)Deep_Ocean_Temp

```
(062) Climate_Feedback_Param = INITIAL ( CO2_Rad_Force_Coeff /
        Climate_Sensitivity)
```
watt/meter/meter/DegreesC
Climate Feedback Parameter - determines feedback effect from temperature increase.
(063)Climate_Sensitivity
(064)CO2_Rad_Force_Coeff
(068)Feedback_Cooling

```
(063) Climate_Sensitivity = 2.908
```
DegreesC
Equilibrium temperature change in response to a 2xCO2 equivalent change in radiative forcing
(062)Climate_Feedback_Param

```
(064) CO2_Rad_Force_Coeff = 4.1
```
watt/meter/meter
Coefficient of Radiative Forcing from CO2
(062)Climate_Feedback_Param
(065)CO2_Rad_Forcing

```
(065) CO2_Rad_Forcing = CO2_Rad_Force_Coeff * LOG(Effective_CO2_in_Atmosphere
        / Preindustrial_CO2, 2)
```
watt/meter/meter
Radiative forcing from accumulation of CO2.
(064)CO2_Rad_Force_Coeff
(002)Effective_CO2_in_Atmosphere
(073)Preindustrial_CO2
(074)Radiative_Forcing

```
(066) Deep_Ocean_Temp = INTEG(Chg_DO_Temp, 0.1)
```
DegreesC
Temperature of the Deep Ocean
(061)Chg_DO_Temp
(075)Temp_Diff

```
(067) DO_Heat_Cap = INITIAL ( Heat_Capacity_Ratio * Heat_Trans_Coeff)
```
*watt*year/DegreesC/meter/meter*
Deep Ocean Heat Capacity per Unit Area
(069)Heat_Capacity_Ratio
(070)Heat_Trans_Coeff
(061)Chg_DO_Temp

(071)Heat_Transfer

(068) Feedback_Cooling = Atmos_UOcean_Temp * Climate_Feedback_Param
watt/meter/meter
Feedback cooling of atmosphere / upper ocean system due to blackbody radiation.
(059)Atmos_UOcean_Temp
(062)Climate_Feedback_Param
(060)Chg_A_UO_Temp

(069) Heat_Capacity_Ratio = 0.44
*watt/(meter*meter*DegreesC)*
Ratio of Thermal Capacity of Deep Ocean to Heat Transfer Time Constant
(067)DO_Heat_Cap

(070) Heat_Trans_Coeff = 500
year
Heat Transfer Coefficient [tau12] (years) Coefficient of heat transfer between the atmosphere & upper ocean and the deep ocean. May be interpreted as a mixing time constant.
(067)DO_Heat_Cap
(071)Heat_Transfer

(071) Heat_Transfer = Temp_Diff * DO_Heat_Cap / Heat_Trans_Coeff
watt/meter/meter
Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean
(067)DO_Heat_Cap
(070)Heat_Trans_Coeff
(075)Temp_Diff
(060)Chg_A_UO_Temp
(061)Chg_DO_Temp

(072) Init_Atmos_UOcean_Temp = 0.2
DegreesC
Initial Temperature of the Atmosphere and Upper Ocean
(059)Atmos_UOcean_Temp

(073) Preindustrial_CO2 = 5.9e+011
TonC
Preindustrial CO2 content of atmosphere.
(479)CO2_Constraint
(065)CO2_Rad_Forcing
(055)CO2_Storage
(028)Equil_CO2_in_Mixed_Layer
(029)Flux_Atm_to_Biomass
(439)Indicated_Carbon_Tax

(074) Radiative_Forcing = CO2_Rad_Forcing + DICE_IPCC_Other_Rad_Forcing
watt/meter/meter
Total Radiative Forcing from All GHGs
(065)CO2_Rad_Forcing
(097)DICE_IPCC_Other_Rad_Forcing
(060)Chg_A_UO_Temp

(075) Temp_Diff = Atmos_UOcean_Temp-Deep_Ocean_Temp
DegreesC
Temperature Difference between Upper and Deep Ocean
(059)Atmos_UOcean_Temp
(066)Deep_Ocean_Temp
(071)Heat_Transfer

.Control

```
Simulation Control Paramaters
```

(076) `FINAL_TIME = 2300`
year
The final time for the simulation.
(414)Depletion_Planning_Horizon
(418)Final_Depletion_Rent

(077) `INITIAL_TIME = 1960`
year
The initial time for the simulation.
(000)Time

(078) `SAVEPER = 5`
year
The frequency with which output is stored.

(079) `TIME_STEP = 0.125`
year
The time step for the simulation.
(007)Emissions_Pulse

.Data

(080) `Average_Energy_Price = (Average_Thermal_Price * (Coal_Production + Gas_Production + Oil_Production) + Elect_Price * Primary_Electricity) / (Coal_Production + Gas_Production + Oil_Production + Primary_Electricity)`
\$/GJ
Average price of energy in physical terms, from data. Electricity in primary equivalent units.
(081)Average_Thermal_Price
(093)Coal_Production
(098)Elect_Price
(106)Gas_Production
(113)Oil_Production
(118)Primary_Electricity

(081) `Average_Thermal_Price = (Oil_Production * World_Crude_Price + Coal_Production * World_Coal_Price + Gas_Production * World_Gas_Price) / (Coal_Production + Gas_Production + Oil_Production)`
\$/GJ
Average price of thermal fuels from data.
(093)Coal_Production
(106)Gas_Production
(113)Oil_Production
(129)World_Coal_Price
(130)World_Crude_Price
(131)World_Gas_Price
(080)Average_Energy_Price

(082) `CO2_Concentration_A`
TonC
IPCC 92a atmospheric concentration

(083) CO2_Concentration_B
TonC
IPCC 92b atmospheric concentration

(084) CO2_Concentration_C
TonC
IPCC 92c atmospheric concentration

(085) CO2_Concentration_D
TonC
IPCC 92d atmospheric concentration

(086) CO2_Concentration_E
TonC
IPCC 92e atmospheric concentration

(087) CO2_Emissions_A
TonC/year
IPCC 92a emissions

(088) CO2_Emissions_B
TonC/year
IPCC 92b emissions

(089) CO2_Emissions_C
TonC/year
IPCC 92c emissions

(090) CO2_Emissions_D
TonC/year
IPCC 92d emissions

(091) CO2_Emissions_E
TonC/year
IPCC 92e emissions

(092) Coal_EIA
GJ/year
EIA coal production data / forecast.

(093) Coal_Production
GJ/year
Coal production data.

(080)Average_Energy_Price
(081)Average_Thermal_Price
(122)Production_Data

(094) Commercial_Energy
GJ/year
Commercial energy data.

(095) Cons_Frac_GDP
dmnl
Consumption as a fraction of GDP (data).

(096) DICE_IPCC_CO2_Rad_Forcing
*watt/(meter*meter)*
IPCC CO2 radiative forcing (from DICE)

(097) DICE_IPCC_Other_Rad_Forcing
*watt/(meter*meter)*

IPCC other GHG radiative forcing (from DICE)

(074)Radiative_Forcing

(098) Elect_Price
$/GJ
Electricity price data.

(080)Average_Energy_Price
(116)Price_Data

(099) EMF_GDP
$/year
EMF-14 world GDP

(100) EMF_Population
people
EMF-14 world population

(101) Energy_CO2_Emissions_A
TonC/year
IPCC 92a energy emissions

(102) Energy_CO2_Emissions_B
TonC/year
IPCC 92b energy emissions

(103) Energy_CO2_Emissions_C
TonC/year
IPCC 92c energy emissions

(104) Energy_CO2_Emissions_D
TonC/year
IPCC 92d energy emissions

(105) Gas_EIA
GJ/year
EIA gas production data / forecast.

(114)OilGas_EIA

(106) Gas_Production
GJ/year
Gas production data.

(080)Average_Energy_Price
(081)Average_Thermal_Price
(116)Price_Data
(122)Production_Data

(107) GDP := World_GDP * 1e+009
$/year
GDP data.

(132)World_GDP

(108) GDP_Deflator
dmnl
GDP deflator data.

(109) Hydro_Electricity
GJ/year
Hydro electricity data (primary equivalent units).

(118)Primary_Electricity
(122)Production_Data

(110) `Invest_Frac_GDP`

dmnl

Investment as a fraction of GDP data.

(133)World_Investment

(111) `Nuclear_Electricity`

GJ/year

Nuclear electricity production data (primary equivalent units).

(118)Primary_Electricity
(122)Production_Data

(112) `Oil_EIA`

GJ/year

EIA oil production data / forecast.

(114)OilGas_EIA

(113) `Oil_Production`

GJ/year

Oil production data.

(080)Average_Energy_Price
(081)Average_Thermal_Price
(116)Price_Data
(122)Production_Data

(114) `OilGas_EIA:= Oil_EIA + Gas_EIA`

GJ/year

EIA oil + gas production data / forecast.

(105)Gas_EIA
(112)Oil_EIA

(115) `Other_Electricity`

GJ/year

Other electricity production data (primary equivalent units).

(118)Primary_Electricity
(122)Production_Data

(116) `Price_Data[Coal] := World_Coal_Price`

```
Price_Data[OilGas] := (World_Crude_Price * Oil_Production +
      World_Gas_Price * Gas_Production) / (Oil_Production +
      Gas_Production)

Price_Data[HN] := Elect_Price

Price_Data[New] := 10 * Elect_Price
```

$/GJ

Price data array for all sources.

(098)Elect_Price
(106)Gas_Production
(113)Oil_Production
(129)World_Coal_Price
(130)World_Crude_Price
(131)World_Gas_Price

(338)Effective_Primary_Energy_Price

(117) `Primary_EIA`

GJ/year

EIA primary production data / forecast.

(118) `Primary_Electricity = Hydro_Electricity + Nuclear_Electricity + Other_Electricity`
GJ/year
Primary electricity production data (primary equivalent units).
(109)Hydro_Electricity
(111)Nuclear_Electricity
(115)Other_Electricity
(080)Average_Energy_Price

(119) `Primary_Energy`
GJ/year
Total primary energy production data.

(120) `Primary_Trabalka`
GJ/year
Trabalka primary production data / forecast.

(121) `Primary_WEC`
GJ/year
WEC primary production data / forecast.

(122) `Production_Data[Coal] := Coal_Production`

`Production_Data[OilGas] := Oil_Production + Gas_Production`

`Production_Data[HN] := Hydro_Electricity + Nuclear_Electricity`

`Production_Data[New] := Other_Electricity`
GJ/year
Production data array for all sources.
(093)Coal_Production
(106)Gas_Production
(109)Hydro_Electricity
(111)Nuclear_Electricity
(113)Oil_Production
(115)Other_Electricity
(389)Energy_Order_Rate
(123)Share_Data
(126)Total_Production_Data

(123) `Share_Data[source] := Production_Data[source] / Total_Production_Data`
dmnl
Energy production share data by source.
(122)Production_Data
(126)Total_Production_Data

(124) `Thermal_Electricity`
GJ/year
Thermal electricity production data (primary equivalent units).

(125) `Total_Electricity`
GJ/year
Total electricity production data (primary equivalent units).

(126) `Total_Production_Data := SUM(Production_Data[source!])`
GJ/year
Total energy production data (physical terms).
(122)Production_Data
(123)Share_Data

(127) `Traditional_Energy`
GJ/year
Traditional energy production data.

(128) `World_Bank_Population:= World_Population * 1e+006`
people
Population data (World Bank).
(135)World_Population

(129) `World_Coal_Price`
$/GJ
Coal price data.
(081)Average_Thermal_Price
(116)Price_Data

(130) `World_Crude_Price`
$/GJ
Oil price data.
(081)Average_Thermal_Price
(116)Price_Data

(131) `World_Gas_Price`
$/GJ
Gas price data.
(081)Average_Thermal_Price
(116)Price_Data

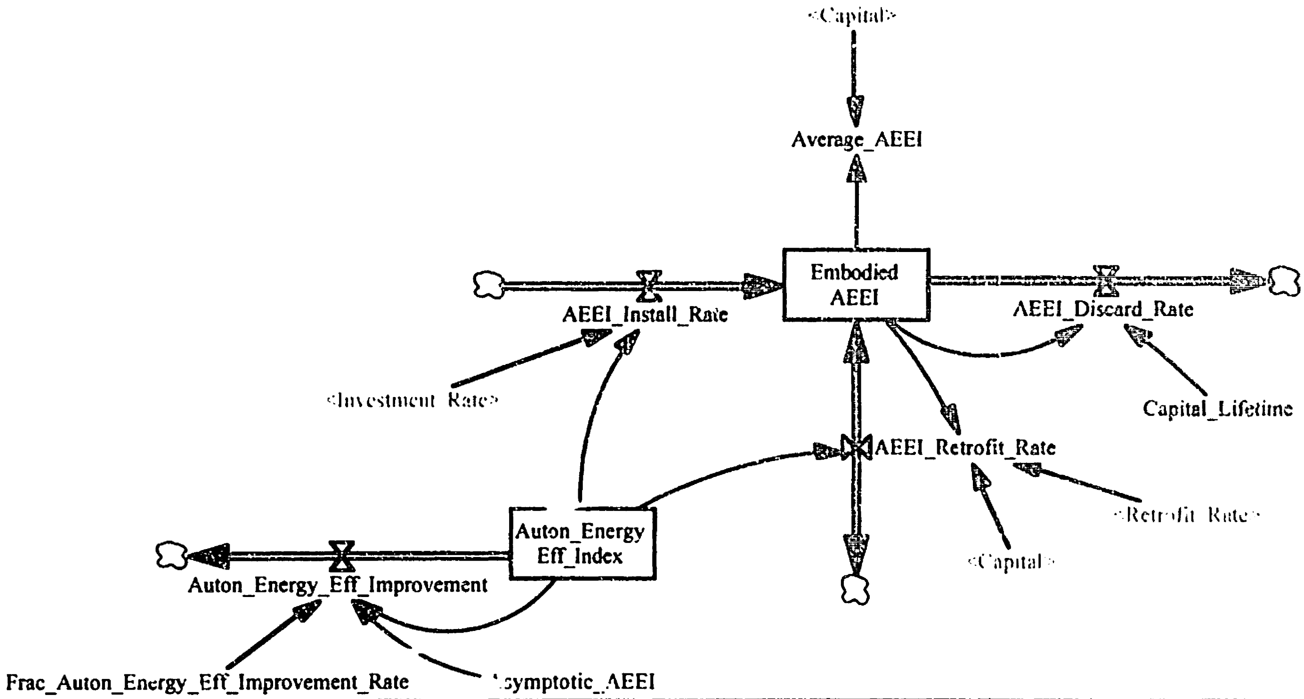
(132) `World_GDP`
$/year
GDP data.
(107)GDP
(133)World_Investment

(133) `World_Investment = World_GDP * Invest_Frac_GDP * 1e+009`
$/year
Investment data.
(110)Invest_Frac_GDP
(132)World_GDP
(163)Desired_Investment

(134) `World_Pop_Growth_Rt`
1/year
Population growth rate data.

(135) `World_Population`
MillionPeople
World Bank population data.
(128)World_Bank_Population

.Economy.AEEI



(136) `AEEI_Discard_Rate = Embodied_AEEI / Capital_Lifetime`
$/year
Embodied energy efficiency technology of discarded capital.
(144)Embodied_AEEI
(143)Capital_Lifetime
(144)Embodied_AEEI

(137) `AEEI_Install_Rate = Investment_Rate * Auton_Energy_Eff_Index`
$/year
Rate of embodiment of autonomous energy efficiency technology from investment in new capital.
(141)Auton_Energy_Eff_Index
(166)Investment_Rate
(144)Embodied_AEEI

(138) `AEEI_Retrofit_Rate = Capital * Retrofit_Rate * Auton_Energy_Eff_Index- Embodied_AEEI * Retrofit_Rate`
$/year
Rate of change of embodied energy efficiency technology due to retrofits.
(141)Auton_Energy_Eff_Index
(157)Capital
(144)Embodied_AEEI
(270)Retrofit_Rate
(144)Embodied_AEEI

(139) `Asymptotic_AEEI = 0.1`
dmnl
Ultimate possible energy efficiency improvement level.
(140)Auton_Energy_Eff_Improvement

(140) `Auton_Energy_Eff_Improvement = (Auton_Energy_Eff_Index-Asymptotic_AEEI) * Frac_Auton_Energy_Eff_Improvement_Rate`

1/year

Rate of autonomous energy efficiency improvement of new capital.

(141)Auton_Energy_Eff_Index
(139)Asymptotic_AEEI
(145)Frac_Auton_Energy_Eff_Improvement_Rate
(141)Auton_Energy_Eff_Index

(141) Auton_Energy_Eff_Index = INTEG(-Auton_Energy_Eff_Improvement, 1)

dmnl

Index of autonomous energy efficiency technology for new capital.

(140)Auton_Energy_Eff_Improvement
(144)Embodied_AEEI
(137)AEEI_Install_Rate
(138)AEEI_Retrofit_Rate
(140)Auton_Energy_Eff_Improvement

(142) Average_AEEI = Embodied_AEEI / Capital

dmnl

Average autonomous energy efficiency index of capital.

(157)Capital
(144)Embodied_AEEI
(146)LR_Energy_Share

(143) Capital_Lifetime = 15

year

Lifetime of goods producing capital.

(136)AEEI_Discard_Rate
(159)Cost_of_Capital
(164)Discard_Rate
(212)Energy_Req_Discard_Rate

(144) Embodied_AEEI = INTEG (AEEI_Install_Rate + AEEI_Retrofit_Rate-
AEEI_Discard_Rate, Auton_Energy_Eff_Index * Capital)

$

Autonomous energy efficiency improvements embodied in capital.

(141)Auton_Energy_Eff_Index
(157)Capital
(136)AEEI_Discard_Rate
(137)AEEI_Install_Rate
(138)AEEI_Retrofit_Rate
(136)AEEI_Discard_Rate
(138)AEEI_Retrofit_Rate
(142)Average_AEEI

(145) Frac_Auton_Energy_Eff_Improvement_Rate = 0.005

1/year

Fractional autonomous energy efficiency improvement rate.

(140)Auton_Energy_Eff_Improvement

(146) LR_Energy_Share = Average_AEEI * Ref_Total_Expenditure / ((1-
Value_Share_of_Labor) * Reference_Output)

dmnl

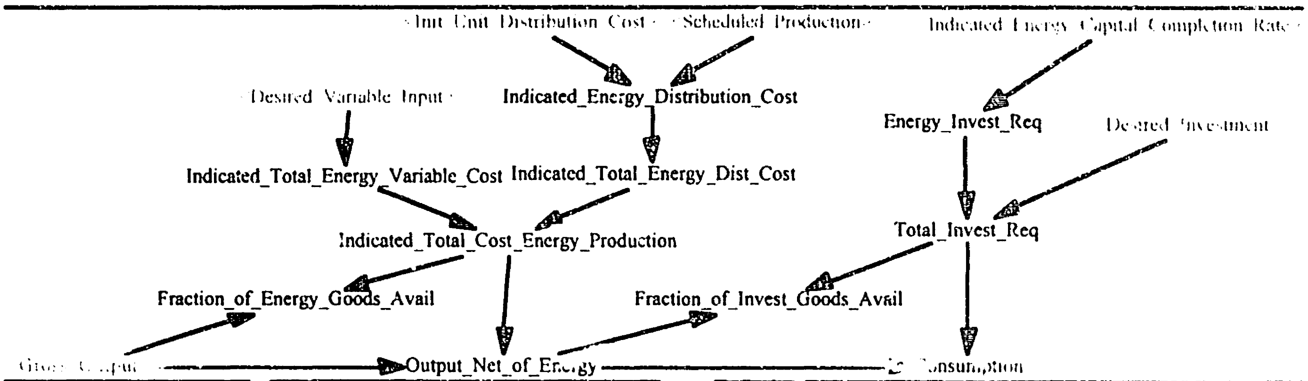
CES value share of aggregate energy good in capital-energy aggregate.

(142)Average_AEEI
(332)Ref_Total_Expenditure
(267)Reference_Output
(268)Value_Share_of_Labor

(218)LR_Capital_Share
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(272)Normal_Capital'Energy_Aggr

.Economy.Allocation

Allocation of goods among climate impacts, energy production, investment, and consumption. Taxes do not appear here, as revenues are assumed to be recycled.



(147) `Consumption = max(0, Output_Net_of_Energy-Total_Invest_Req)`
$/year
Goods consumption.
(155)Output_Net_of_Energy
(156)Total_Invest_Req
(407)Consumption_Equiv_Loss
(244)Consumption_Growth_Rate
(460)Consumption_per_Cap

(148) `Energy_Invest_Req = SUM(Indicated_Energy_Capital_Completion_Rate[source!])`
$/year
Total goods required for energy investment.
(293)Indicated_Energy_Capital_Completion_Rate
(326)Total_Energy_Cost
(156)Total_Invest_Req

(149) `Fraction_of_Energy_Goods_Avail = MIN(1, Gross_Output / Indicated_Total_Cost_Energy_Production)`
dmnl
Availability of goods for energy sector investment and production.
(262)Gross_Output
(152)Indicated_Total_Cost_Energy_Production
(386)Energy_Capacity_Utilization
(326)Total_Energy_Cost

(150) `Fraction_of_Invest_Goods_Avail = MIN(1, Output_Net_of_Energy / Total_Invest_Req)`
dmnl
Fraction of desired investment goods available.
(155)Output_Net_of_Energy
(156)Total_Invest_Req
(284)Energy_Capital_Completion_Rate

(166)Investment_Rate
(326)Total_Energy_Cost

```
(151) Indicated_Energy_Distribution_Cost[source] =
        Init_Unit_Distribution_Cost[source] * Scheduled_Production[source]
```
$/year
Goods required for energy distribution, by source.
(344)Init_Unit_Distribution_Cost
(399)Scheduled_Production
(153)Indicated_Total_Energy_Dist_Cost

```
(152) Indicated_Total_Cost_Energy_Production =
        Indicated_Total_Energy_Dist_Cost +
        Indicated_Total_Energy_Variable_Cost
```
$/year
Total goods required for energy production and distribution.
(153)Indicated_Total_Energy_Dist_Cost
(154)Indicated_Total_Energy_Variable_Cost
(149)Fraction_of_Energy_Goods_Avail
(155)Output_Net_of_Energy
(326)Total_Energy_Cost

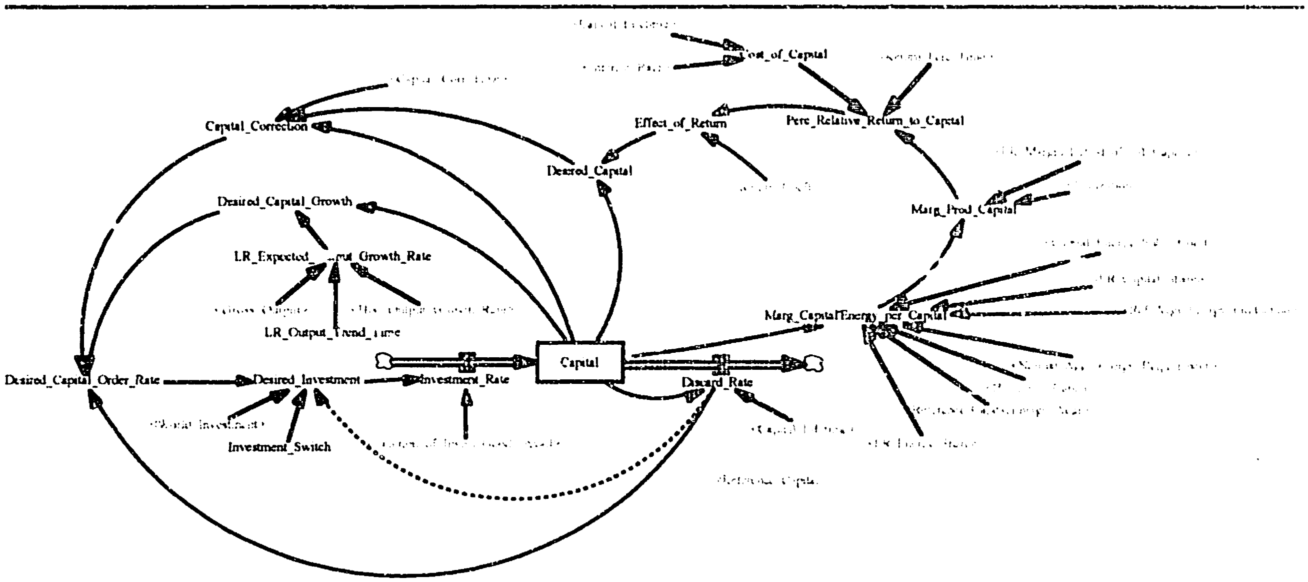
```
(153) Indicated_Total_Energy_Dist_Cost =
        SUM(Indicated_Energy_Distribution_Cost[source!])
```
$/year
Total goods required for energy distribution.
(151)Indicated_Energy_Distribution_Cost
(152)Indicated_Total_Cost_Energy_Production

```
(154) Indicated_Total_Energy_Variable_Cost =
        SUM(Desired_Variable_Input[source!])
```
$/year
Total goods required for variable costs of energy production.
(385)Desired_Variable_Input
(152)Indicated_Total_Cost_Energy_Production

```
(155) Output_Net_of_Energy = max(0, Gross_Output-
        Indicated_Total_Cost_Energy_Production)
```
$/year
Goods production less climate damages and energy production / distribution expenses. Available for consumption and investment.
(262)Gross_Output
(152)Indicated_Total_Cost_Energy_Production
(147)Consumption
(150)Fraction_of_Invest_Goods_Avail

```
(156) Total_Invest_Req = Desired_Investment + Energy_Invest_Req
```
$/year
Total investment required for goods and energy producing sectors.
(163)Desired_Investment
(148)Energy_Invest_Req
(147)Consumption
(150)Fraction_of_Invest_Goods_Avail

.Economy.Capital



(157) `Capital = INTEG ( Investment_Rate-Discard_Rate, Reference_Capital)`

$

Capital stock for goods production.

(164)Discard_Rate
(166)Investment_Rate
(227)Reference_Capital

(144)Embodied_AEEI
(138)AEEI_Retrofit_Rate
(142)Average_AEEI
(158)Capital_Correction
(160)Desired_Capital
(161)Desired_Capital_Growth
(164)Discard_Rate
(004)Emissions_Intensity_of_Capital
(211)Energy_Intensity_of_Capital
(269)Energy_Req_Retrofit_Rate
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(272)Normal_Capital'Energy_Aggr
(248)Total_Capital
(233)Total_Energy_Intensity

(158) `Capital_Correction = (Desired_Capital-Capital) / Capital_Corr_Time`

$/year

Rate of correction to capital.

(157)Capital
(278)Capital_Corr_Time
(160)Desired_Capital

(162)Desired_Capital_Order_Rate

(159) `Cost_of_Capital = Interest_Rate + 1 / Capital_Lifetime`

1/year

Cost of capital for investment decision.

(143)Capital_Lifetime

(255)Interest_Rate

(172)Perc_Relative_Return_to_Capital

(160) Desired_Capital = Capital * Effect_of_Return

$

Desired capital, anchored to existing capital stock and adjusted for return.

(157)Capital

(165)Effect_of_Return

(158)Capital_Correction

(161) Desired_Capital_Growth = Capital * LR_Expected_Output_Growth_Rate

$/year

Capital orders to meet expected growth in output. Since goods production (unlike energy production) is not order driven, there is no order trend to follow; output growth is used instead.

(157)Capital

(168)LR_Expected_Output_Growth_Rate

(162)Desired_Capital_Order_Rate

(162) Desired_Capital_Order_Rate = Capital_Correction + Discard_Rate + Desired_Capital_Growth

$/year

Desired capital order rate. Orders replace discards, provide for growth, and adjust capital stock to desired level.

(158)Capital_Correction

(161)Desired_Capital_Growth

(164)Discard_Rate

(163)Desired_Investment

(163) Desired_Investment = IF_THEN_ELSE(Investment_Switch = 1, max(0, Desired_Capital_Order_Rate), IF_THEN_ELSE(Investment_Switch = 2, Discard_Rate, World_Investment))

$/year

Desired investment rate in goods producing capital; switchable between endogenous, equilibrium, and exogenous drivers.

(162)Desired_Capital_Order_Rate

(164)Discard_Rate

(167)Investment_Switch

(133)World_Investment

(166)Investment_Rate

(156)Total_Invest_Req

(164) Discard_Rate = Capital / Capital_Lifetime

$/year

Goods producing capital discard rate.

(157)Capital

(143)Capital_Lifetime

(157)Capital

(162)Desired_Capital_Order_Rate

(163)Desired_Investment

(165) Effect_of_Return = Perc_Relative_Return_to_Capital ^ Return_Coeff

dmnl

Effect of perceived relative return on desired capital.

(172)Perc_Relative_Return_to_Capital

(173)Return_Coeff

(160)Desired_Capital

(166) `Investment_Rate = Desired_Investment * Fraction_of_Invest_Goods_Avail`
$/year
Investment rate. Constrained by availability of investment goods in extreme conditions.
(163)Desired_Investment
(150)Fraction_of_Invest_Goods_Avail
(157)Capital
(137)AEEI_Install_Rate
(213)Energy_Req_Install_Rate
(249)Total_Investment

(167) `Investment_Switch = 1`
dmnl
0 = exogenous 1 = endogenous 2 = equilibrium Switches investment rate between between endogenous, equilibrium, and exogenous drivers. In equilibrium case, capital orders just replace discards.
(163)Desired_Investment

(168) `LR_Expected_Output_Growth_Rate = TREND(Gross_Output, LR_Output_Trend_Time, Hist Output_Growth_Rate)`
1/year
Perceived long run trend in energy orders.
(262)Gross_Output
(254)Hist_Output_Growth_Rate
(169)LR_Output_Trend_Time
(161)Desired_Capital_Growth

(169) `LR_Output_Trend_Time = 5`
year
Time to establish long-term trend in output, for capital planning.
(168)LR_Expected_Output_Growth_Rate

(170) `Marg_Capital'Energy_per_Capital = Reference_Capital'Energy_Aggr * (LR_Capital_Share * (Capital / Reference_Capital) ^ Capital_Energy_Subst_Coeff + LR_Energy_Share * (Normal_Aggr_Energy_Requirement / Ref_Aggr_Energy_Production) ^ Capital_Energy_Subst_Coeff) ^ (1 / Capital_Energy_Subst_Coeff-1) * LR_Capital_Share * (Capital / Reference_Capital) ^ (Capital_Energy_Subst_Coeff-1) / Reference_Capital`
Eff$/$
Marginal output of capital-energy bundle per unit capital input.
(157)Capital
(204)Capital_Energy_Subst_Coeff
(218)LR_Capital_Share
(146)LR_Energy_Share
(224)Normal_Aggr_Energy_Requirement
(330)Ref_Aggr_Energy_Production
(227)Reference_Capital
(228)Reference_Capital'Energy_Aggr
(171)Marg_Prod_Capital

(171) `Marg_Prod_Capital = LR_Marginal_Prod_of_Eff_Capital * Marg_Capital'Energy_per_Capital * Utilization`
$/year/$
Marginal productivity of capital. In contrast to the energy sector formulation, utilization is considered here, as the goods producing sector is not order driven, and thus there is no separate production pressure effect.

(219)LR_Marginal_Prod_of_Eff_Capital
(170)Marg_Capital'Energy_per_Capital
(277)Utilization

(172)Perc_Relative_Return_to_Capital

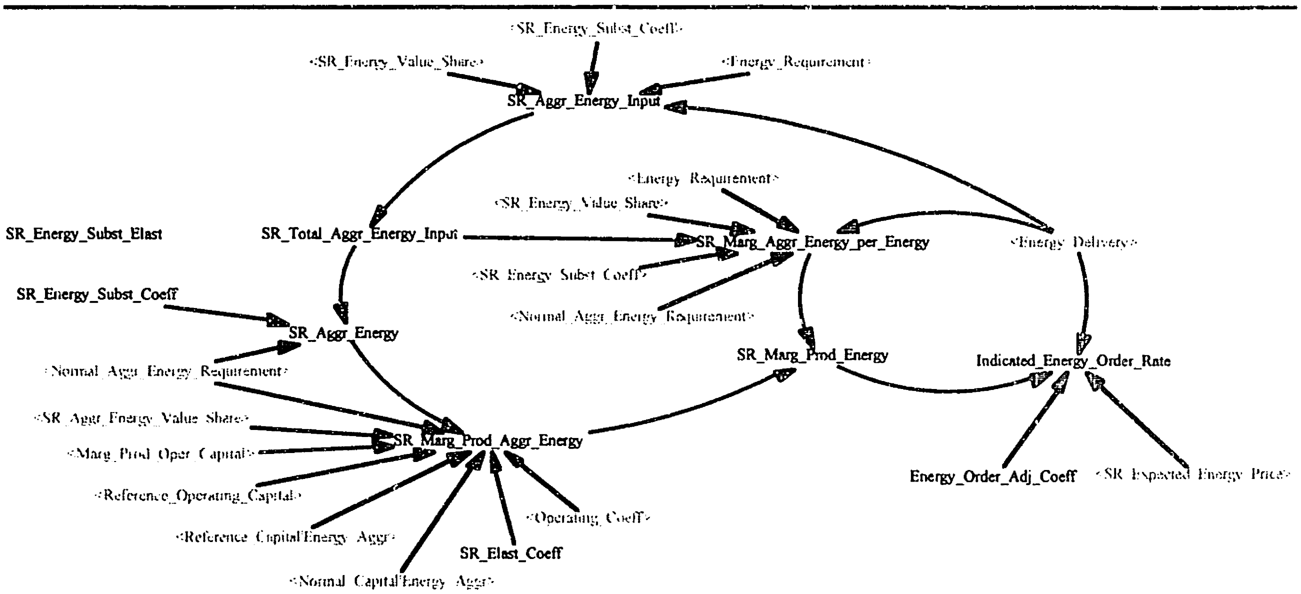
(172) Perc_Relative_Return_to_Capital = SMOOTHI(Marg_Prod_Capital / Cost_of_Capital, Return_Perc_Time, 1)
dmnl
Ratio of marginal productivity to cost of capital.
(159)Cost_of_Capital
(171)Marg_Prod_Capital
(301)Return_Perc_Time

(165)Effect_of_Return

(173) Return_Coeff = 1
dmnl
Coefficient of effect of relative return on desired capital.

(165)Effect_of_Return
(282)Effect_of_Return_on_Energy_Capital

.Economy.EnergyInput



(174) Energy_Order_Adj_Coeff = 0.1
dmnl
Coefficient of energy input adjustment in response to price / productivity imbalance. Really a behavioral parameter, but should be roughly equal to the short run own-price elasticity if agents know the slope of the short run production function.

(175)Indicated_Energy_Order_Rate

(175) Indicated_Energy_Order_Rate[source] = Energy_Delivery[source] * (SR_Marg_Prod_Energy[source] / SR_Expected_Energy_Price[source]) ^ Energy_Order_Adj_Coeff
GJ/year
Decision makers anchor on current energy consumption rate and adjust for relative price and marginal productivity. There is a very small error in energy ordering, as there is no trend extrapolation to compensate for the delivery delay.

(387)Energy_Delivery
(174)Energy_Order_Adj_Coeff
(199)SR_Expected_Energy_Price
(185)SR_Marg_Prod_Energy
(389)Energy_Order_Rate

```
(176) Operating_Coeff = (1-SR_Aggr_Energy_Value_Share) +
        SR_Aggr_Energy_Value_Share * (SR_Aggr_Energy /
        Normal_Aggr_Energy_Requirement) ^ SR_Elast_Coeff
```
dmnl
Coefficient of energy production capacity utilization, based on energy input relative to energy requirements.
(224)Normal_Aggr_Energy_Requirement
(177)SR_Aggr_Energy
(179)SR_Aggr_Energy_Value_Share
(180)SR_Elast_Coeff
(184)SR_Marg_Prod_Aggr_Energy
(277)Utilization

```
(177) SR_Aggr_Energy = Normal_Aggr_Energy_Requirement *
        SR_Total_Aggr_Energy_Input ^ (1 / SR_Energy_Subst_Coeff)
```
GJequiv/year
Output of the aggregate energy good.
(224)Normal_Aggr_Energy_Requirement
(181)SR_Energy_Subst_Coeff
(186)SR_Total_Aggr_Energy_Input
(003)Emissions_Intensity_of_Aggr_Energy
(176)Operating_Coeff
(184)SR_Marg_Prod_Aggr_Energy

```
(178) SR_Aggr_Energy_Input[source] = SR_Energy_Value_Share[source] *
        (Energy_Delivery[source] / Energy_Requirement[source]) ^
        SR_Energy_Subst_Coeff
```
dmnl
CES term for contribution of individual energy source to aggregate energy good.
(214)Energy_Requirement
(387)Energy_Delivery
(181)SR_Energy_Subst_Coeff
(276)SR_Energy_Value_Share
(186)SR_Total_Aggr_Energy_Input

```
(179) SR_Aggr_Energy_Value_Share = Marg_Capital'Energy_per_Aggr_Energy *
        Normal_Aggr_Energy_Requirement / Normal_Capital'Energy_Aggr
```
dmnl
Value share of each energy source in the short run CES aggregate energy good.
(271)Marg_Capital'Energy_per_Aggr_Energy
(224)Normal_Aggr_Energy_Requirement
(272)Normal_Capital'Energy_Aggr
(176)Operating_Coeff
(184)SR_Marg_Prod_Aggr_Energy

```
(180) SR_Elast_Coeff = INITIAL((SR_Elasticity-1) / SR_Elasticity)
```
dmnl
Short run CES coefficient of substitution between fixed capital and aggregate energy good.
(275)SR_Elasticity
(176)Operating_Coeff

(184)SR_Marg_Prod_Aggr_Energy
(277)Utilization

(181) SR_Energy_Subst_Coeff = INITIAL((SR_Energy_Subst_Elast-1) / SR_Energy_Subst_Elast)
dmnl
CES coefficient of subsitution among energy sources.
(182)SR_Energy_Subst_Elast
(177)SR_Aggr_Energy
(178)SR_Aggr_Energy_Input
(183)SR_Marg_Aggr_Energy_per_Energy

(182) SR_Energy_Subst_Elast = 0.2
dmnl
CES elasticity of substitution among energy sources.
(181)SR_Energy_Subst_Coeff

(183) SR_Marg_Aggr_Energy_per_Energy[source] = Normal_Aggr_Energy_Requirement / Energy_Requirement[source] * SR_Total_Aggr_Energy_Input ^ (1 / SR_Energy_Subst_Coeff-1) * (Energy_Delivery[source] / Energy_Requirement[source]) ^ (SR_Energy_Subst_Coeff-1) * SR_Energy_Value_Share[source]
GJequiv/GJ
Marginal output of the aggregate energy good per unit of physical energy input.
(214)Energy_Requirement
(387)Energy_Delivery
(224)Normal_Aggr_Energy_Requirement
(181)SR_Energy_Subst_Coeff
(276)SR_Energy_Value_Share
(186)SR_Total_Aggr_Energy_Input
(185)SR_Marg_Prod_Energy

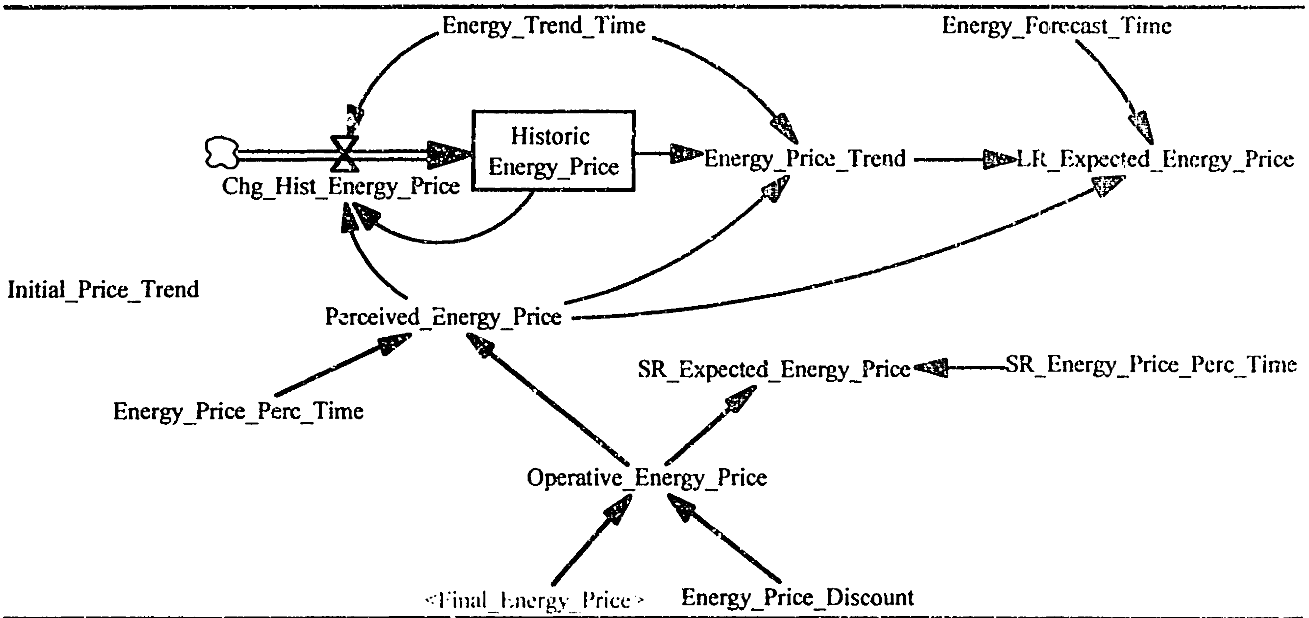
(184) SR_Marg_Prod_Aggr_Energy = Marg_Prod_Oper_Capital * Normal_Capital'Energy_Aggr / Normal_Aggr_Energy_Requirement * SR_Aggr_Energy_Value_Share * Operating_Coeff ^ (1 / SR_Elast_Coeff-1) * (SR_Aggr_Energy / Normal_Aggr_Energy_Requirement) ^ (SR_Elast_Coeff-1) * Reference_Operating_Capital / Reference_Capital'Energy_Aggr
$/GJequiv
Short run marginal productivity of aggregate energy good.
(263)Marg_Prod_Oper_Capital
(224)Normal_Aggr_Energy_Requirement
(272)Normal_Capital'Energy_Aggr
(176)Operating_Coeff
(228)Reference_Capital'Energy_Aggr
(266)Reference_Operating_Capital
(177)SR_Aggr_Energy
(179)SR_Aggr_Energy_Value_Share
(180)SR_Elast_Coeff
(185)SR_Marg_Prod_Energy

(185) SR_Marg_Prod_Energy[source] = SR_Marg_Aggr_Energy_per_Energy[source] * SR_Marg_Prod_Aggr_Energy
$/GJ
Short run marginal productivity of energy, by source.
(183)SR_Marg_Aggr_Energy_per_Energy

(184)SR_Marg_Prod_Aggr_Energy
(175)Indicated_Energy_Order_Rate

(186) SR_Total_Aggr_Energy_Input = SUM(SR_Aggr_Energy_Input[source!])
dmnl
Total contribution of CES terms for each energy source.
(178)SR_Aggr_Energy_Input
(177)SR_Aggr_Energy
(183)SR_Marg_Aggr_Energy_per_Energy

.Economy.EnergyPricePerception



(187) Chg_Hist_Energy_Price[source] = (Perceived_Energy_Price[source] - Historic_Energy_Price[source]) / Energy_Trend_Time
$/GJ/year
Rate of change of historic energy prices.
(193)Historic_Energy_Price
(192)Energy_Trend_Time
(197)Perceived_Energy_Price
(193)Historic_Energy_Price

(188) Energy_Forecast_Time = 10
year
Time horizon for energy price extrapolation.
(195)LR_Expected_Energy_Price

(189) Energy_Price_Discount = 1
dmnl
Discount or bias in energy price perception; 1 = normal (unbiased).
(196)Operative_Energy_Price
(333)Reference_Final_Expenditure

(190) Energy_Price_Perc_Time = 5
year
Time to smooth energy prices for long-run decisions.
(197)Perceived_Energy_Price

(191) `Energy_Price_Trend[source] = LN(Perceived_Energy_Price[source] / Historic_Energy_Price[source]) / Energy_Trend_Time`
1/year
Rate of change in energy prices.
(193)Historic_Energy_Price
(192)Energy_Trend_Time
(197)Perceived_Energy_Price
(195)LR_Expected_Energy_Price

(192) `Energy_Trend_Time = 10`
year
Time to establish energy price trends.
(193)Historic_Energy_Price
(187)Chg_Hist_Energy_Price
(191)Energy_Price_Trend

(193) `Historic_Energy_Price[source] = INTEG ( Chg_Hist_Energy_Price[source], Operative_Energy_Price[source] / exp(Initial_Price_Trend[source] * Energy_Trend_Time))`
$/GJ
Historic energy prices, for calculation of price trends.
(187)Chg_Hist_Energy_Price
(192)Energy_Trend_Time
(194)Initial_Price_Trend
(196)Operative_Energy_Price
(187)Chg_Hist_Energy_Price
(191)Energy_Price_Trend

(194) `Initial_Price_Trend[source] = 0`
1/year
Initial perceived trend in energy prices.
(193)Historic_Energy_Price

(195) `LR_Expected_Energy_Price[source] = Perceived_Energy_Price[source] * exp(Energy_Forecast_Time * Energy_Price_Trend[source])`
$/GJ
Long-run expected energy price, with perception delay and trend extrapolation.
(188)Energy_Forecast_Time
(191)Energy_Price_Trend
(197)Perceived_Energy_Price
(200)Adj_Energy_Intensity
(225)Normal_Energy_Expenditure

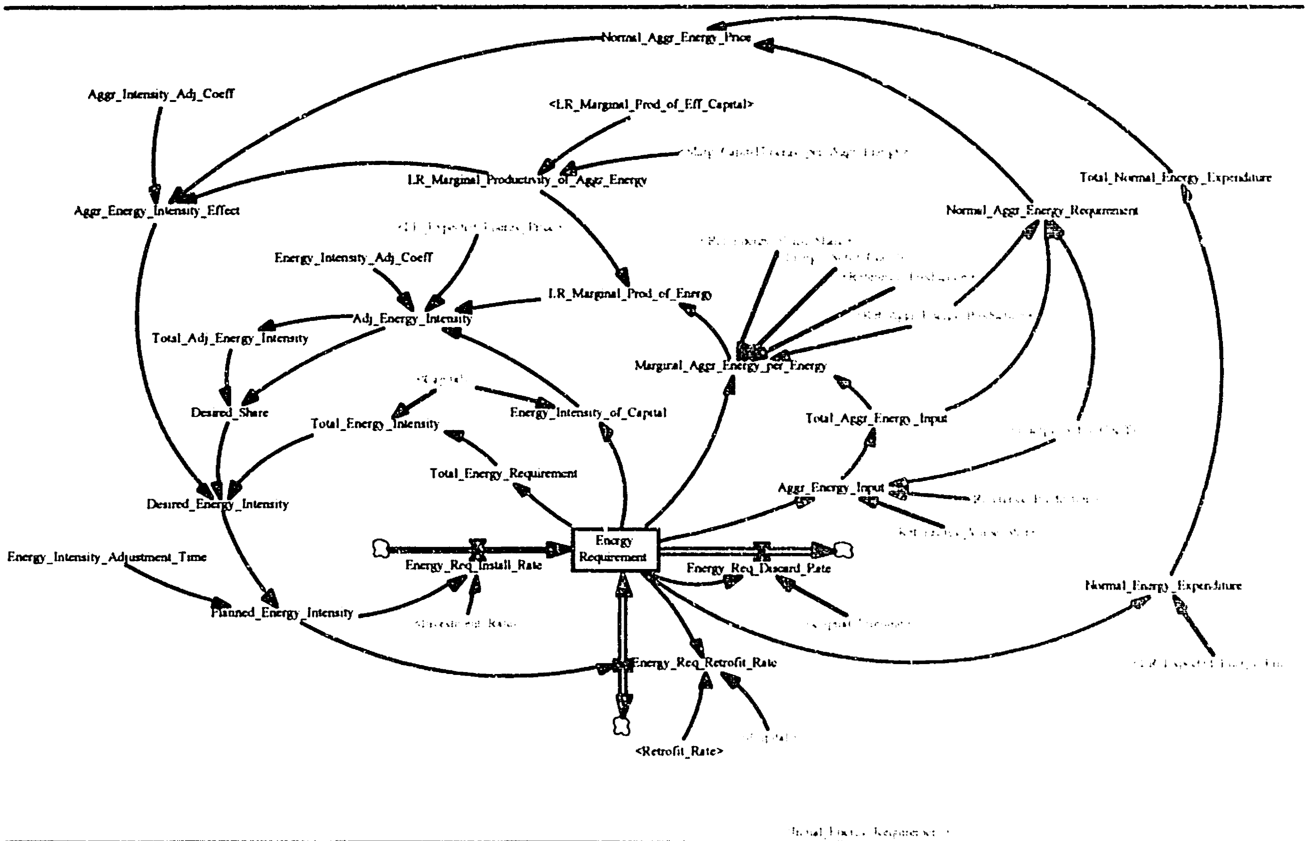
(196) `Operative_Energy_Price[source] = Final_Energy_Price[source] * Energy_Price_Discount`
$/GJ
Operative energy price for price perception. If availability switch is active, the operative energy price is the greater of the energy sector price or the short-run marginal product of energy in the economy. A systematic discount may be applied to the perceived price to represent systematic biases in energy price perception.
(189)Energy_Price_Discount
(342)Final_Energy_Price
(193)Historic_Energy_Price
(197)Perceived_Energy_Price
(199)SR_Expected_Energy_Price

(197) Perceived_Energy_Price[source] = SMOOTH(Operative_Energy_Price[source],
Energy_Price_Perc_Time)
$/GJ
Perceived energy price for long-run (energy intensity of capital) decisions.
(190)Energy_Price_Perc_Time
(196)Operative_Energy_Price
(187)Chg_Hist_Energy_Price
(191)Energy_Price_Trend
(195)LR_Expected_Energy_Price

(198) SR_Energy_Price_Perc_Time = 1
year
Time to perceive energy price for short-run (utilization) decisions.
(199)SR_Expected_Energy_Price

(199) SR_Expected_Energy_Price[source] =
SMOOTH(Operative_Energy_Price[source], SR_Energy_Price_Perc_Time)
$/GJ
Perceived energy price for short-run (utilization) decisions.
(196)Operative_Energy_Price
(198)SR_Energy_Price_Perc_Time
(175)Indicated_Energy_Order_Rate

.Economy.EnergyRequirement



(200) Adj_Energy_Intensity[source] = Energy_Intensity_of_Capital[source] *
(LR_Marginal_Prod_of_Energy[source] /
LR_Expected_Energy_Price[source]) ^ Energy_Intensity_Adj_Coeff

GJ/year/$

Desired energy intensity of new capital for fuel switching. Adjusted from current energy intensity of new capital according to perceived price / productivity gradient.

(209)Energy_Intensity_Adj_Coeff
(211)Energy_Intensity_of_Capital
(195)LR_Expected_Energy_Price
(220)LR_Marginal_Prod_of_Energy
(207)Desired_Share
(231)Total_Adj_Energy_Intensity

```
(201) Aggr_Energy_Input[source] = Ref_Energy_Value_Share[source] *
        (Energy_Requirement[source] / Reference_Production[source]) ^
        Energy_Subst_Coeff
```

dmnl

CES term for contribution of energy sources to aggregate energy good.

(214)Energy_Requirement
(215)Energy_Subst_Coeff
(331)Ref_Energy_Value_Share
(229)Reference_Production
(232)Total_Aggr_Energy_Input

```
(202) Aggr_Energy_Intensity_Effect = (LR_Marginal_Productivity_of_Aggr_Energy
        / Normal_Aggr_Energy_Price) ^ Aggr_Intensity_Adj_Coeff
```

dmnl

Effect of aggregate energy intensity on desired energy intensity of new capital.

(203)Aggr_Intensity_Adj_Coeff
(221)LR_Marginal_Productivity_of_Aggr_Energy
(223)Normal_Aggr_Energy_Price
(206)Desired_Energy_Intensity

```
(203) Aggr_Intensity_Adj_Coeff = INITIAL (Capital_Energy_Subst_Elast *
        Energy_Adj_Coeff)
```

dmnl

Coefficient of adjustment of aggregate energy intensity.

(205)Capital_Energy_Subst_Elast
(208)Energy_Adj_Coeff
(202)Aggr_Energy_Intensity_Effect

```
(204) Capital_Energy_Subst_Coeff = INITIAL((Capital_Energy_Subst_Elast-1) /
        Capital_Energy_Subst_Elast)
```

dmnl

CES coefficient of substitution in capital-energy aggregate.

(205)Capital_Energy_Subst_Elast
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(272)Normal_Capital'Energy_Aggr

```
(205) Capital_Energy_Subst_Elast = 0.75
```

dmnl

Elasticity of substitution between capital and aggregate energy good in capital-energy aggregate.

(203)Aggr_Intensity_Adj_Coeff
(204)Capital_Energy_Subst_Coeff

```
(206) Desired_Energy_Intensity[source] = Total_Energy_Intensity *
        Aggr_Energy_Intensity_Effect * Desired_Share[source]
```

GJ/year/$

Desired intensity of energy use for new capital, by source. Reflects rebalancing of aggregate energy intensity and fuel switching.
(202)Aggr_Energy_Intensity_Effect
(207)Desired_Share
(233)Total_Energy_Intensity
(226)Planned_Energy_Intensity

(207) Desired_Share[source] = Adj_Energy_Intensity[source] / Total_Adj_Energy_Intensity
dmnl
Desired share of energy sources in total energy intensity of capital.
(200)Adj_Energy_Intensity
(231)Total_Adj_Energy_Intensity
(206)Desired_Energy_Intensity

(208) Energy_Adj_Coeff = 0.33
dmnl
Ratio of actual adjustment in energy intensity to optimal adjustment. If value is 1, agents know the local slope of the long-run capital-energy and inter-energy production functions, and adjust desired energy intensities fully and immediately. If value is less than 1, adjustment is only partial, for behavioral or structural reasons.
(203)Aggr_Intensity_Adj_Coeff
(209)Energy_Intensity_Adj_Coeff

(209) Energy_Intensity_Adj_Coeff = INITIAL (Energy_Subst_Elast * Energy_Adj_Coeff)
dmnl
Coefficient of adjustment of fuel shares.
(208)Energy_Adj_Coeff
(216)Energy_Subst_Elast
(200)Adj_Energy_Intensity

(210) Energy_Intensity_Adjustment_Time = 4
years
Time required (for R&D, retooling, etc.) to adjust energy intensity of new capital
(226)Planned_Energy_Intensity

(211) Energy_Intensity_of_Capital[source] = Energy_Requirement[source] / Capital
GJ/year/$
Energy intensity of capital, by source.
(157)Capital
(214)Energy_Requirement
(200)Adj_Energy_Intensity

(212) Energy_Req_Discard_Rate[source] = Energy_Requirement[source] / Capital_Lifetime
GJ/year/year
Energy requirements of discarded capital. Co-flow with capital discards.
(214)Energy_Requirement
(143)Capital_Lifetime
(214)Energy_Requirement

(213) Energy_Req_Install_Rate[source] = Planned_Energy_Intensity[source] * Investment_Rate
GJ/year/year
Energy requirements of installed capital. Co-flow with investment.

(166)Investment_Rate
(226)Planned_Energy_Intensity
(214)Energy_Requirement

```
(214) Energy_Requirement[source] = INTEG ( Energy_Req_Install_Rate[source] +
        Energy_Req_Retrofit_Rate[source]-Energy_Req_Discard_Rate [source],
        Initial_Energy_Requirement[source])
```
GJ/year
Energy requirements embodied in capital stock.
(212)Energy_Req_Discard_Rate
(213)Energy_Req_Install_Rate
(269)Energy_Req_Retrofit_Rate
(217)Initial_Energy_Requirement
(201)Aggr_Energy_Input
(211)Energy_Intensity_of_Capital
(212)Energy_Req_Discard_Rate
(269)Energy_Req_Retrofit_Rate
(222)Marginal_Aggr_Energy_per_Energy
(225)Normal_Energy_Expenditure
(178)SR_Aggr_Energy_Input
(276)SR_Energy_Value_Share
(183)SR_Marg_Aggr_Energy_per_Energy
(234)Total_Energy_Requirement

```
(215) Energy_Subst_Coeff = INITIAL((Energy_Subst_Elast-1) /
        Energy_Subst_Elast)
```
dmnl
Long-run CES coefficient of subsitution among energy sources.
(216)Energy_Subst_Elast
(201)Aggr_Energy_Input
(222)Marginal_Aggr_Energy_per_Energy
(224)Normal_Aggr_Energy_Requirement

```
(216) Energy_Subst_Elast = 2
```
dmnl
Long-run CES elasticity of substitution among energy sources.
(209)Energy_Intensity_Adj_Coeff
(215)Energy_Subst_Coeff

```
(217) Initial_Energy_Requirement[source] = 5.67e+010, 6.28e+010, 6.4e+009,
        2.36e+007
```
GJ/year
Initial embodied energy requirements, by source. Oil, Gas: 4.53e+010, 1.75e+010
(214)Energy_Requirement

```
(218) LR_Capital_Share = 1-LR_Energy_Share
```
dmnl
CES value share of capital in capital-energy aggregate.
(146)LR_Energy_Share
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(272)Normal_Capital'Energy_Aggr

```
(219) LR_Marginal_Prod_of_Eff_Capital = Marg_Prod_Oper_Capital *
        Reference_Operating_Capital / Reference_Capital'Energy_Aggr
```
$/year/Eff$

Long run marginal productivity of capital-energy aggregate good; equals marginal productivity of operating capital multiplied by the ratio of operating to effective capital (i.e. utilization). Here the normal ratio of operating capital to the capital-energy aggregate is used, rather than the actual, since in the long run utilization can be expected to be normal.

(263)Marg_Prod_Oper_Capital
(228)Reference_Capital'Energy_Aggr
(266)Reference_Operating_Capital
(221)LR_Marginal_Productivity_of_Aggr_Energy
(171)Marg_Prod_Capital

```
(220) LR_Marginal_Prod_of_Energy[source] =
        LR_Marginal_Productivity_of_Aggr_Energy *
        Marginal_Aggr_Energy_per_Energy[source]
```
$/GJ

Long-run marginal productivity of energy, by source.

(221)LR_Marginal_Productivity_of_Aggr_Energy
(222)Marginal_Aggr_Energy_per_Energy
(200)Adj_Energy_Intensity

```
(221) LR_Marginal_Productivity_of_Aggr_Energy =
        LR_Marginal_Prod_of_Eff_Capital *
        Marg_Capital'Energy_per_Aggr_Energy
```
$/GJequiv

Long-run marginal productivity of aggregate energy good in capital-energy aggregate.

(219)LR_Marginal_Prod_of_Eff_Capital
(271)Marg_Capital'Energy_per_Aggr_Energy
(202)Aggr_Energy_Intensity_Effect
(220)LR_Marginal_Prod_of_Energy

```
(222) Marginal_Aggr_Energy_per_Energy[source] = Ref_Aggr_Energy_Production /
        Reference_Production[source] * Total_Aggr_Energy_Input ^ (1 /
        Energy_Subst_Coeff-1) * (Energy_Requirement[source] /
        Reference_Production[source]) ^ (Energy_Subst_Coeff-1) *
        Ref_Energy_Value_Share[source]
```
GJequiv/GJ

Marginal output of aggregate energy good per unit of physical energy input.

(214)Energy_Requirement
(215)Energy_Subst_Coeff
(330)Ref_Aggr_Energy_Production
(331)Ref_Energy_Value_Share
(229)Reference_Production
(232)Total_Aggr_Energy_Input
(220)LR_Marginal_Prod_of_Energy
(276)SR_Energy_Value_Share

```
(223) Normal_Aggr_Energy_Price = Total_Normal_Energy_Expenditure /
        Normal_Aggr_Energy_Requirement
```
$/GJequiv

Expected price of aggregate energy good, with normal capacity utilization.

(224)Normal_Aggr_Energy_Requirement
(235)Total_Normal_Energy_Expenditure
(202)Aggr_Energy_Intensity_Effect

```
(224) Normal_Aggr_Energy_Requirement = Ref_Aggr_Energy_Production *
        Total_Aggr_Energy_Input ^ (1 / Energy_Subst_Coeff)
```

GJequiv/year
Input of aggregate energy good, with normal capacity utilization.
(215)Energy_Subst_Coeff
(330)Ref_Aggr_Energy_Production
(232)Total_Aggr_Energy_Input
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(223)Normal_Aggr_Energy_Price
(272)Normal_Capital'Energy_Aggr
(176)Operating_Coeff
(177)SR_Aggr_Energy
(179)SR_Aggr_Energy_Value_Share
(276)SR_Energy_Value_Share
(183)SR_Marg_Aggr_Energy_per_Energy
(184)SR_Marg_Prod_Aggr_Energy

```
(225) Normal_Energy_Expenditure[source] = LR_Expected_Energy_Price[source] *
        Energy_Requirement[source]
```
$/year
Expected expenditures for energy, by source, with normal capacity utilization.
(214)Energy_Requirement
(195)LR_Expected_Energy_Price
(235)Total_Normal_Energy_Expenditure

```
(226) Planned_Energy_Intensity[source] =
        SMOOTH(Desired_Energy_Intensity[source],
        Energy_Intensity_Adjustment_Time)
```
GJ/year/$
Energy intensity of new capital; lags desired energy intensity due to lead time needed for R&D, retooling, etc.
(206)Desired_Energy_Intensity
(210)Energy_Intensity_Adjustment_Time
(213)Energy_Req_Install_Rate
(269)Energy_Req_Retrofit_Rate

```
(227) Reference_Capital = 1.22e+013
```
$
Reference capital stock, assuming 15 year lifetime. Alternate value: 1.5e13 with capital lifetime of 20 years
(157)Capital
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(272)Normal_Capital'Energy_Aggr
(228)Reference_Capital'Energy_Aggr

```
(228) Reference_Capital'Energy_Aggr = INITIAL(Reference_Capital *
        Reference_Productivity)
```
Eff$
Reference output of aggregate capital-energy good. (long-run CES capital-energy aggregate).
(227)Reference_Capital
(230)Reference_Productivity
(219)LR_Marginal_Prod_of_Eff_Capital
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(272)Normal_Capital'Energy_Aggr
(273)Operating_Capital

(266)Reference_Operating_Capital
(184)SR_Marg_Prod_Aggr_Energy

```
(229) Reference_Production[source] = 5.67e+010, 6.28e+010, 6.4e+009, 2.36e+007
```
GJ/year
Reference production of energy by source. Oil, gas: 4.53e+010, 1.75e+010
(201)Aggr_Energy_Input
(222)Marginal_Aggr_Energy_per_Energy

```
(230) Reference_Productivity = 1
```
Eff$/$
Reference productivity of capital (normal output of capital-energy aggregate per unit of capital input).
(228)Reference_Capital'Energy_Aggr

```
(231) Total_Adj_Energy_Intensity = SUM(Adj_Energy_Intensity[source!])
```
GJ/year/$
Sum of adjusted energy intensities for individual sources.
(200)Adj_Energy_Intensity
(207)Desired_Share

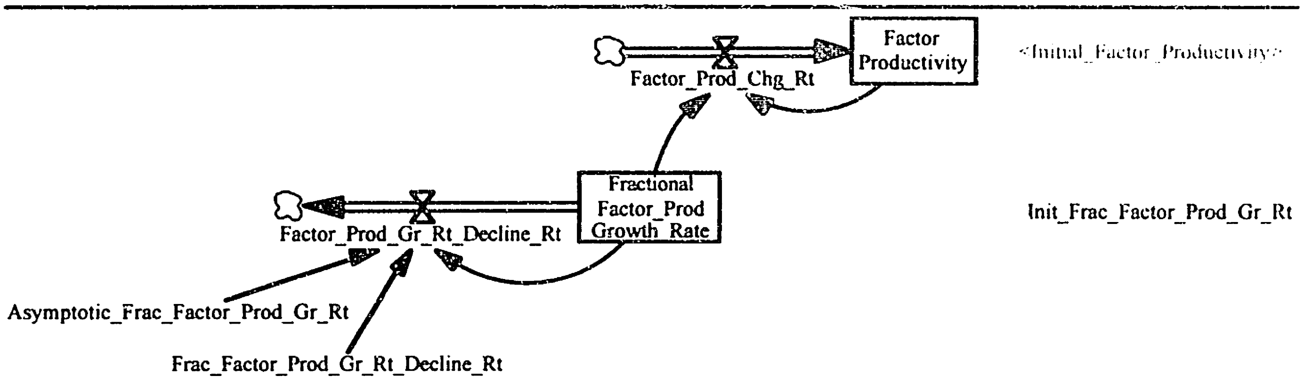
```
(232) Total_Aggr_Energy_Input = SUM(Aggr_Energy_Input[source!])
```
dmnl
Sum of CES terms for contribution of energy sources to aggregate energy good.
(201)Aggr_Energy_Input
(222)Marginal_Aggr_Energy_per_Energy
(224)Normal_Aggr_Energy_Requirement

```
(233) Total_Energy_Intensity = Total_Energy_Requirement / Capital
```
GJ/year/$
Total energy intensity of capital (in physical terms).
(157)Capital
(234)Total_Energy_Requirement
(206)Desired_Energy_Intensity

```
(234) Total_Energy_Requirement = SUM(Energy_Requirement[source!])
```
GJ/year
Total energy requirements embodied in capital (in physical terms).
(214)Energy_Requirement
(233)Total_Energy_Intensity

```
(235) Total_Normal_Energy_Expenditure =
        SUM(Normal_Energy_Expenditure[source!])
```
$/year
Total expected energy expenditures, with normal capacity utilization.
(225)Normal_Energy_Expenditure
(223)Normal_Aggr_Energy_Price

.Economy.FactorProductivity



(236) Asymptotic_Frac_Factor_Prod_Gr_Rt = 0.0075
1/year
Asymptotic rate of technological change.
(238)Factor_Prod_Gr_Rt_Decline_Rt

(237) Factor_Prod_Chg_Rt = Factor_Productivity * Fractional_Factor_Prod_Growth_Rate
1/year
Rate of change of autonomous technology.
(239)Factor_Productivity
(241)Fractional_Factor_Prod_Growth_Rate
(239)Factor_Productivity

(238) Factor_Prod_Gr_Rt_Decline_Rt = (Fractional_Factor_Prod_Growth_Rate - Asymptotic_Frac_Factor_Prod_Gr_Rt) * Frac_Factor_Prod_Gr_Rt_Decline_Rt
1/year/year
Rate at which the technology growth rate decays to its asymptotic value.
(241)Fractional_Factor_Prod_Growth_Rate
(236)Asymptotic_Frac_Factor_Prod_Gr_Rt
(240)Frac_Factor_Prod_Gr_Rt_Decline_Rt
(241)Fractional_Factor_Prod_Growth_Rate

(239) Factor_Productivity = INTEG (Factor_Prod_Chg_Rt, Initial_Factor_Productivity)
dmnl
Autonomous technology level.
(237)Factor_Prod_Chg_Rt
(243)Initial_Factor_Productivity
(237)Factor_Prod_Chg_Rt
(262)Gross_Output

(240) Frac_Factor_Prod_Gr_Rt_Decline_Rt = 0.01
1/year
Fractional rate of decline of the factor productivity growth rate.
(238)Factor_Prod_Gr_Rt_Decline_Rt

(241) Fractional_Factor_Prod_Growth_Rate = INTEG (- Factor_Prod_Gr_Rt_Decline_Rt, Init_Frac_Factor_Prod_Gr_Rt)
1/year
Relative rate of change of technology.
(238)Factor_Prod_Gr_Rt_Decline_Rt

(242)Init_Frac_Factor_Prod_Gr_Rt
(237)Factor_Prod_Chg_Rt
(238)Factor_Prod_Gr_Rt_Decline_Rt

(242) `Init_Frac_Factor_Prod_Gr_Rt = 0.015`
1/year
Initial fractional rate of technology growth.
(241)Fractional_Factor_Prod_Growth_Rate

(243) `Initial_Factor_Productivity = 1`
dmnl
Initial technology level.
(239)Factor_Productivity

.Economy.Indicators

(244) `Consumption_Growth_Rate = TREND(Consumption, Growth_Trend_Time, Hist_Output_Growth_Rate)`
1/year
Fractional rate of change of consumption.
(147)Consumption
(245)Growth_Trend_Time
(254)Hist_Output_Growth_Rate

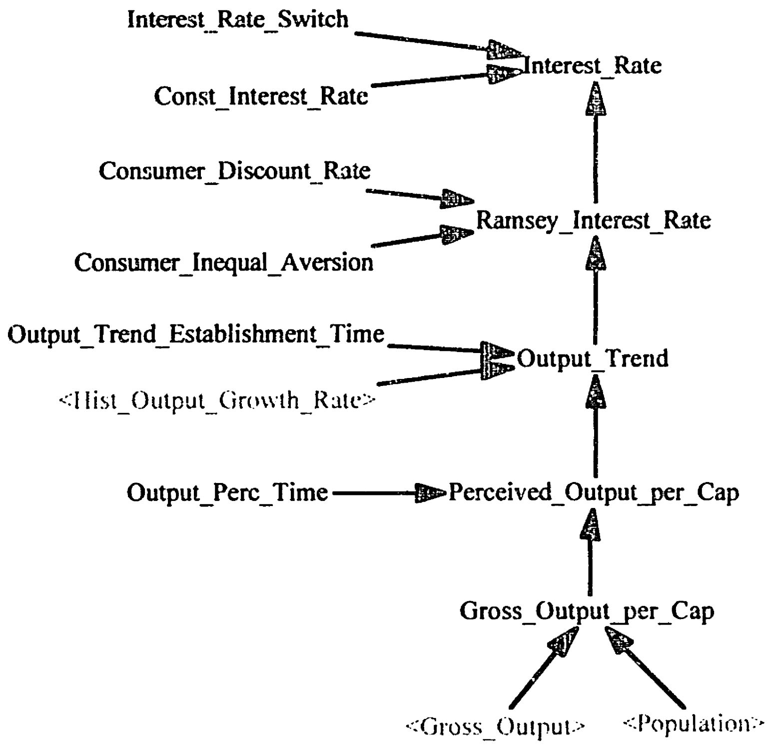
(245) `Growth_Trend_Time = 1`
year
Time for measuring consumption and output growth trends.
(244)Consumption_Growth_Rate
(246)Output_Growth_Rate

(246) `Output_Growth_Rate = TREND(Gross_Output, Growth_Trend_Time, Hist_Output_Growth_Rate)`
1/year
Fractional rate of change of gross output.
(262)Gross_Output
(245)Growth_Trend_Time
(254)Hist_Output_Growth_Rate

(247) `Savings_Rate = Total_Investment / Gross_Output`
dmnl
Fraction of output invested.
(262)Gross_Output
(249)Total_Investment

(248) `Total_Capital = Capital + Total_Energy_Capital`
$
Total capital in all sectors.
(157)Capital
(325)Total_Energy_Capital

(249) `Total_Investment = Investment_Rate + Total_Energy_Investment`
$/year
Investment in all sectors.
(166)Investment_Rate
(328)Total_Energy_Investment
(247)Savings_Rate



(250) `Const_Interest_Rate = 0.055`
1/year
Constant exogenous interest rate.
(255)Interest_Rate

(251) `Consumer_Discount_Rate = 0.03`
1/year
Effective discount rate for interest-rate setting.
(261)Ramsey_Interest_Rate

(252) `Consumer_Inequal_Aversion = 1`
dmnl
Effective elasticity of marginal utility (rate of inequality aversion) for interest-rate setting.
(261)Ramsey_Interest_Rate

(253) `Gross_Output_per_Cap = Gross_Output / Population`
$/person/year
Gross output of goods and services per capita.
(458)Population
(262)Gross_Output
(260)Perceived_Output_per_Cap

(254) `Hist_Output_Growth_Rate = 0.04`
1/year
Historic growth rate of output and investment.
(244)Consumption_Growth_Rate
(168)LR_Expected_Output_Growth_Rate
(246)Output_Growth_Rate
(258)Output_Trend

```
(255) Interest_Rate = Interest_Rate_Switch * Const_Interest_Rate + (1-
        Interest_Rate_Switch) * Ramsey_Interest_Rate
```
1/year
Interest rate, switchable between constant and endogenous inputs.
(250)Const_Interest_Rate
(256)Interest_Rate_Switch
(261)Ramsey_Interest_Rate
(412)Chg_Depletion_Rent
(159)Cost_of_Capital
(286)Energy_Capital_Cost
(420)Indicated_Depletion_Rent

```
(256) Interest_Rate_Switch = 0
```
dmnl
0 = Ramsey rule, 1 = constant interest rate. Switch for determining basis for interest rate calculation.
(255)Interest_Rate

```
(257) Output_Perc_Time = 5
```
year
Time to perceive output per capita.
(260)Perceived_Output_per_Cap

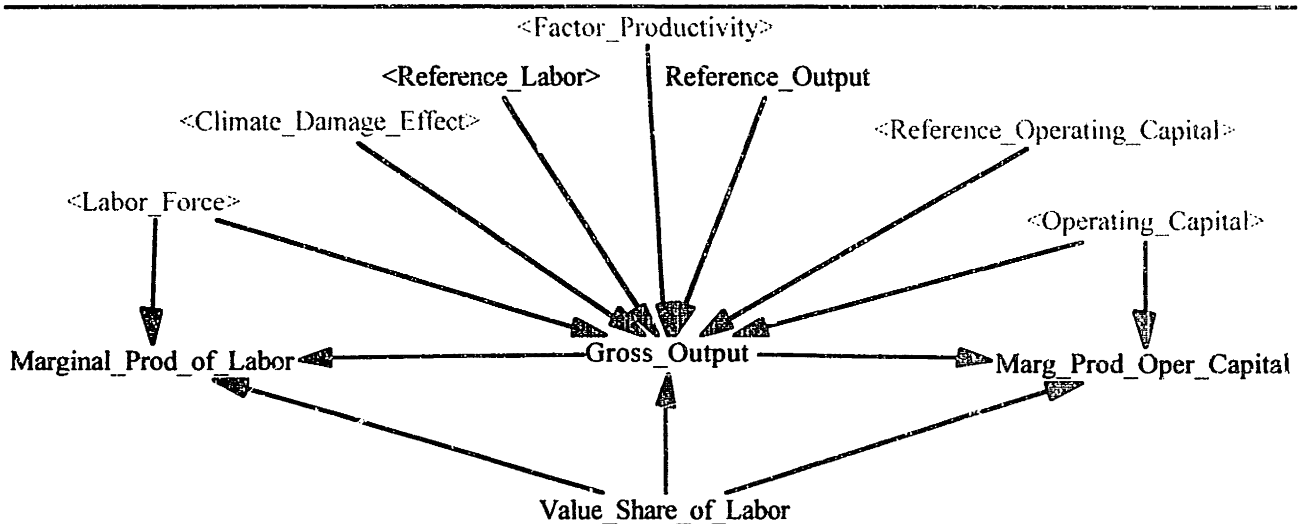
```
(258) Output_Trend = TREND(Perceived_Output_per_Cap,
        Output_Trend_Establishment_Time, Hist_Output_Growth_Rate)
```
1/year
Trend in per capita output.
(254)Hist_Output_Growth_Rate
(259)Output_Trend_Establishment_Time
(260)Perceived_Output_per_Cap
(261)Ramsey_Interest_Rate

```
(259) Output_Trend_Establishment_Time = 20
```
year
Time to establish output trends.
(258)Output_Trend

```
(260) Perceived_Output_per_Cap = SMOOTH(Gross_Output_per_Cap,
        Output_Perc_Time)
```
$/person/year
Perceived output per capita.
(253)Gross_Output_per_Cap
(257)Output_Perc_Time
(258)Output_Trend

```
(261) Ramsey_Interest_Rate = Output_Trend * Consumer_Inequal_Aversion +
        Consumer_Discount_Rate
```
1/year
Interest rate from Ramsey rule.
(251)Consumer_Discount_Rate
(252)Consumer_Inequal_Aversion
(258)Output_Trend
(255)Interest_Rate

.Economy.Output




```
(262) Gross_Output = Reference_Output * Factor_Productivity *
        Climate_Damage_Effect[Tangible] * (Labor_Force / Reference_Labor)
        ^ Value_Share_of_Labor * (Operating_Capital /
        Reference_Operating_Capital) ^ (1-Value_Share_of_Labor)
```

$/year

Production of goods. Goods output price is fixed at $1.

(239)Factor_Productivity
(404)Climate_Damage_Effect
(452)Labor_Force
(273)Operating_Capital
(265)Reference_Labor
(266)Reference_Operating_Capital
(267)Reference_Output
(268)Value_Share_of_Labor

(006)Emissions_Intensity_of_Output
(149)Fraction_of_Energy_Goods_Avail
(253)Gross_Output_per_Cap
(168)LR_Expected_Output_Growth_Rate
(263)Marg_Prod_Oper_Capital
(264)Marginal_Prod_of_Labor
(246)Output_Growth_Rate
(410)Output_Loss
(155)Output_Net_of_Energy
(247)Savings_Rate

```
(263) Marg_Prod_Oper_Capital = (1-Value_Share_of_Labor) * Gross_Output /
        Operating_Capital
```

$/year/Op$

Marginal productivity of operating capital; i.e. marginal output [production] per unit of operating capital (the short-run fixed capital-energy aggregate).

(262)Gross_Output
(273)Operating_Capital
(268)Value_Share_of_Labor

(219)LR_Marginal_Prod_of_Eff_Capital
(184)SR_Marg_Prod_Aggr_Energy

(264) Marginal_Prod_of_Labor = Value_Share_of_Labor * Gross_Output /
Labor_Force
$/year/FTE
Marginal productivity of labor.
(262)Gross_Output
(452)Labor_Force
(268)Value_Share_of_Labor

(265) Reference_Labor = INITIAL(Labor_Force)
FTE
Reference labor force.
(452)Labor_Force
(262)Gross_Output

(266) Reference_Operating_Capital = INITIAL(Reference_Operating_Ratio *
Reference_Capital'Energy_Aggr)
Op$
Reference operating capital (short run fixed capital-energy aggregate).
(228)Reference_Capital'Energy_Aggr
(274)Reference_Operating_Ratio
(262)Gross_Output
(219)LR_Marginal_Prod_of_Eff_Capital
(273)Operating_Capital
(184)SR_Marg_Prod_Aggr_Energy

(267) Reference_Output = 6.124e+012
$/year
Reference goods output.
(262)Gross_Output
(146)LR_Energy_Share

(268) Value_Share_of_Labor = 0.7
dmnl
Cobb-Douglas value share of labor in output.
(262)Gross_Output
(146)LR_Energy_Share
(263)Marg_Prod_Oper_Capital
(264)Marginal_Prod_of_Labor

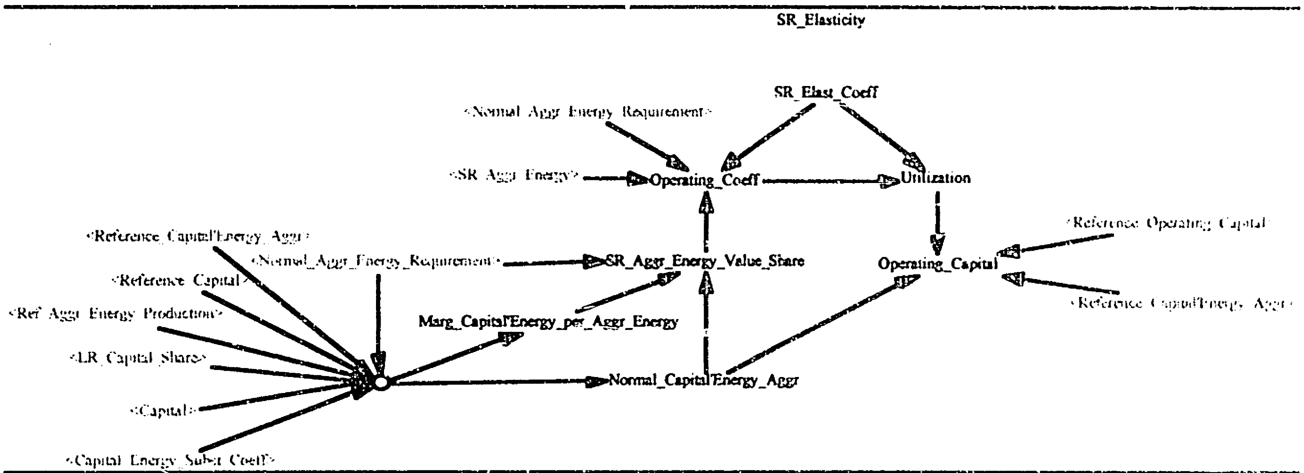
.Economy.Retrofit

(269) Energy_Req_Retrofit_Rate[source] = Capital * Retrofit_Rate *
Planned_Energy_Intensity[source]-Energy_Requirement[source] *
Retrofit_Rate
GJ/year/year
Rate of change of embodied energy requirements due to retrofits on existing capital.
(157)Capital
(214)Energy_Requirement
(226)Planned_Energy_Intensity
(270)Retrofit_Rate
(214)Energy_Requirement

(270) Retrofit_Rate = 0
1/year
Fractional rate of retrofit to existing capital.
(138)AEEI_Retrofit_Rate

(269)Energy_Req_Retrofit_Rate

.Economy.Utilization




```
(271) Marg_Capital'Energy_per_Aggr_Energy = Reference_Capital'Energy_Aggr *
        (LR_Capital_Share * (Capital / Reference_Capital) ^
        Capital_Energy_Subst_Coeff + LR_Energy_Share *
        (Normal_Aggr_Energy_Requirement / Ref_Aggr_Energy_Production) ^
        Capital_Energy_Subst_Coeff) ^ (1 / Capital_Energy_Subst_Coeff-1) *
        LR_Energy_Share * (Normal_Aggr_Energy_Requirement /
        Ref_Aggr_Energy_Production) ^ (Capital_Energy_Subst_Coeff-1) /
        Ref_Aggr_Energy_Production
```

*Eff$/GJequiv*year*

Marginal output of capital-energy aggregate per unit aggregate energy input.

(157)Capital
(204)Capital_Energy_Subst_Coeff
(218)LR_Capital_Share
(146)LR_Energy_Share
(224)Normal_Aggr_Energy_Requirement
(330)Ref_Aggr_Energy_Production
(227)Reference_Capital
(228)Reference_Capital'Energy_Aggr

(221)LR_Marginal_Productivity_of_Aggr_Energy
(179)SR_Aggr_Energy_Value_Share

```
(272) Normal_Capital'Energy_Aggr = Reference_Capital'Energy_Aggr *
        (LR_Capital_Share * (Capital / Reference_Capital) ^
        Capital_Energy_Subst_Coeff + LR_Energy_Share *
        (Normal_Aggr_Energy_Requirement / Ref_Aggr_Energy_Production) ^
        Capital_Energy_Subst_Coeff) ^ (1 / Capital_Energy_Subst_Coeff)
```

Eff$

Output of capital-energy aggregate good at normal capacity utilization.

(157)Capital
(204)Capital_Energy_Subst_Coeff
(218)LR_Capital_Share
(146)LR_Energy_Share
(224)Normal_Aggr_Energy_Requirement
(330)Ref_Aggr_Energy_Production

(227)Reference_Capital
(228)Reference_Capital'Energy_Aggr
(273)Operating_Capital
(179)SR_Aggr_Energy_Value_Share
(184)SR_Marg_Prod_Aggr_Energy

```
(273) Operating_Capital = Normal_Capital'Energy_Aggr * Utilization *
        Reference_Operating_Capital / Reference_Capital'Energy_Aggr
```
Op$
Operating capital. Equals the long-run CES capital-energy aggregate adjusted for short-run utilization (from variation of energy input).
(272)Normal_Capital'Energy_Aggr
(228)Reference_Capital'Energy_Aggr
(266)Reference_Operating_Capital
(277)Utilization
(262)Gross_Output
(263)Marg_Prod_Oper_Capital

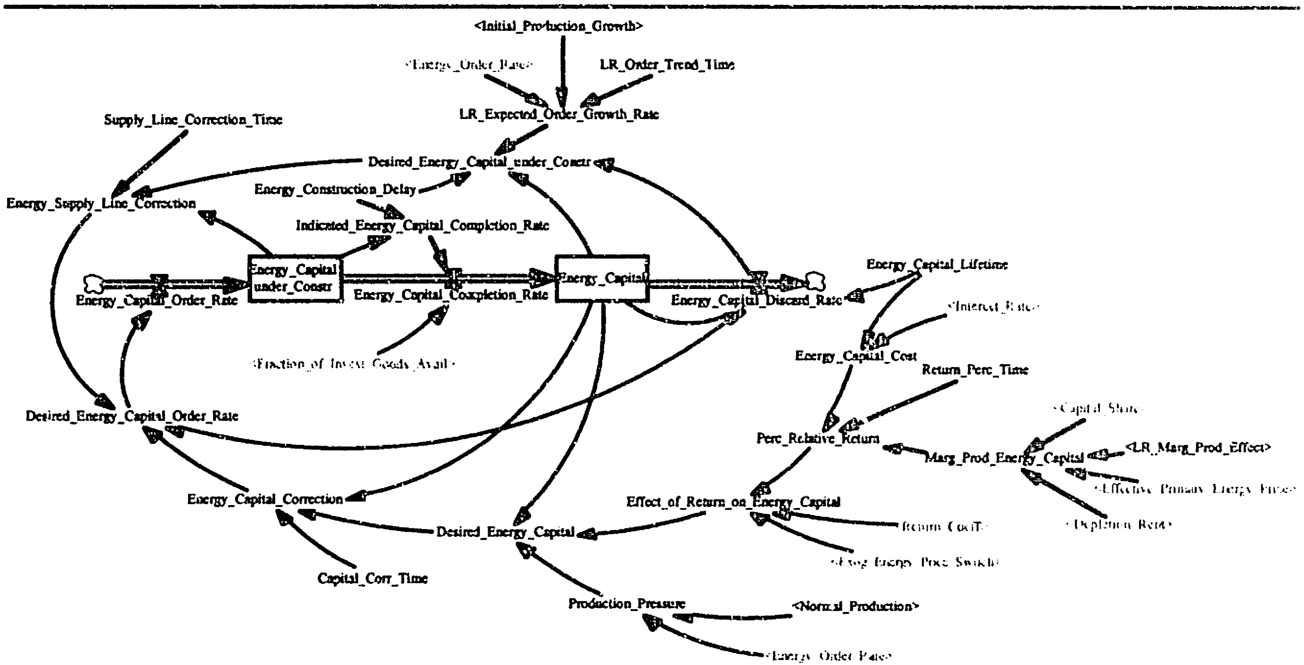
```
(274) Reference_Operating_Ratio = 1
```
Op$/Eff$
Reference ratio of operating capital to capital-energy aggregate.
(266)Reference_Operating_Capital

```
(275) SR_Elasticity = 0.1
```
dmnl
Short run elasticity of substitution between capital and aggregate energy input.
(180)SR_Elast_Coeff

```
(276) SR_Energy_Value_Share[source] = Energy_Requirement[source] *
        Marginal_Aggr_Energy_per_Energy[source] /
        Normal_Aggr_Energy_Requirement
```
dmnl
CES value share of aggregate energy good in capital-energy aggregate.
(214)Energy_Requirement
(222)Marginal_Aggr_Energy_per_Energy
(224)Normal_Aggr_Energy_Requirement
(178)SR_Aggr_Energy_Input
(183)SR_Marg_Aggr_Energy_per_Energy

```
(277) Utilization = Operating_Coeff ^ (1 / SR_Elast_Coeff)
```
dmnl
Utilization of capital-energy aggregate. Can be interpreted as capacity utilization in the goods producing sector (1 = normal).
(176)Operating_Coeff
(180)SR_Elast_Coeff
(171)Marg_Prod_Capital
(273)Operating_Capital

.Energy.Capital



(278) `Capital_Corr_Time = 4`

yr

Time to adjust capital stock.

(158)Capital_Correction
(285)Energy_Capital_Correction

(279) `Desired_Energy_Capital[source] = Energy_Capital[source] * Production_Pressure[source] * Effect_of_Return_on_Energy_Capital[source]`

$

Desired energy capital; equals current capital adjusted for production pressure and relative return.

(283)Energy_Capital
(282)Effect_of_Return_on_Energy_Capital
(352)Production_Pressure
(285)Energy_Capital_Correction

(280) `Desired_Energy_Capital_Order_Rate[source] = Energy_Capital_Discard_Rate[source] + Energy_Capital_Correction[source] + Energy_Supply_Line_Correction[source]`

$/year

Desired energy capital order rate; equals discard rate plus corrections for capital and supply line stocks.

(285)Energy_Capital_Correction
(287)Energy_Capital_Discard_Rate
(292)Energy_Supply_Line_Correction
(289)Energy_Capital_Order_Rate

(281) `Desired_Energy_Capital_under_Constr[source] = (Energy_Capital_Discard_Rate[source] +`

```
LR_Expected_Order_Growth_Rate[source] * Energy_Capital[source]) *
Energy_Construction_Delay[source]
```

$

Desired energy capital under construction; equals quantity needed to replace discards and meet growth.

(283)Energy_Capital
(287)Energy_Capital_Discard_Rate
(291)Energy_Construction_Delay
(295)LR_Expected_Order_Growth_Rate

(290)Energy_Capital_under_Constr
(292)Energy_Supply_Line_Correction

```
(282) Effect_of_Return_on_Energy_Capital[source] =
      Exog_Energy_Price_Switch[source] + (1-
      Exog_Energy_Price_Switch[source]) * Perc_Relative_Return[source] ^
      Return_Coeff
```

dmnl

Effect of relative return on desired energy capital. When exogenous energy prices are used, effect of return is switched off.

(340)Exog_Energy_Price_Switch
(299)Perc_Relative_Return
(173)Return_Coeff

(279)Desired_Energy_Capital

```
(283) Energy_Capital[source] = INTEG(Energy_Capital_Completion_Rate[source]-
      Energy_Capital_Discard_Rate[source],
      Reference_Energy_Capital[source])
```

$

Energy production capital stock. For fossil fuels, can be conceived of as developed fields or mines.

(284)Energy_Capital_Completion_Rate
(287)Energy_Capital_Discard_Rate
(300)Reference_Energy_Capital

(336)Capital_Cost
(279)Desired_Energy_Capital
(281)Desired_Energy_Capital_under_Constr
(385)Desired_Variable_Input
(285)Energy_Capital_Correction
(287)Energy_Capital_Discard_Rate
(373)Energy_Scale_Economy
(379)Init_Cum_Energy_Investment
(296)LR_Marg_Prod_Effect
(423)LR_Marginal_Cost_of_Energy_Prod
(347)Marginal_Variable_Input
(393)Max_Effective_Energy_Capital_Ratio
(312)Normal_Effective_Energy_Capital_Rati
o
(396)Normal_Variable_Cost
(325)Total_Energy_Capital

```
(284) Energy_Capital_Completion_Rate[source] =
      Indicated_Energy_Capital_Completion_Rate[source] *
      Fraction_of_Invest_Goods_Avail
```

$/yr

Rate of completion of capital under construction, constrained by availability of investment goods.

(150)Fraction_of_Invest_Goods_Avail
(293)Indicated_Energy_Capital_Completion_Rate
(368)Cumulative_Energy_Investment
(283)Energy_Capital
(290)Energy_Capital_under_Constr
(328)Total_Energy_Investment

(285) `Energy_Capital_Correction[source] = (Desired_Energy_Capital[source] - Energy_Capital[source]) / Capital_Corr_Time`
$/year
Rate of correction to energy capital stock.

(283)Energy_Capital
(278)Capital_Corr_Time
(279)Desired_Energy_Capital
(280)Desired_Energy_Capital_Order_Rate

(286) `Energy_Capital_Cost[source] = Interest_Rate + 1 / Energy_Capital_Lifetime[source]`
1/year
Price of capital, including interest and depreciation.

(288)Energy_Capital_Lifetime
(255)Interest_Rate
(336)Capital_Cost
(423)LR_Marginal_Cost_of_Energy_Prod
(299)Perc_Relative_Return
(300)Reference_Energy_Capital
(398)Relative_Variable_Intensity

(287) `Energy_Capital_Discard_Rate[source] = Energy_Capital[source] / Energy_Capital_Lifetime[source]`
$/year
Energy capital discard rate.

(283)Energy_Capital
(288)Energy_Capital_Lifetime
(283)Energy_Capital
(280)Desired_Energy_Capital_Order_Rate
(281)Desired_Energy_Capital_under_Constr

(288) `Energy_Capital_Lifetime[source] = 20, 20, 40, 30`
year
Lifetime of capital.

(286)Energy_Capital_Cost
(287)Energy_Capital_Discard_Rate
(379)Init_Cum_Energy_Investment

(289) `Energy_Capital_Order_Rate[source] = max(0, Desired_Energy_Capital_Order_Rate[source])`
$/yr
Energy capital order rate. Constrained to be nonnegative (no cancellations).

(280)Desired_Energy_Capital_Order_Rate
(290)Energy_Capital_under_Constr

(290) `Energy_Capital_under_Constr[source] = INTEG(Energy_Capital_Order_Rate[source]-`

```
        Energy_Capital_Completion_Rate[source],
        Desired_Energy_Capital_under_Constr[source])
```
$

Stock of energy capital under construction.

(281)Desired_Energy_Capital_under_Constr
(284)Energy_Capital_Completion_Rate
(289)Energy_Capital_Order_Rate
(292)Energy_Supply_Line_Correction
(293)Indicated_Energy_Capital_Completion_Rate

```
(291) Energy_Construction_Delay[source] = 10
```
yr

Time required to construct new energy capital (planning as well as physical construction and exploitation). Delay is unaffected by demand on the energy capital construction sectors, which are not explicitly modeled.

(281)Desired_Energy_Capital_under_Constr
(293)Indicated_Energy_Capital_Completion_Rate

```
(292) Energy_Supply_Line_Correction[source] =
        (Desired_Energy_Capital_under_Constr[source]-
        Energy_Capital_under_Constr[source]) / Supply_Line_Correction_Time
```
$/year

Correction to supply line of capital under construction.

(290)Energy_Capital_under_Constr
(281)Desired_Energy_Capital_under_Constr
(302)Supply_Line_Correction_Time
(280)Desired_Energy_Capital_Order_Rate

```
(293) Indicated_Energy_Capital_Completion_Rate[source] =
        Energy_Capital_under_Constr[source] /
        Energy_Construction_Delay[source]
```
$/year

Indicated rate of completion of energy capital on order.

(290)Energy_Capital_under_Constr
(291)Energy_Construction_Delay
(284)Energy_Capital_Completion_Rate
(148)Energy_Invest_Req

```
(294) Initial_Production_Growth[source] =
        INITIAL(Hist_Energy_Growth_Rate[source])
```
1/year

Initial growth rate of production; equal to historic rates.

(376)Hist_Energy_Growth_Rate
(295)LR_Expected_Order_Growth_Rate

```
(295) LR_Expected_Order_Growth_Rate[source] = TREND(Energy_Order_Rate[source],
        LR_Order_Trend_Time, Initial_Production_Growth[source])
```
1/year

Perceived long run trend in energy orders.

(389)Energy_Order_Rate
(294)Initial_Production_Growth
(297)LR_Order_Trend_Time
(281)Desired_Energy_Capital_under_Constr

```
(296) LR_Marg_Prod_Effect[source] = Normal_Production[source] /
        Energy_Capital[source] * Marginal_Resource_Effect[source]
```
GJ/$/year

Effect of long run factors on marginal productivity of energy capital. For nonrenewables, varies with depletion and technology. For renewables, varies with technology and saturation.

(283)Energy_Capital
(309)Marginal_Resource_Effect
(313)Normal_Production
(298)Marg_Prod_Energy_Capital

```
(297) LR_Order_Trend_Time = 5
```
year

Time to establish long-term trends in orders, for capital planning.

(295)LR_Expected_Order_Growth_Rate

```
(298) Marg_Prod_Energy_Capital[nonrenewable] = Capital_Share[nonrenewable] *
        (Effective_Primary_Energy_Price[nonrenewable]-
        Depletion_Rent[nonrenewable]) * LR_Marg_Prod_Effect[nonrenewable]

      Marg_Prod_Energy_Capital[Renewable] = Capital_Share[Renewable] *
        Effective_Primary_Energy_Price[Renewable] *
        LR_Marg_Prod_Effect[Renewable]
```
1/year

Marginal productivity of capital, incorporating effects of output price, depletion / exploitation / technology, and utilization.

(383)Capital_Share
(415)Depletion_Rent
(338)Effective_Primary_Energy_Price
(296)LR_Marg_Prod_Effect
(299)Perc_Relative_Return

```
(299) Perc_Relative_Return[source] = SMOOTHI(Marg_Prod_Energy_Capital[source]
        / Energy_Capital_Cost[source], Return_Perc_Time, 1)
```
dmnl

Perceived relative return to capital; equal to delayed ratio of marginal product to price of capital.

(286)Energy_Capital_Cost
(298)Marg_Prod_Energy_Capital
(301)Return_Perc_Time
(282)Effect_of_Return_on_Energy_Capital

```
(300) Reference_Energy_Capital[source] =
        INITIAL(Reference_Pretax_Expenditure[source] *
        Capital_Share[source] / Energy_Capital_Cost[source])
```
$

Reference capital stock for energy production.

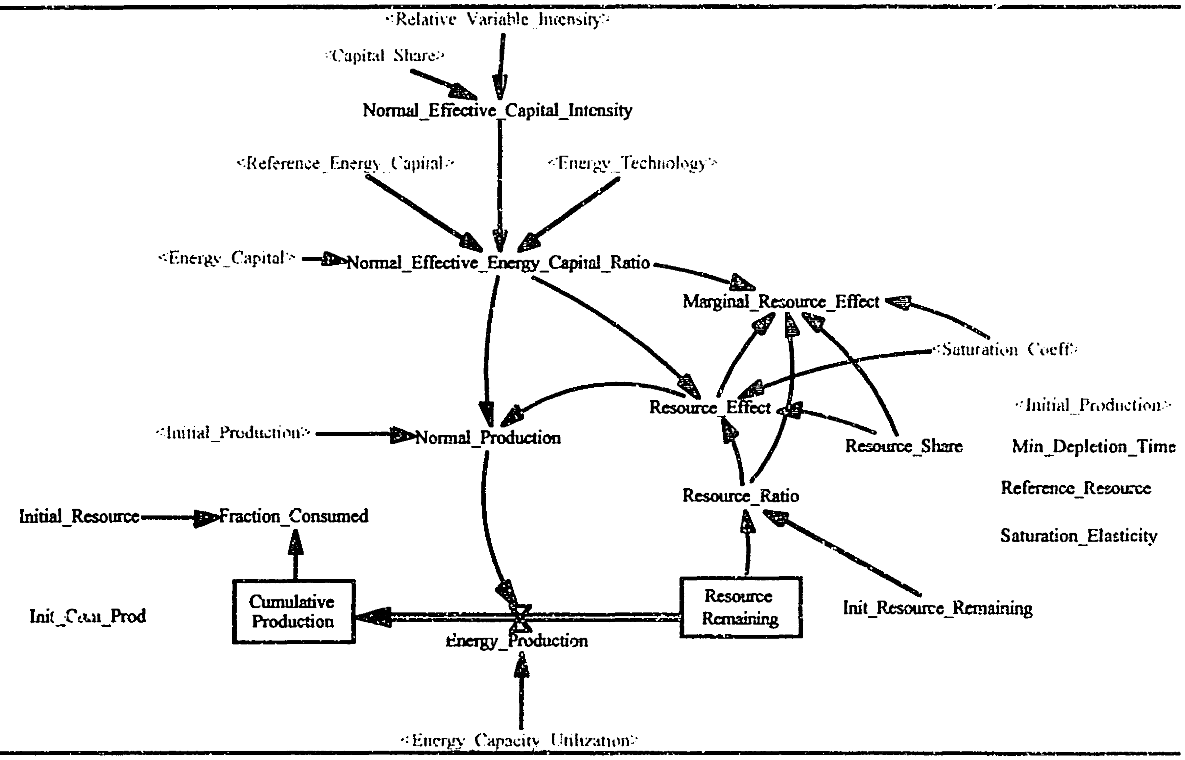
(383)Capital_Share
(286)Energy_Capital_Cost
(334)Reference_Pretax_Expenditure
(283)Energy_Capital
(385)Desired_Variable_Input
(373)Energy_Scale_Economy
(347)Marginal_Variable_Input
(393)Max_Effective_Energy_Capital_Ratio
(312)Normal_Effective_Energy_Capital_Ratio

(396)Normal_Variable_Cost
(398)Relative_Variable_Intensity

(301) Return_Perc_Time = 2
year
Time to perceive relative return on capital.
(299)Perc_Relative_Return
(172)Perc_Relative_Return_to_Capital

(302) Supply_Line_Correction_Time = 4
year
Time to adjust supply line of capital under construction.
(292)Energy_Supply_Line_Correction

.Energy.DepletionSaturation



(303) Cumulative_Production[nonrenewable] =
INTEG(Energy_Production[nonrenewable],
Init_Cum_Prod[nonrenewable])
GJ
Cumulative production of energy.
(390)Energy_Production
(306)Init_Cum_Prod
(304)Fraction_Consumed

(304) Fraction_Consumed[nonrenewable] = Cumulative_Production[nonrenewable] /
Initial_Resource[nonrenewable]
dmnl
Fraction of ultimate resource consumed.
(303)Cumulative_Production
(308)Initial_Resource

```
(305) Fraction_Exploited[Renewable] = Normal_Production[Renewable] /
        Reference_Resource[Renewable]
```
dmnl

Fraction of renewable resource potential exploited.

(313)Normal_Production
(314)Reference_Resource

```
(306) Init_Cum_Prod[nonrenewable] = INITIAL(Initial_Production[nonrenewable] /
        Hist_Energy_Growth_Rate[nonrenewable])
```
GJ

Initial cumulative production; "backstrapolated" using current production and historical growth rate.

(376)Hist_Energy_Growth_Rate
(391)Initial_Production

(303)Cumulative_Production
(307)Init_Resource_Remaining

```
(307) Init_Resource_Remaining[nonrenewable] = INITIAL (
        Initial_Resource[nonrenewable]-Init_Cum_Prod[nonrenewable])
```
GJ

Initial resource remaining.

(306)Init_Cum_Prod
(308)Initial_Resource

(317)Resource_Remaining
(424)Marginal_Resource_Eff_Energy_Capital_Ratio
(316)Resource_Ratio
(318)Resource_Share

```
(308) Initial_Resource[Coal] = 3e+014

      Initial_Resource[OilGas] = 3.05e+013
```
GJ

EMF-14 values (95th percentile). Alternate values: 4.34e+014, 2.51e+013

(304)Fraction_Consumed
(307)Init_Resource_Remaining

```
(309) Marginal_Resource_Effect[source] = (Resource_Share[source] *
        Resource_Ratio[source] ^ Resource_Coeff[source] + (1 -
        Resource_Share[source]) *
        Normal_Effective_Energy_Capital_Ratio[source] ^
        Resource_Coeff[source]) ^ (1 / Resource_Coeff[source] - 1) *
        Normal_Effective_Energy_Capital_Ratio[source] ^
        (Resource_Coeff[source] - 1) / Resource_Effect[source] { * (1 -
        Resource Share[source])}
```
dmnl

Marginal effect of depletion and saturation on productivity, expressed as ratio of marginal to average product, at normal utilization. The last term (in brackets) is omitted because the fixed factor (i.e. the resource endowment) is unremunerated.

(312)Normal_Effective_Energy_Capital_Ratio
(315)Resource_Effect
(316)Resource_Ratio
(318)Resource_Share
(319)Resource_Coeff

(335)Adjusted_Average_Cost
(296)LR_Marg_Prod_Effect

(310) `Min_Depletion_Time = 20`
year
Minimum time to deplete remaining nonrenewable resource
(318)Resource_Share

(311) `Normal_Effective_Capital_Intensity[source] =`
`Relative_Variable_Intensity[source] ^ (1-Capital_Share[source])`
dmnl
Ratio of current vs. initial ratio of output to capital. Output intensity varies as interest rate variations affect desired balance of capital and variable inputs.
(383)Capital_Share
(398)Relative_Variable_Intensity
(312)Normal_Effective_Energy_Capital_Ratio

(312) `Normal_Effective_Energy_Capital_Ratio[source] = Energy_Capital[source] /`
`Reference_Energy_Capital[source] * Energy_Technology[source] *`
`Normal_Effective_Capital_Intensity[source]`
dmnl
Ratio current vs. initial production effort, with adjustments for capital scale, technology, and varying input intensity.
(283)Energy_Capital
(375)Energy_Technology
(311)Normal_Effective_Capital_Intensity
(300)Reference_Energy_Capital
(423)LR_Marginal_Cost_of_Energy_Prod
(309)Marginal_Resource_Effect
(313)Normal_Production
(315)Resource_Effect

(313) `Normal_Production[source] = Initial_Production[source] *`
`Resource_Effect[source] *`
`Normal_Effective_Energy_Capital_Ratio[source]`
GJ/year
Energy production at normal utilization, incorporating effects of scale of effort, depletion (for nonrenewables), and saturation (for renewables).
(391)Initial_Production
(312)Normal_Effective_Energy_Capital_Ratio
(315)Resource_Effect
(336)Capital_Cost
(386)Energy_Capacity_Utilization
(390)Energy_Production
(305)Fraction_Exploited
(296)LR_Marg_Prod_Effect
(352)Production_Pressure

(314) `Reference_Resource[HN] = 1.28e+011`

`Reference_Resource[New] = 1.9e+012`
GJ/year
Upper limit to renewable output. Upper limit for HN based primarily on hydro endowment, with nuclear potential implicitly assumed to be politically limited.
(305)Fraction_Exploited
(318)Resource_Share

(315) `Resource_Effect[source] = (Resource_Share[source] *`
`Resource_Ratio[source] ^ Resource_Coeff[source] + (1 -`

```
        Resource_Share[source]) *
        Normal_Effective_Energy_Capital_Ratio[source] ^
        Resource_Coeff[source]) ^ (1 / Resource_Coeff[source]) /
        Normal_Effective_Energy_Capital_Ratio[source]
```

dmnl

Effect of depletion and saturation on average productivity of capital.

(312)Normal_Effective_Energy_Capital_Ratio
(316)Resource_Ratio
(318)Resource_Share
(319)Resource_Coeff

(309)Marginal_Resource_Effect
(313)Normal_Production

```
(316) Resource_Ratio[Renewable] = 1

      Resource_Ratio[nonrenewable] = Resource_Remaining[nonrenewable] /
            Init_Resource_Remaining[nonrenewable]
```

dmnl

Ratio of current to initial resource endowment. For renewables, this is by definition 1, as the resource size is unchanging. For nonrenewables, this equals the resource remaining expressed as a fraction of initial resource remaining.

(317)Resource_Remaining
(307)Init_Resource_Remaining

(384)Desired_Eff_Energy_Capital_Ratio
(346)Marginal_Eff_Energy_Capital_Ratio
(424)Marginal_Resource_Eff_Energy_Capital_Ratio
(309)Marginal_Resource_Effect
(395)Max_Production
(315)Resource_Effect

```
(317) Resource_Remaining[nonrenewable] = INTEG ( -
            Energy_Production[nonrenewable],
            Init_Resource_Remaining[nonrenewable])
```

GJ

Resources remaining.

(390)Energy_Production
(307)Init_Resource_Remaining

(316)Resource_Ratio

```
(318) Resource_Share[Renewable] = INITIAL ( (Reference_Resource[Renewable] /
            Initial_Production[Renewable]) ^ Resource_Coeff[Renewable])

      Resource_Share[nonrenewable] = INITIAL
            ((Init_Resource_Remaining[nonrenewable] / Min_Depletion_Time /
            Initial_Production[nonrenewable]) ^ Resource_Coeff[nonrenewable])
```

dmnl

Share of fixed factors (resource endowment) in renewable energy production; set such that upper limit to renewable output is at a specified level.

(307)Init_Resource_Remaining
(391)Initial_Production
(310)Min_Depletion_Time
(314)Reference_Resource
(319)Resource_Coeff

(384)Desired_Eff_Energy_Capital_Ratio
(346)Marginal_Eff_Energy_Capital_Ratio

(424)Marginal_Resource_Eff_Energy_Capital_Ratio
(309)Marginal_Resource_Effect
(395)Max_Production
(315)Resource_Effect

```
(319) Resource_Coeff[source] = INITIAL (
```

(Resource_Elasticity[source] - 1) / Resource_Elasticity[source])

dmnl

CES coefficient of substitution between fixed resource endowment and other inputs.

(320)Resource_Elasticity

(384)Desired_Eff_Energy_Capital_Ratio
(346)Marginal_Eff_Energy_Capital_Ratio
(424)Marginal_Resource_Eff_Energy_Capital_Ratio
(309)Marginal_Resource_Effect
(395)Max_Production
(315)Resource_Effect
(318)Resource_Share

```
(320) Resource_Elasticity[nonrenewable] = 0.7

      Resource_Elasticity[Renewable] = 0.5
```

dmnl

Elasticity of substitution between fixed factors and capital for renewable sources, for saturation effect.

(319)Resource_Coeff

.Energy.Indicators

```
(321) Availability[source] = Energy_Production[source] /
          Energy_Order_Rate[source]
```

dmnl

Relative availability of energy sources, expressed as a fraction of orders.

(389)Energy_Order_Rate
(390)Energy_Production

```
(322) Avg_Energy_Price = Total_Energy_Expenditure / Total_Energy_Production
```

$/GJ

Average energy price, weighted by physical energy production rates.

(327)Total_Energy_Expenditure
(400)Total_Energy_Production

```
(323) Primary_Energy_Order_Rate = SUM(Energy_Order_Rate[source!])
```

GJ/year

Order rate of primary energy in physical terms.

(389)Energy_Order_Rate

```
(324) Production_Share[source] = Energy_Production[source] /
          Total_Energy_Production
```

dmnl

Share of energy sources in total production (in physical terms).

(390)Energy_Production
(400)Total_Energy_Production

```
(325) Total_Energy_Capital = SUM(Energy_Capital[source!])
```

$
Total energy capital for all sources.
(283)Energy_Capital
(248)Total_Capital

(326) Total_Energy_Cost = Indicated_Total_Cost_Energy_Production * Fraction_of_Energy_Goods_Avail + Energy_Invest_Req * Fraction_of_Invest_Goods_Avail
$/year
Total outlays for variable costs of energy production and investment in energy capital.
(148)Energy_Invest_Req
(149)Fraction_of_Energy_Goods_Avail
(150)Fraction_of_Invest_Goods_Avail
(152)Indicated_Total_Cost_Energy_Production

(327) Total_Energy_Expenditure = SUM(Source_Expenditure[source!])
$/year
Total expenditure on energy, calculated in monetary terms (price x quantity).
(353)Source_Expenditure
(322)Avg_Energy_Price

(328) Total_Energy_Investment = SUM(Energy_Capital_Completion_Rate[source!])
$/year
Total investment in all energy producing capital.
(284)Energy_Capital_Completion_Rate
(249)Total_Investment

.Energy.Initialization

(329) Exog_Order_Switch = 0
dmnl
0 = endogenous 1 = exogenous (production data) Switches energy orders between data and endogenous drivers.
(389)Energy_Order_Rate

(330) Ref_Aggr_Energy_Production = 1.26e+011
GJequiv/year
Reference production of CES aggregate energy good.
(271)Marg_Capital'Energy_per_Aggr_Energy
(170)Marg_Capital'Energy_per_Capital
(222)Marginal_Aggr_Energy_per_Energy
(224)Normal_Aggr_Energy_Requirement
(272)Normal_Capital'Energy_Aggr

(331) Ref_Energy_Value_Share[Coal] = 0.185

Ref_Energy_Value_Share[OilGas] = 1-Ref_Energy_Value_Share[Coal] - Ref_Energy_Value_Share[HN]-Ref_Energy_Value_Share[New]

Ref_Energy_Value_Share[HN] = 0.216

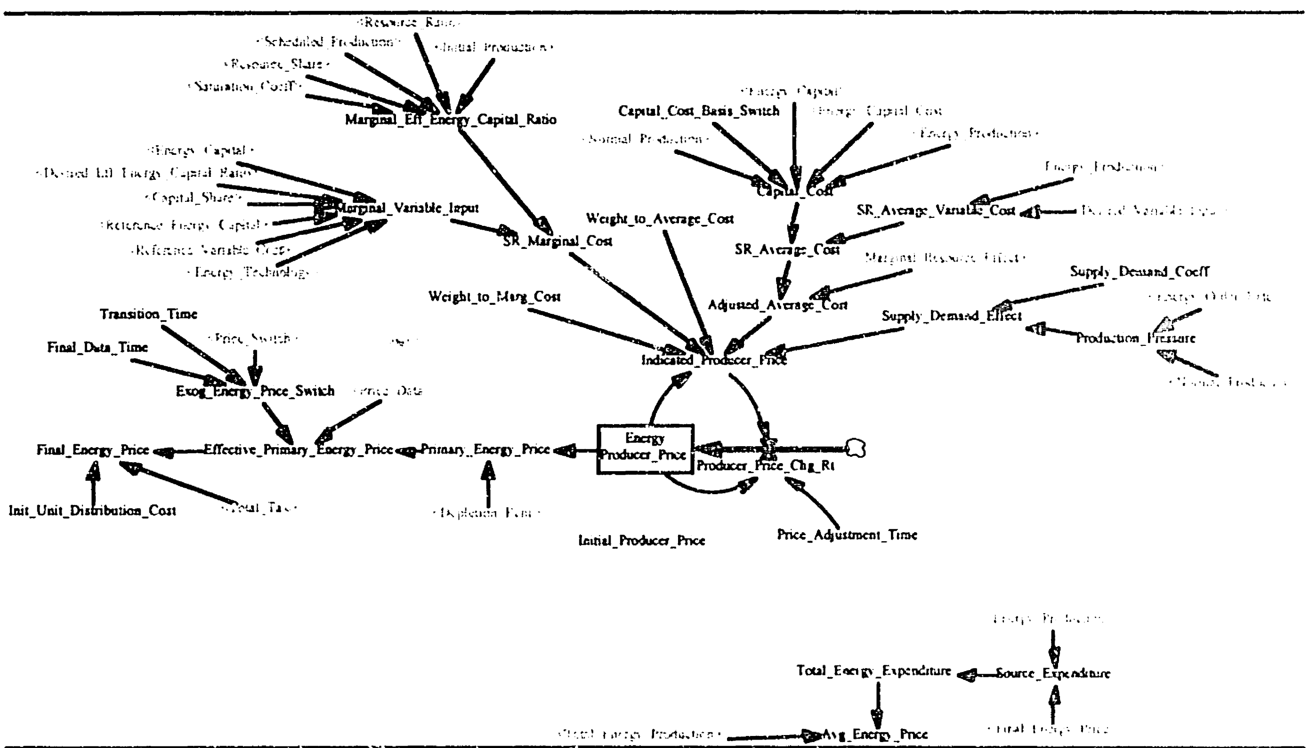
Ref_Energy_Value_Share[New] = 0.0101
dmnl
Reference CES value share of energy sources.
(201)Aggr_Energy_Input
(222)Marginal_Aggr_Energy_per_Energy

```
(332) Ref_Total_Expenditure =
        INITIAL(SUM(Reference_Final_Expenditure[source!]))
```
$/year
Reference total energy expenditure.
(333)Reference_Final_Expenditure
(146)LR_Energy_Share

```
(333) Reference_Final_Expenditure[source] = INITIAL (
        Final_Energy_Price[source] * Initial_Production[source] *
        Energy_Price_Discount)
```
$/year
Reference energy expenditure by source, including taxes and distribution costs.
(189)Energy_Price_Discount
(342)Final_Energy_Price
(391)Initial_Production
(332)Ref_Total_Expenditure

```
(334) Reference_Pretax_Expenditure[source] =
        INITIAL(Initial_Production[source] *
        Initial_Producer_Price[source])
```
$/year
Reference energy expenditure by source, excluding taxes and distribution costs.
(345)Initial_Producer_Price
(391)Initial_Production
(300)Reference_Energy_Capital
(397)Reference_Variable_Cost

.Energy.Pricing




```
(335) Adjusted_Average_Cost[source] = SR_Average_Cost[source] /
        Marginal_Resource_Effect[source]
```

$/GJ
Average cost of energy production, adjusted for long run (resource) effects on marginal cost, but not short run (utilization) effects.
(309)Marginal_Resource_Effect
(354)SR_Average_Cost
(343)Indicated_Producer_Price

```
(336) Capital_Cost[source] = (Energy_Capital_Cost[source] *
        Energy_Capital[source]) / (Capical_Cost_Basis_Switch *
        Energy_Production[source] + (1 - Capital_Cost_Basis_Switch) *
        Normal_Production[source])
```
$/GJ
Unit capital cost, on the basis of production (leads to utility death spiral) or normal production (leads to nonrecovery of capital costs with low demand).
(283)Energy_Capital
(337)Capital_Cost_Basis_Switch
(286)Energy_Capital_Cost
(390)Energy_Production
(313)Normal_Production
(354)SR_Average_Cost

```
(337) Capital_Cost_Basis_Switch = 0
```
dmnl
Basis for calculating unit capital costs. 0 = normal production (nonrecovery of capital costs with low demand) 1 = actual production (allows utility death spiral)
(336)Capital_Cost

```
(338) Effective_Primary_Energy_Price[source] =
        Exog_Energy_Price_Switch[source] * Price_Data[source] + (1-
        Exog_Energy_Price_Switch[source]) * Primary_Energy_Price[source]
```
$/GJ
Primary energy price, switchable between endogenous and exogenous drivers.
(340)Exog_Energy_Price_Switch
(116)Price_Data
(350)Primary_Energy_Price
(342)Final_Energy_Price
(298)Marg_Prod_Energy_Capital

```
(339) Energy_Producer_Price[source] = INTEG(Producer_Price_Chg_Rt[source],
        Initial_Producer_Price[source])
```
$/GJ
Endogenous primary energy price; adjusts to indicated price with a delay.
(345)Initial_Producer_Price
(351)Producer_Price_Chg_Rt
(343)Indicated_Producer_Price
(350)Primary_Energy_Price
(351)Producer_Price_Chg_Rt

```
(340) Exog_Energy_Price_Switch[source] = Price_Switch[source] * (1-RAMP(1 /
        Transition_Time, Final_Data_Time, Final_Data_Time +
        Transition_Time))
```
dmnl
Switch between exogenous and endogenous energy prices and capacity planning. Units error in RAMP is a Vensim bug.
(341)Final_Data_Time
(349)Price_Switch

(359)Transition_Time
(416)Depletion_Rent_Correction
(282)Effect_of_Return_on_Energy_Capital
(338)Effective_Primary_Energy_Price

```
(341) Final_Data_Time = 1990
```
year
Year in which transition from price data to endogenous prices begins.
(340)Exog_Energy_Price_Switch

```
(342) Final_Energy_Price[source] = Effective_Primary_Energy_Price[source] +
        Total_Tax[source] + Init_Unit_Distribution_Cost[source]
```
$/GJ
Price of energy sources, including taxes and distribution costs.
(338)Effective_Primary_Energy_Price
(344)Init_Unit_Distribution_Cost
(446)Total_Tax
(196)Operative_Energy_Price
(333)Reference_Final_Expenditure
(353)Source_Expenditure

```
(343) Indicated_Producer_Price[source] = Energy_Producer_Price[source] *
        Supply_Demand_Effect[source] * (SR_Marginal_Cost[source] /
        Energy_Producer_Price[source]) ^ Weight_to_Marg_Cost *
        (Adjusted_Average_Cost[source] / Energy_Producer_Price[source]) ^
        Weight_to_Average_Cost
```
$/GJ
Indicated price of energy sources, prior to taxes and distribution costs. Switchable between marginal and average cost prices.
(339)Energy_Producer_Price
(335)Adjusted_Average_Cost
(356)SR_Marginal_Cost
(358)Supply_Demand_Effect
(360)Weight_to_Average_Cost
(361)Weight_to_Marg_Cost
(351)Producer_Price_Chg_Rt

```
(344) Init_Unit_Distribution_Cost[source] = 0
```
$/GJ
Initial unit energy distribution cost.
(342)Final_Energy_Price
(151)Indicated_Energy_Distribution_Cost

```
(345) Initial_Producer_Price[source] = 1.278, 1.297, 6.648, 60
```
$/GJ
Initial prices of energy. From price data series. Oil, gas: 1.145, 1.69, weighted by initial production.
(339)Energy_Producer_Price
(334)Reference_Pretax_Expenditure

```
(346) Marginal_Eff_Energy_Capital_Ratio[source] =
        (((Scheduled_Production[source] / Initial_Production[source]) ^
        Resource_Coeff[source] - Resource_Share[source] *
        Resource_Ratio[source] ^ Resource_Coeff[source]) / (1 -
        Resource_Share[source])) ^ (1 / Resource_Coeff[source] - 1) *
        (Scheduled_Production[source] / Initial_Production[source]) ^
```

```
(Resource_Coeff[source] - 1) / Initial_Production[source] / (1 -
Resource_Share[source])
```
year/GJ
Marginal increase in capital-variable aggregate per unit increase in production.
(391)Initial_Production
(316)Resource_Ratio
(318)Resource_Share
(319)Resource_Coeff
(399)Scheduled_Production
(356)SR_Marginal_Cost

```
(347) Marginal_Variable_Input[source] = Reference_Variable_Cost[source] *
      ((Desired_Eff_Energy_Capital_Ratio[source] /
      Energy_Technology[source]) / (Energy_Capital[source] /
      Reference_Energy_Capital[source]) ^ Capital_Share[source]) ^ (1 /
      (1-Capital_Share[source])-1) / Energy_Technology[source] /
      (Energy_Capital[source] / Reference_Energy_Capital[source]) ^
      Capital_Share[source] * (1 / (1-Capital_Share[source]))
```
$/year
Marginal variable cost per unit increase in capital-variable aggregate.
(283)Energy_Capital
(383)Capital_Share
(384)Desired_Eff_Energy_Capital_Ratio
(375)Energy_Technology
(300)Reference_Energy_Capital
(397)Reference_Variable_Cost
(356)SR_Marginal_Cost

```
(348) Price_Adjustment_Time = 1
```
year
Time to adjust energy prices. Reflects delays in behavior as well as contract turnover and regulatory adjustment times.
(351)Producer_Price_Chg_Rt

```
(349) Price_Switch[nonrenewable] = 1

      Price_Switch[Renewable] = 0
```
dmnl
0 = endogenous, 1 = exogenous Switches between endogenous and exogenous price drivers.
(340)Exog_Energy_Price_Switch

```
(350) Primary_Energy_Price[nonrenewable] = Energy_Producer_Price[nonrenewable]
      + Depletion_Rent[nonrenewable]

      Primary_Energy_Price[Renewable] = Energy_Producer_Price[Renewable]
```
$/GJ
Price of primary energy, including depletion rent.
(339)Energy_Producer_Price
(415)Depletion_Rent
(338)Effective_Primary_Energy_Price

```
(351) Producer_Price_Chg_Rt[source] = (Indicated_Producer_Price[source]-
      Energy_Producer_Price[source]) / Price_Adjustment_Time
```
$/GJ/year
Rate of adjustment of energy price.
(339)Energy_Producer_Price
(343)Indicated_Producer_Price

(348)Price_Adjustment_Time
(339)Energy_Producer_Price

(352) Production_Pressure[source] = Energy_Order_Rate[source] / Normal_Production[source]
dmnl
Production pressure, expressed as ratio of orders to normal production.
(389)Energy_Order_Rate
(313)Normal_Production
(279)Desired_Energy_Capital
(358)Supply_Demand_Effect

(353) Source_Expenditure[source] = Final_Energy_Price[source] * Energy_Production[source]
$/year
Energy expenditures, by source.
(390)Energy_Production
(342)Final_Energy_Price
(327)Total_Energy_Expenditure

(354) SR_Average_Cost[source] = SR_Average_Variable_Cost[source] + Capital_Cost[source]
$/GJ
Indicated price of energy on the basis of average variable cost and capital cost, scaled to reflect demand pressure.
(336)Capital_Cost
(355)SR_Average_Variable_Cost
(335)Adjusted_Average_Cost

(355) SR_Average_Variable_Cost[source] = Desired_Variable_Input[source] / Energy_Production[source]
$/GJ
Short run average variable cost of energy production.
(385)Desired_Variable_Input
(390)Energy_Production
(354)SR_Average_Cost

(356) SR_Marginal_Cost[source] = Marginal_Variable_Input[source] * Marginal_Eff_Energy_Capital_Ratio[source]
$/GJ
Short run marginal cost of energy production.
(346)Marginal_Eff_Energy_Capital_Ratio
(347)Marginal_Variable_Input
(343)Indicated_Producer_Price

(357) Supply_Demand_Coeff = 2
dmnl
Coefficient of production pressure effect on average cost price.
(358)Supply_Demand_Effect

(358) Supply_Demand_Effect[source] = Production_Pressure[source] ^ Supply_Demand_Coeff
dmnl
Effect of production pressure (demand / supply ratio) on average cost price.
(352)Production_Pressure
(357)Supply_Demand_Coeff
(343)Indicated_Producer_Price

(359) Transition_Time = 5
years
Time for transition between exogenous and endogenous energy prices.
(340)Exog_Energy_Price_Switch

(360) Weight_to_Average_Cost = 1
dmnl
Weight to average cost in price calculation.
(343)Indicated_Producer_Price

(361) Weight_to_Marg_Cost = 0
dmnl
Weight to short run marginal cost in price setting.
(343)Indicated_Producer_Price

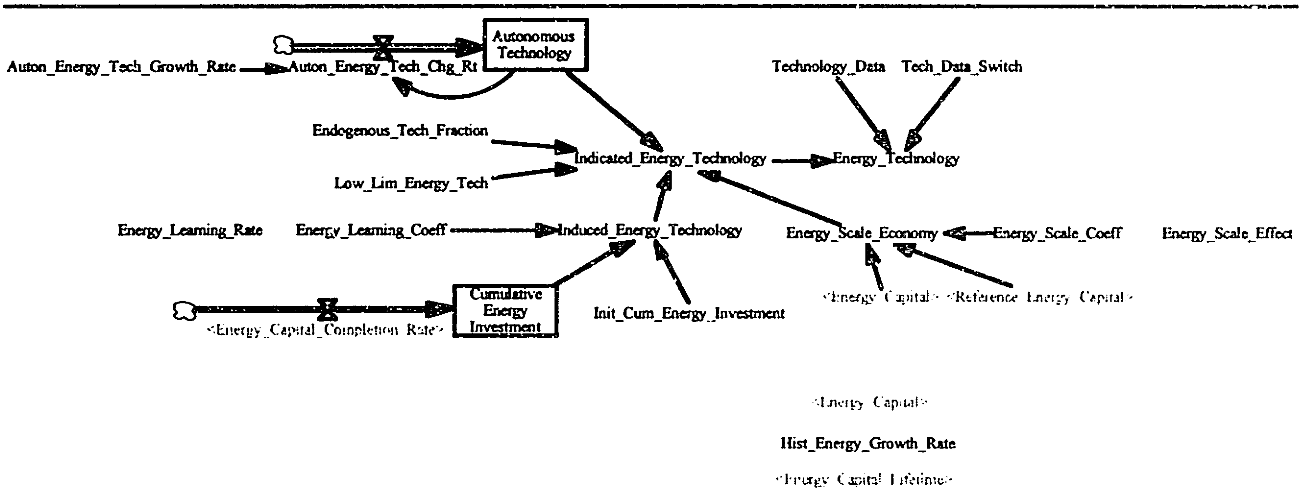
.Energy.Sources

(362) nonrenewable : Coal, OilGas
Nonrenewable energy sources.

(363) Renewable : HN, New
Renewable energy sources.

(364) source : Coal, OilGas, HN, New
Energy sources. Coal represents coal and similar solid fuels. OilGas represents oil, gas, and natural gas liquids. HN = hydro / nuclear aggregate; New = new renewables (solar, wind, biomass, etc.).

.Energy.Technology



(365) Auton_Energy_Tech_Chg_Rt[source] = Autonomous_Technology[source] *
Auton_Energy_Tech_Growth_Rate[source]
1/year
Rate of autonomous technological improvement.
(367)Autonomous_Technology
(366)Auton_Energy_Tech_Growth_Rate
(367)Autonomous_Technology

(366) Auton_Energy_Tech_Growth_Rate[source] = 0.01, 0.01, 0.01, 0.05
1/year

Fractional rate of autonomous energy technology improvement.
(365)Auton_Energy_Tech_Chg_Rt

```
(367) Autonomous_Technology[source] = INTEG (
        Auton_Energy_Tech_Chg_Rt[source], 1)
```
dmnl
Effect of autonomous technological improvement on energy technology level.
(365)Auton_Energy_Tech_Chg_Rt
(365)Auton_Energy_Tech_Chg_Rt
(377)Indicated_Energy_Technology

```
(368) Cumulative_Energy_Investment[source] = INTEG (
        Energy_Capital_Completion_Rate[source],
        Init_Cum_Energy_Investment[source])
```
$
Cumulative investment in energy capital; drives learning process.
(284)Energy_Capital_Completion_Rate
(379)Init_Cum_Energy_Investment
(378)Induced_Energy_Technology

```
(369) Endogenous_Tech_Fraction = 1
```
dmnl
Weight of induced technology in aggregate technological change (0 = completely autonomous; 1 = completely induced).
(377)Indicated_Energy_Technology

```
(370) Energy_Learning_Coeff = INITIAL ( -LOG(Energy_Learning_Rate, 2))
```
dmnl
Coefficient of learning curve effect.
(371)Energy_Learning_Rate
(378)Induced_Energy_Technology

```
(371) Energy_Learning_Rate = 0.8
```
dmnl
Coefficient of induced technological change, expressed as a standard learning rate. 1 = no learning; .7 to .9 typical.
(370)Energy_Learning_Coeff

```
(372) Energy_Scale_Coeff = INITIAL ( -LOG(Energy_Scale_Effect, 2))
```
dmnl
Coefficient of energy scale economy effect.
(374)Energy_Scale_Effect
(373)Energy_Scale_Economy

```
(373) Energy_Scale_Economy[source] = (Energy_Capital[source] /
        Reference_Energy_Capital[source]) ^ Energy_Scale_Coeff
```
dmnl
Cost-reducing economies of scale in energy production.
(283)Energy_Capital
(372)Energy_Scale_Coeff
(300)Reference_Energy_Capital
(377)Indicated_Energy_Technology

```
(374) Energy_Scale_Effect = 1
```
dmnl
Cost reducing returns to scale in energy production. 1 = constant returns. Expressed in same terms as learning coefficient - cost reduction per doubling of scale - so a value of .8 implies 20% cost reduction for a doubling of scale.

(372)Energy_Scale_Coeff

(375) `Energy_Technology[source] = (1 - Tech_Data_Switch) * Indicated_Energy_Technology[source] + Tech_Data_Switch * Technology_Data[source]`

dmnl

Energy technology level, switchable between exogenous (data from another run) and endogenous drivers.

(377)Indicated_Energy_Technology
(381)Tech_Data_Switch
(382)Technology_Data

(385)Desired_Variable_Input
(347)Marginal_Variable_Input
(393)Max_Effective_Energy_Capital_Ratio
(312)Normal_Effective_Energy_Capital_Rati
o

(376) `Hist_Energy_Growth_Rate[source] = 0.02, 0.06, 0.02, 0.06`

1/year

Historic growth rate of energy production, for estimating initial cumulative production stocks. Relatively unimportant, as recent history dominates cumulative production. Oil: 1938-1960, Coal 1960-1970, Gas 1960-1970, HN, 1925-1960, New arbitrary.

(379)Init_Cum_Energy_Investment
(306)Init_Cum_Prod
(294)Initial_Production_Growth

(377) `Indicated_Energy_Technology[source] = 1 / (Low_Lim_Energy_Tech[source] + (1-Low_Lim_Energy_Tech[source]) / Induced_Energy_Technology[source] ^ Endogenous_Tech_Fraction / Autonomous_Technology[source] ^ (1-Endogenous_Tech_Fraction) / Energy_Scale_Economy[source])`

dmnl

Indicated energy technology level, including effect of lower bound to cost reduction from technological improvement.

(367)Autonomous_Technology
(369)Endogenous_Tech_Fraction
(373)Energy_Scale_Economy
(378)Induced_Energy_Technology
(380)Low_Lim_Energy_Tech

(375)Energy_Technology

(378) `Induced_Energy_Technology[source] = (Cumulative_Energy_Investment[source] / Init_Cum_Energy_Investment[source]) ^ Energy_Learning_Coeff`

dmnl

Effect of learning on energy technology.

(368)Cumulative_Energy_Investment
(370)Energy_Learning_Coeff
(379)Init_Cum_Energy_Investment

(377)Indicated_Energy_Technology

(379) `Init_Cum_Energy_Investment[source] = INITIAL(Energy_Capital[source] / Energy_Capital_Lifetime[source] / Hist_Energy_Growth_Rate[source])`

$

Initial cumulative energy investment; "backstrapolated" using current capital and historical growth rate.

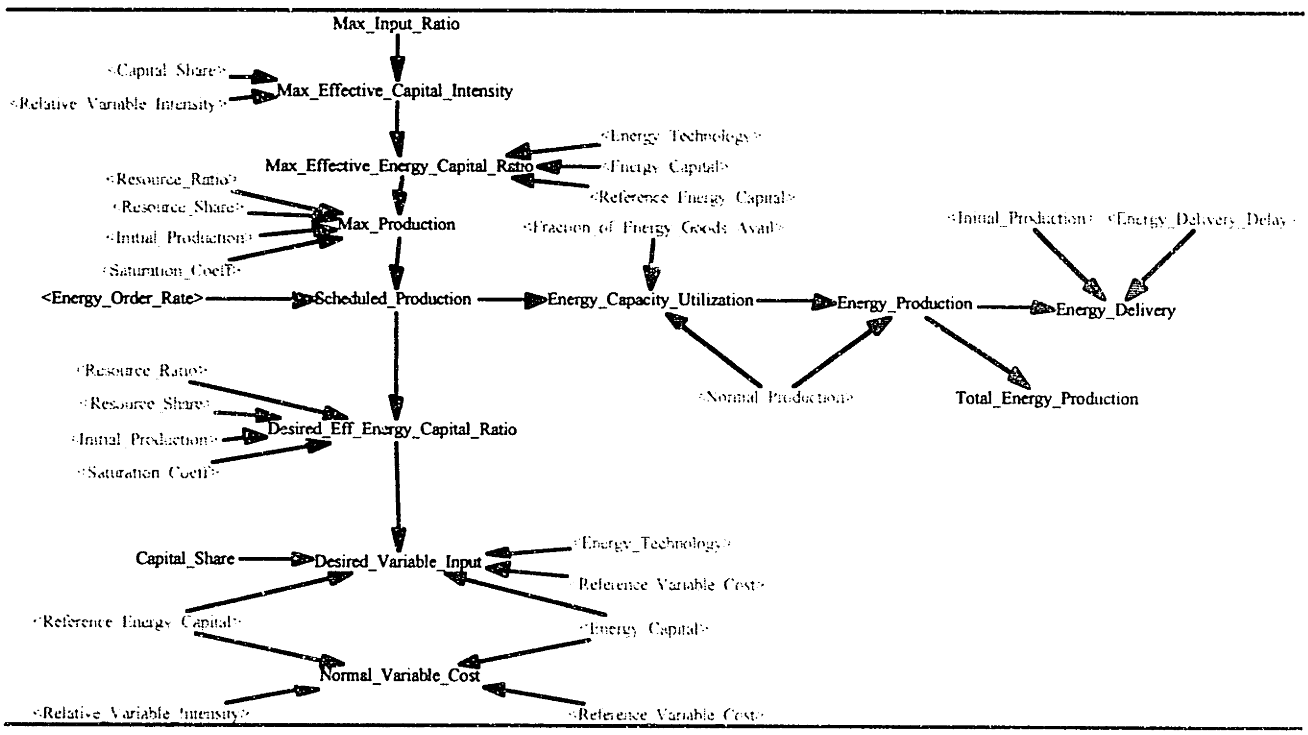
(283)Energy_Capital
(288)Energy_Capital_Lifetime
(376)Hist_Energy_Growth_Rate
(368)Cumulative_Energy_Investment
(378)Induced_Energy_Technology

(380) Low_Lim_Energy_Tech[source] = 0.1, 0.1, 0.1, 0.01
dmnl
Lower limit to energy production cost reduction from energy technology. A nonzero value implies that there are some irreducible costs of energy production.
(377)Indicated_Energy_Technology

(381) Tech_Data_Switch = 0
dmnl
Weight to technology from exogenous data series in calculation of total technology level; 0 = model generated, 1 = data.
(375)Energy_Technology

(382) Technology_Data[source]
dmnl
Technology data series (normally from another run)
(375)Energy_Technology

.Energy.Utilization



(383) Capital_Share[source] = 0.6, 0.6, 0.8, 0.8
dmnl
CES value share of capital in output.
(385)Desired_Variable_Input
(298)Marg_Prod_Energy_Capital
(347)Marginal_Variable_Input
(392)Max_Effective_Capital_Intensity
(311)Normal_Effective_Capital_Intensity

(300)Reference_Energy_Capital
(398)Relative_Variable_Intensity
(401)Variable_Share

```
(384) Desired_Eff_Energy_Capital_Ratio[source] =
        (((Scheduled_Production[source] / Initial_Production[source]) ^
        Resource_Coeff[source] - Resource_Share[source] *
        Resource_Ratio[source] ^ Resource_Coeff[source]) / (1 -
        Resource_Share[source])) ^ (1 / Resource_Coeff[source])
```

dmnl

Desired ratio of intensive inputs to normal level.

(391)Initial_Production
(316)Resource_Ratio
(318)Resource_Share
(319)Resource_Coeff
(399)Scheduled_Production
(385)Desired_Variable_Input
(347)Marginal_Variable_Input

```
(385) Desired_Variable_Input[source] = Reference_Variable_Cost[source] *
        ((Desired_Eff_Energy_Capital_Ratio[source] /
        Energy_Technology[source]) / (Energy_Capital[source] /
        Reference_Energy_Capital[source]) ^ Capital_Share[source]) ^ (1 /
        (1-Capital_Share[source]))
```

$/year

Desired input of goods to energy production.

(283)Energy_Capital
(383)Capital_Share
(384)Desired_Eff_Energy_Capital_Ratio
(375)Energy_Technology
(300)Reference_Energy_Capital
(397)Reference_Variable_Cost
(154)Indicated_Total_Energy_Variable_Cost
(355)SR_Average_Variable_Cost

```
(386) Energy_Capacity_Utilization[source] = Scheduled_Production[source] /
        Normal_Production[source] * Fraction_of_Energy_Goods_Avail
```

dmnl

Effect of variable input on production level (can be thought of as capacity utilization, where 1 = normal).

(149)Fraction_of_Energy_Goods_Avail
(313)Normal_Production
(399)Scheduled_Production
(390)Energy_Production

```
(387) Energy_Delivery[source] = SMOOTHI(Energy_Production[source],
        Energy_Delivery_Delay, Initial_Production[source])
```

GJ/year

Energy delivery rate; equals delayed production. !

(388)Energy_Delivery_Delay
(390)Energy_Production
(391)Initial_Production
(175)Indicated_Energy_Order_Rate
(178)SR_Aggr_Energy_Input
(183)SR_Marg_Aggr_Energy_per_Energy

(388) `Energy_Delivery_Delay = 0.25`
year
Delay between production and delivery of energy to goods producing sector.
(387)Energy_Delivery

(389) `Energy_Order_Rate[source] = Exog_Order_Switch * Production_Data[source] + (1-Exog_Order_Switch) * Indicated_Energy_Order_Rate[source]`
GJ/year
Incoming orders for energy sources; switchable between endogenous and exogenous drivers.
(329)Exog_Order_Switch
(175)Indicated_Energy_Order_Rate
(122)Production_Data
(321)Availability
(295)LR_Expected_Order_Growth_Rate
(323)Primary_Energy_Order_Rate
(352)Production_Pressure
(399)Scheduled_Production

(390) `Energy_Production[source] = Normal_Production[source] * Energy_Capacity_Utilization[source]`
GJ/year
Actual energy production, based on normal production adjusted for production effort (utilization).
(386)Energy_Capacity_Utilization
(313)Normal_Production
(303)Cumulative_Production
(317)Resource_Remaining
(321)Availability
(336)Capital_Cost
(010)Energy_Carbon_Emissions
(387)Energy_Delivery
(324)Production_Share
(353)Source_Expenditure
(355)SR_Average_Variable_Cost
(400)Total_Energy_Production

(391) `Initial_Production[source] = 5.67e+010, 6.28e+010, 6.4e+009, 2.36e+007`
GJ/year
Oil, Gas: 4.53e+010, 1.75e+010
(384)Desired_Eff_Energy_Capital_Ratio
(387)Energy_Delivery
(306)Init_Cum_Prod
(346)Marginal_Eff_Energy_Capital_Ratio
(424)Marginal_Resource_Eff_Energy_Capital_Ratio
(395)Max_Production
(313)Normal_Production
(333)Reference_Final_Expenditure
(334)Reference_Pretax_Expenditure
(318)Resource_Share

(392) `Max_Effective_Capital_Intensity[source] = (Max_Input_Ratio * Relative_Variable_Intensity[source]) ^ (1 - Capital_Share[source])`
dmnl
Ratio of current vs. initial ratio of output to capital. Output intensity varies as interest rate variations affect desired balance of capital and variable inputs.

(383)Capital_Share
(394)Max_Input_Ratio
(398)Relative_Variable_Intensity
(393)Max_Effective_Energy_Capital_Ratio

(393) Max_Effective_Energy_Capital_Ratio[source] = Energy_Capital[source] / Reference_Energy_Capital[source] * Energy_Technology[source] * Max_Effective_Capital_Intensity[source]
dmnl
Ratio current vs. initial production effort, with adjustments for capital scale, technology, and varying input intensity.
(283)Energy_Capital
(375)Energy_Technology
(392)Max_Effective_Capital_Intensity
(300)Reference_Energy_Capital
(395)Max_Production

(394) Max_Input_Ratio = 10
dmnl
Maximum allowable ratio of variable inputs to normal variable input level. Normally, in CES aggregate between capital and variable inputs, the short run (fixed capital) upper limit to production is attained only with infinite variable input. This formulation assumes that there is actually a practical or behavioral upper limit to variable input. Thus the realizable upper limit to production is less than the CES upper limit with infinite inputs.
(392)Max_Effective_Capital_Intensity

(395) Max_Production[source] = Initial_Production[source] * (Resource_Share[source] * Resource_Ratio[source] ^ Resource_Coeff[source] + (1-Resource_Share[source]) * Max_Effective_Energy_Capital_Ratio[source] ^ Resource_Coeff[source]) ^ (1 / Resource_Coeff[source])
GJ/year
Upper limit to production in the short run (when capital is fixed).
(391)Initial_Production
(393)Max_Effective_Energy_Capital_Ratio
(316)Resource_Ratio
(318)Resource_Share
(319)Resource_Coeff
(399)Scheduled_Production

(396) Normal_Variable_Cost[source] = Reference_Variable_Cost[source] * Energy_Capital[source] / Reference_Energy_Capital[source] * Relative_Variable_Intensity[source]
$/year
Normal rate of variable cost inputs to energy production. Anchored to reference variable cost and adjusted for changes in capital scale and capital-variable factor balance.
(283)Energy_Capital
(300)Reference_Energy_Capital
(397)Reference_Variable_Cost
(398)Relative_Variable_Intensity
(423)LR_Marginal_Cost_of_Energy_Prod

(397) Reference_Variable_Cost[source] = INITIAL(Reference_Pretax_Expenditure[source] * Variable_Share[source])
$/year

Reference variable cost (goods) input rate by source.
(334)Reference_Pretax_Expenditure
(401)Variable_Share
(385)Desired_Variable_Input
(347)Marginal_Variable_Input
(396)Normal_Variable_Cost
(398)Relative_Variable_Intensity

```
(398) Relative_Variable_Intensity[source] = (Energy_Capital_Cost[source] *
        Reference_Energy_Capital[source] * (1 - Capital_Share[source])) /
        (1 * Reference_Variable_Cost[source] * Capital_Share[source])
```
dmnl
Ratio of current to initial intensity of variable inputs to energy production. The intensity of variable (vs. capital) inputs to production falls as interest rates fall.
(383)Capital_Share
(286)Energy_Capital_Cost
(300)Reference_Energy_Capital
(397)Reference_Variable_Cost
(392)Max_Effective_Capital_Intensity
(311)Normal_Effective_Capital_Intensity
(396)Normal_Variable_Cost

```
(399) Scheduled_Production[source] = MIN(Max_Production[source],
        Energy_Order_Rate[source])
```
GJ/year
Scheduled energy production rate; equals incoming orders adjusted for an upper limit to production.
(389)Energy_Order_Rate
(395)Max_Production
(384)Desired_Eff_Energy_Capital_Ratio
(386)Energy_Capacity_Utilization
(151)Indicated_Energy_Distribution_Cost
(346)Marginal_Eff_Energy_Capital_Ratio
(424)Marginal_Resource_Eff_Energy_Capital_Ratio

```
(400) Total_Energy_Production = SUM(Energy_Production[source!])
```
GJ/year
Total energy production (in physical terms).
(390)Energy_Production
(322)Avg_Energy_Price
(005)Emissions_Intensity_of_Energy
(324)Production_Share

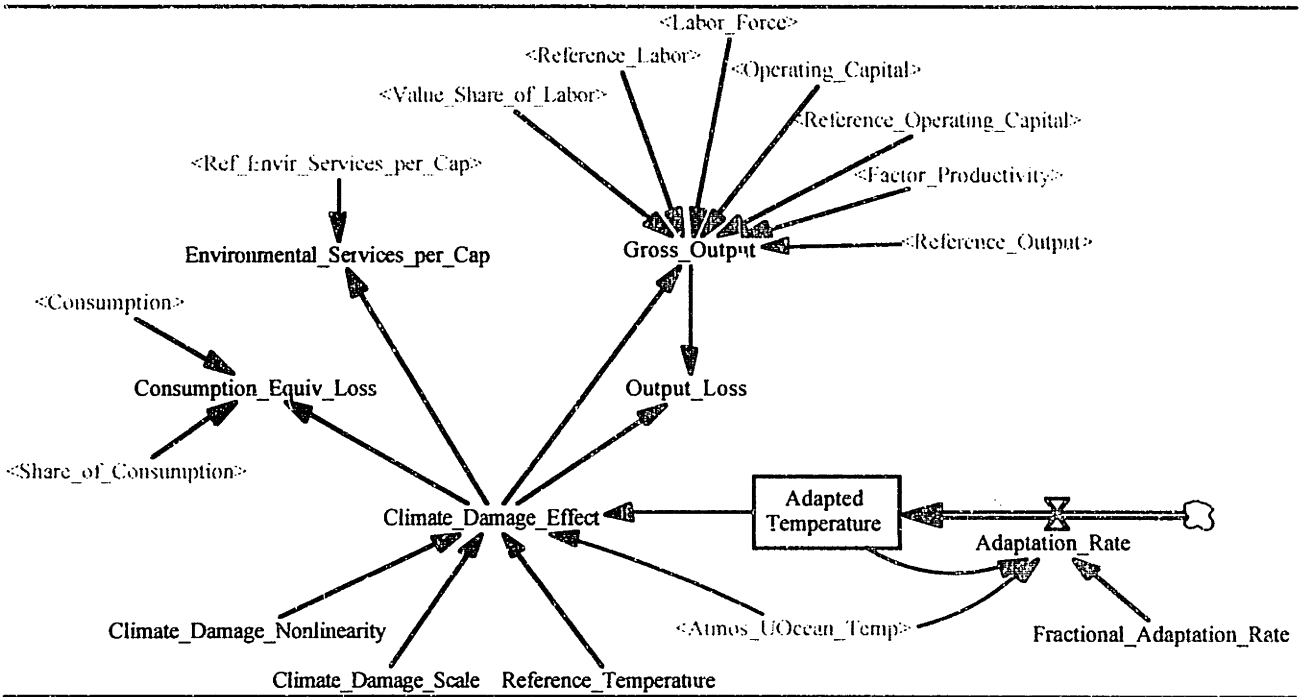
```
(401) Variable_Share[source] = INITIAL(1-Capital_Share[source])
```
dmnl
CES value share of variable costs in short-run output.
(383)Capital_Share
(397)Reference_Variable_Cost

.Impact

Impacts are drawn from Nordhaus' DICE model, with a modification for intangibles in the spirit of Tol. See:

Nordhaus, W. D. 1994. Managing the Global Commons. Cambridge, MA: MIT Press.

Tol, R. S. J. 1994. The Damage Costs of Climate Change: a Note on Tangibles and Intangibles, Applied to DICE. Energy Policy 22(5): 436-438.




```
(402) Adaptation_Rate[Damage] = (Atmos_UOcean_Temp -
        Adapted_Temperature[Damage]) * Fractional_Adaptation_Rate[Damage]
```
DegreesC/year

Rate of adaptation to altered climatic conditions.

(403)Adapted_Temperature
(059)Atmos_UOcean_Temp
(409)Fractional_Adaptation_Rate

(403)Adapted_Temperature

```
(403) Adapted_Temperature[Damage] = INTEG ( Adaptation_Rate[Damage], 0)
```
DegreesC

Temperature to which the economy or biosphere is adapted.

(402)Adaptation_Rate

(402)Adaptation_Rate
(404)Climate_Damage_Effect

```
(404) Climate_Damage_Effect[Damage] = 1 / (1 + Climate_Damage_Scale[Damage] *
        ((Atmos_UOcean_Temp-Adapted_Temperature[Damage]) /
        Reference_Temperature) ^ Climate_Damage_Nonlinearity[Damage])
```
dmnl

Multiplier for climate damage effect on output (tangible) or environmental services (intangible).

(403)Adapted_Temperature
(059)Atmos_UOcean_Temp
(405)Climate_Damage_Nonlinearity
(406)Climate_Damage_Scale
(411)Reference_Temperature

(407)Consumption_Equiv_Loss
(465)Environmental_Services_per_Cap
(262)Gross_Output

(410)Output_Loss

(405) `Climate_Damage_Nonlinearity[Damage] = 2`
dmnl
Nonlinearity of Climate Damage Cost Fraction.
(404)Climate_Damage_Effect

(406) `Climate_Damage_Scale[Damage] = 0.013`
dmnl
Climate damage scale, expressed as the fractional loss at the reference temperature deviation.
(404)Climate_Damage_Effect

(407) `Consumption_Equiv_Loss = Consumption * (Climate_Damage_Effect[Intangible] ^ ((Share_of_Consumption-1) / Share_of_Consumption)-1)`
$/year
Intangible climate damages, expressed as their consumption equivalent (i.e. the additional consumption needed to produce equal welfare).
(404)Climate_Damage_Effect
(147)Consumption
(476)Share_of_Consumption

(408) `Damage: Tangible, Intangible`
Type of climate damage (tangible or intangible).

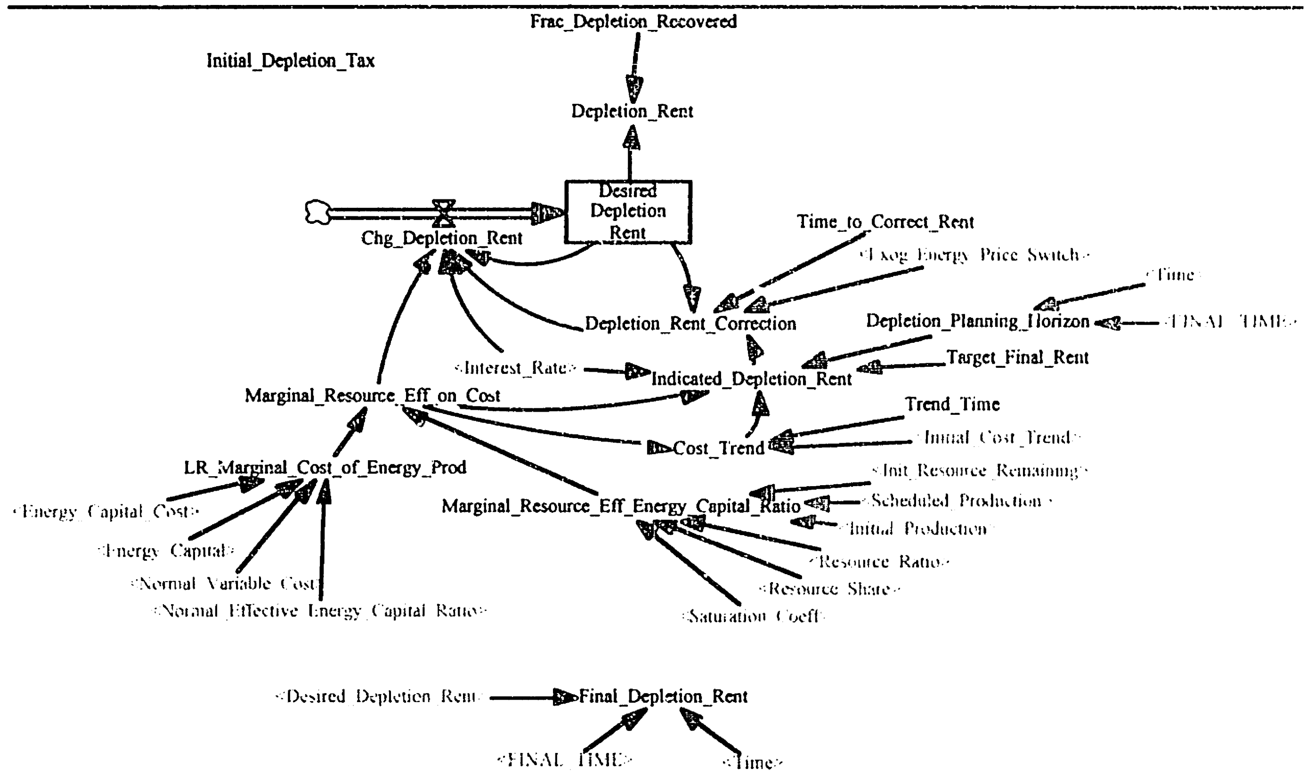
(409) `Fractional_Adaptation_Rate[Damage] = 0`
1/year
Fractional rate of adaptation to altered climatic conditions; inverse of the time constant for adaptation. 0 implies that damages depend on the absolute temperature deviation from preindustrial levels.
(402)Adaptation_Rate

(410) `Output_Loss = Gross_Output * (1-Climate_Damage_Effect[Tangible]) / Climate_Damage_Effect[Tangible]`
$/year
Tangible climate damages, expressed as their output equivalent (i.e. the additional output that could be produced with no climate effects).
(404)Climate_Damage_Effect
(262)Gross_Output

(411) `Reference_Temperature = 3`
DegreesC
Reference temperature deviation (from adapted level) for calculation of climate damages.
(404)Climate_Damage_Effect

.Policy.Depletion

Near-optimal taxation of resource depletion in order to restore intertemporal efficiency in oil and gas production. Note that this structure is intended to allow testing of a scenario of efficient resource allocation, not as a plausible representation of behavior.



(412) Chg_Depletion_Rent[OilGas] = Desired_Depletion_Rent[OilGas] *
Interest_Rate + Marginal_Resource_Eff_on_Cost[OilGas] +
Depletion_Rent_Correction[OilGas]

$/GJ/year

Rate of change of depletion rent.

(417)Desired_Depletion_Rent
(416)Depletion_Rent_Correction
(255)Interest_Rate
(425)Marginal_Resource_Eff_on_Cost
(417)Desired_Depletion_Rent

(413) Cost_Trend[OilGas] = LN(Marginal_Resource_Eff_on_Cost[OilGas] /
SMOOTHI(Marginal_Resource_Eff_on_Cost[OilGas], Trend_Time,
Marginal_Resource_Eff_on_Cost[OilGas] * exp(-Trend_Time *
Initial_Cost_Trend))) / Trend_Time

1/year

Fractional rate of change of the marginal effect of resource availability on extraction costs.

(421)Initial_Cost_Trend
(425)Marginal_Resource_Eff_on_Cost
(428)Trend_Time
(420)Indicated_Depletion_Rent

(414) Depletion_Planning_Horizon = FINAL_TIME-Time

year

Planning horizon for depletion decision.

(000)Time
(076)FINAL_TIME
(420)Indicated_Depletion_Rent

(415) Depletion_Rent[nonrenewable] = Frac_Depletion_Recovered * max(0,
Desired_Depletion_Rent[nonrenewable])

$/GJ
Energy tax for depletion.
(417)Desired_Depletion_Rent
(419)Frac_Depletion_Recovered
(298)Marg_Prod_Energy_Capital
(350)Primary_Energy_Price

```
(416) Depletion_Rent_Correction[OilGas] = (1 -
        Exog_Energy_Price_Switch[OilGas]) *
        (Indicated_Depletion_Rent[OilGas] -
        Desired_Depletion_Rent[OilGas]) / Time_to_Correct_Rent
```
$/GJ/year
Correction to depletion rent; applied over the Time to Correct Rent, but active only while energy prices are endogenous.
(417)Desired_Depletion_Rent
(340)Exog_Energy_Price_Switch
(420)Indicated_Depletion_Rent
(427)Time_to_Correct_Rent
(412)Chg_Depletion_Rent

```
(417) Desired_Depletion_Rent[OilGas] = INTEG ( Chg_Depletion_Rent[OilGas],
        Initial_Depletion_Tax[OilGas])

      Desired_Depletion_Rent[Coal] = 0
```
$/GJ
Desired depletion rent.
(412)Chg_Depletion_Rent
(422)Initial_Depletion_Tax
(412)Chg_Depletion_Rent
(415)Depletion_Rent
(416)Depletion_Rent_Correction
(418)Final_Depletion_Rent

```
(418) Final_Depletion_Rent = IF_THEN_ELSE(Time = FINAL_TIME,
        ABS(Desired_Depletion_Rent[OilGas]), 0)
```
$/GJ
Depletion rent in final time step (for calibration purposes)
(000)Time
(417)Desired_Depletion_Rent
(076)FINAL_TIME

```
(419) Frac_Depletion_Recovered = 0
```
dmnl
Fraction of desired depletion rent actually collected by resource managers.
(415)Depletion_Rent

```
(420) Indicated_Depletion_Rent[OilGas] = exp(-Depletion_Planning_Horizon *
        Interest_Rate) * (Target_Final_Rent-
        Marginal_Resource_Eff_on_Cost[OilGas] * (exp(Interest_Rate *
        Depletion_Planning_Horizon) -exp(Cost_Trend[OilGas] *
        Depletion_Planning_Horizon)) / (Interest_Rate-Cost_Trend[OilGas]))
```
$/GJ
Indicated depletion rent, based on extrapolation of current rate of resource cost increase, to adjust depletion rent to target level at end of planning horizon.
(413)Cost_Trend
(414)Depletion_Planning_Horizon
(255)Interest_Rate

(425)Marginal_Resource_Eff_on_Cost
(426)Target_Final_Rent
(416)Depletion_Rent_Correction

(421) Initial_Cost_Trend = 0.04
1/year
Initial trend in resource extraction cost.
(413)Cost_Trend

(422) Initial_Depletion_Tax[OilGas] = 0.3
$/GJ
Initial depletion rent
(417)Desired_Depletion_Rent

(423) LR_Marginal_Cost_of_Energy_Prod[OilGas] = (Energy_Capital[OilGas] *
Energy_Capital_Cost[OilGas] + Normal_Variable_Cost[OilGas]) /
Normal_Effective_Energy_Capital_Ratio[OilGas]
$/year
Long run marginal cost of energy production.
(283)Energy_Capital
(286)Energy_Capital_Cost
(312)Normal_Effective_Energy_Capital_Ratio
(396)Normal_Variable_Cost
(425)Marginal_Resource_Eff_on_Cost

(424) Marginal_Resource_Eff_Energy_Capital_Ratio[OilGas] =
(((Scheduled_Production[OilGas] / Initial_Production[OilGas]) ^
Resource_Coeff[OilGas] - Resource_Share[OilGas] *
Resource_Ratio[OilGas] ^ Resource_Coeff[OilGas]) / (1 -
Resource_Share[OilGas])) ^ (1 / Resource_Coeff[OilGas] - 1) *
Resource_Ratio[OilGas] ^ (Resource_Coeff[OilGas] - 1) * (-
Resource_Share[OilGas]) / (1 - Resource_Share[OilGas]) /
Init_Resource_Remaining[OilGas]
1/GJ
Marginal increase in capital-variable aggregate per unit increase in production.
(307)Init_Resource_Remaining
(391)Initial_Production
(316)Resource_Ratio
(318)Resource_Share
(319)Resource_Coeff
(399)Scheduled_Production
(425)Marginal_Resource_Eff_on_Cost

(425) Marginal_Resource_Eff_on_Cost[OilGas] =
LR_Marginal_Cost_of_Energy_Prod[OilGas] *
Marginal_Resource_Eff_Energy_Capital_Ratio[OilGas]
$/GJ/year
Marginal effect of resource depletion on extraction cost.
(423)LR_Marginal_Cost_of_Energy_Prod
(424)Marginal_Resource_Eff_Energy_Capital_Ratio
(412)Chg_Depletion_Rent
(413)Cost_Trend
(420)Indicated_Depletion_Rent

(426) Target_Final_Rent = 0
$/GJ
Target depletion rent at final time.

(420)Indicated_Depletion_Rent

(427) Time_to_Correct_Rent = 20
year
Time to make extrapolative corrections to depletion rent.
(416)Depletion_Rent_Correction

(428) Trend_Time = 20
year
Time to establish trend in extraction costs.
(413)Cost_Trend

.Policy.Tax

(429) Carbon_Content[nonrenewable] = 0.0247, 0.0171
TonC/GJ
Carbon content of fuels. Oil, Gas: 0.0207, 0.0134, weighted by resource endowment.
(010)Energy_Carbon_Emissions
(444)Specific_Carbon_Tax

(430) Carbon_Tax = INTEG (Carbon_Tax_Adj_Rate, 0)
$/TonC
Effective carbon tax on carbon-based energy sources.
(431)Carbon_Tax_Adj_Rate
(431)Carbon_Tax_Adj_Rate
(444)Specific_Carbon_Tax

(431) Carbon_Tax_Adj_Rate = STEP((Indicated_Carbon_Tax-Carbon_Tax) / Tax_Adj_Time, Initial_Tax_Time)
$/TonC/year
Rate of change of implemented carbon tax.
(430)Carbon_Tax
(439)Indicated_Carbon_Tax
(440)Initial_Tax_Time
(445)Tax_Adj_Time
(430)Carbon_Tax

(432) Concentration_Coeff = 0
$/TonC
Coefficient for atmospheric concentration contribution to carbon tax.
(439)Indicated_Carbon_Tax

(433) Constant_Energy_Tax = 0
$/GJ
Constant component of carbon tax.
(438)Energy_Tax_Adj_Rate

(434) Constant_Tax = 0
$/TonC
Constant term in carbon tax.
(439)Indicated_Carbon_Tax

(435) Emissions_Coeff = 0
$/TonC
Coefficient for emissions rate contribution to carbon tax.
(439)Indicated_Carbon_Tax

(436) Emissions_Perception_Time = 1

year
Time to perceive carbon emissions rate.

(442)Perceived_Emissions_Rate

(437) Energy_Tax = INTEG (Energy_Tax_Adj_Rate, 0)
$/GJ
Tax on all energy sources.

(438)Energy_Tax_Adj_Rate

(438)Energy_Tax_Adj_Rate
(446)Total_Tax

(438) Energy_Tax_Adj_Rate = STEP((Constant_Energy_Tax-Energy_Tax) / Tax_Adj_Time, Initial_Tax_Time)
$/GJ/year
Rate of adjustment of tax on all energy sources.

(437)Energy_Tax
(433)Constant_Energy_Tax
(440)Initial_Tax_Time
(445)Tax_Adj_Time

(437)Energy_Tax

(439) Indicated_Carbon_Tax = max(Minimum_Carbon_Tax, (Effective_CO2_in_Atmosphere-Preindustrial_CO2) / Preindustrial_CO2 * Concentration_Coeff + (Perceived_Emissions_Rate-Reference_Emissions_Rate) / Reference_Emissions_Rate * Emissions_Coeff + Constant_Tax)
$/TonC
Indicated carbon tax level.

(432)Concentration_Coeff
(434)Constant_Tax
(002)Effective_CO2_in_Atmosphere
(435)Emissions_Coeff
(441)Minimum_Carbon_Tax
(442)Perceived_Emissions_Rate
(073)Preindustrial_CO2
(443)Reference_Emissions_Rate

(431)Carbon_Tax_Adj_Rate

(440) Initial_Tax_Time = 1995
year
Year in which tax implementation begins.

(431)Carbon_Tax_Adj_Rate
(438)Energy_Tax_Adj_Rate

(441) Minimum_Carbon_Tax = 0
$/TonC
Minimum carbon tax; constrains tax to prevent negative taxes (i.e. subsidies) from creating negative energy prices. Negative minimum taxes should be tested occasionally for full exploration of the policy space.

(439)Indicated_Carbon_Tax

(442) Perceived_Emissions_Rate = SMOOTH(Total_Energy_Carbon_Emissions, Emissions_Perception_Time)
TonC/year
Perceived rate of carbon emissions from energy production.

(436)Emissions_Perception_Time
(013)Total_Energy_Carbon_Emissions

(439)Indicated_Carbon_Tax

```
(443) Reference_Emissions_Rate = 5e+009
```
TonC/year
Reference carbon emissions rate.

(439)Indicated_Carbon_Tax

```
(444) Specific_Carbon_Tax[nonrenewable] = Carbon_Tax *
          Carbon_Content[nonrenewable]
```
$/GJ
Carbon tax by energy source.

(430)Carbon_Tax
(429)Carbon_Content

(446)Total_Tax

```
(445) Tax_Adj_Time = 5
```
year
Time to adjust taxes to indicated levels.

(431)Carbon_Tax_Adj_Rate
(438)Energy_Tax_Adj_Rate

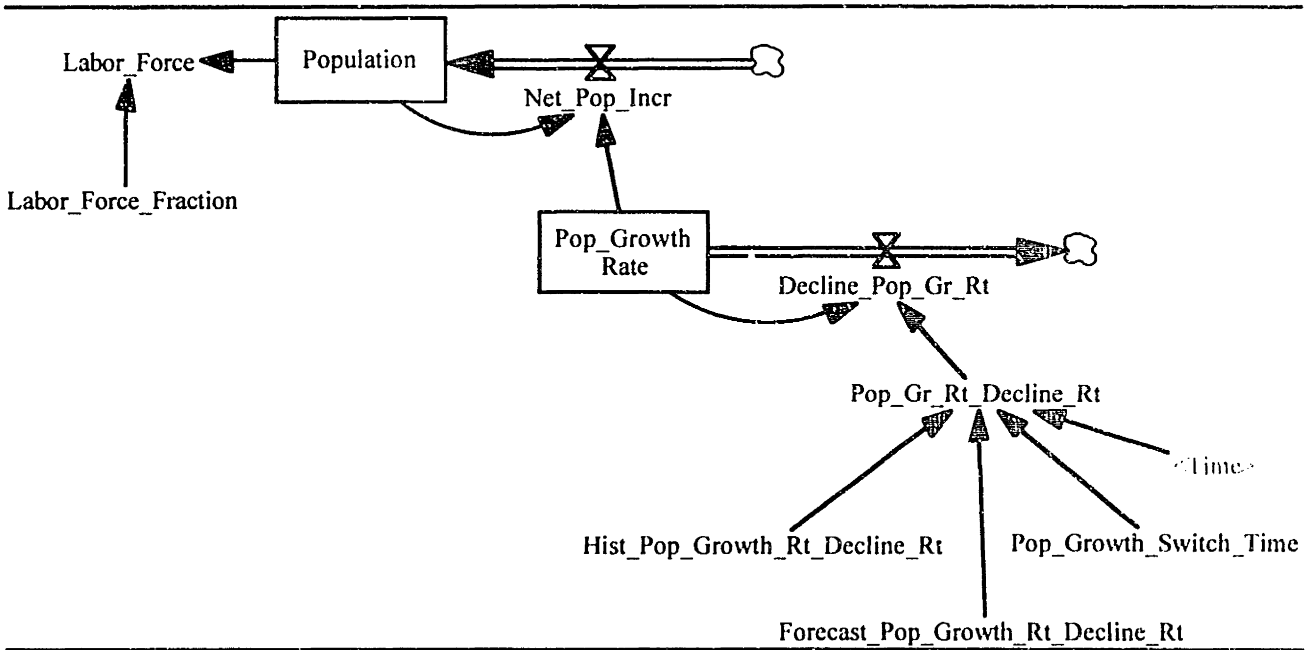
```
(446) Total_Tax[nonrenewable] = Energy_Tax + Specific_Carbon_Tax[nonrenewable]

      Total_Tax[Renewable] = Energy_Tax
```
$/GJ
Indicated tax on energy sources.

(437)Energy_Tax
(444)Specific_Carbon_Tax

(342)Final_Energy_Price

.Population




```
(447) Decline_Pop_Gr_Rt = Pop_Growth_Rate * Pop_Gr_Rt_Decline_Rt
```
1/year/year
Decline of Population Growth Rate

(456)Pop_Growth_Rate

(455)Pop_Gr_Rt_Decline_Rt
(456)Pop_Growth_Rate

(448) Forecast_Pop_Growth_Rt_Decline_Rt = 0.02
1/year
Forecast rate of decline of population growth rate. Calibrated (roughly) to EMF-14 scenario.
(455)Pop_Gr_Rt_Decline_Rt

(449) Hist_Pop_Growth_Rt_Decline_Rt = 0.01
1/year
Historic rate of decline of population growth rate. Calibrated to World Bank data.
(455)Pop_Gr_Rt_Decline_Rt

(450) Initial_Pop_Growth_Rt = 0.0224
1/year
Initial population growth rate.
(456)Pop_Growth_Rate

(451) Initial_Population = 3.041e+009
people
Initial population.
(458)Population

(452) Labor_Force = Labor_Force_Fraction * Population
FTE
Labor force. Assumes invariable labor participation.
(458)Population
(453)Labor_Force_Fraction
(262)Gross_Output
(264)Marginal_Prod_of_Labor
(265)Reference_Labor

(453) Labor_Force_Fraction = 0.25
FTE/person
Fraction of population participating in labor force.
(452)Labor_Force

(454) Net_Pop_Incr = Population * Pop_Growth_Rate
person/year
Net Population Increase
(456)Pop_Growth_Rate
(458)Population
(458)Population

(455) Pop_Gr_Rt_Decline_Rt = IF_THEN_ELSE(Time > Pop_Growth_Switch_Time, Forecast_Pop_Growth_Rt_Decline_Rt , Hist_Pop_Growth_Rt_Decline_Rt)
1/year
Rate of Decline of Population Growth Rate
(000)Time
(448)Forecast_Pop_Growth_Rt_Decline_Rt
(449)Hist_Pop_Growth_Rt_Decline_Rt
(457)Pop_Growth_Switch_Time
(447)Decline_Pop_Gr_Rt

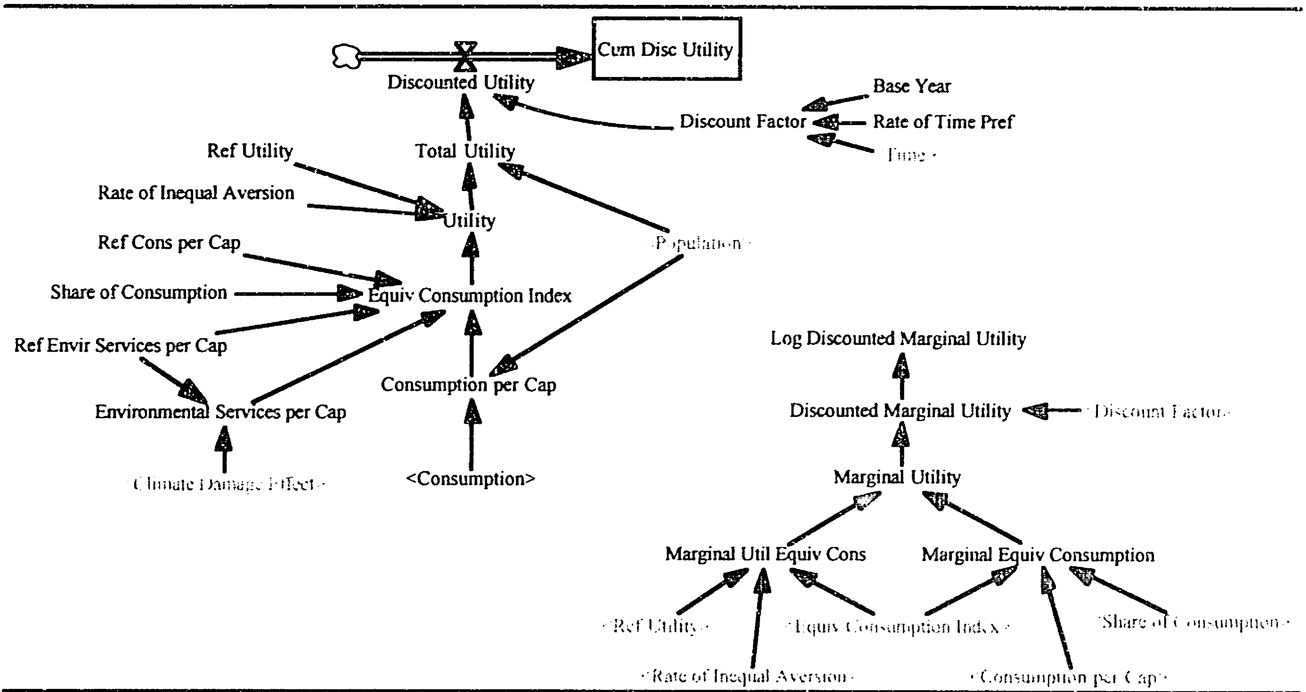
(456) Pop_Growth_Rate = INTEG(- Decline_Pop_Gr_Rt, Initial_Pop_Growth_Rt)
1/year
Population Growth Rate
(447)Decline_Pop_Gr_Rt

(450)Initial_Pop_Growth_Rt
(447)Decline_Pop_Gr_Rt
(454)Net_Pop_Incr

(457) Pop_Growth_Switch_Time = 1990
year
Year of switch from historic to forecast population growth rate decline rate.
(455)Pop_Gr_Rt_Decline_Rt

(458) Population = INTEG(Net_Pop_Incr, Initial_Population)
person
Population
(451)Initial_Population
(454)Net_Pop_Incr
(460)Consumption_per_Cap
(253)Gross_Output_per_Cap
(452)Labor_Force
(454)Net_Pop_Incr
(477)Total_Utility

.Welfare



(459) Base_Year = 1990
year
Base Year for Discounting Model is denominated in 1990 dollars, and discounting is performed relative to 1990.
(462)Discount_Factor

(460) Consumption_per_Cap = Consumption / Population
$/person/year
Per capita goods consumption.
(458)Population
(147)Consumption

(466)Equiv_Consumption_Index
(468)Marginal_Equiv_Consumption

(461) `Cum_Disc_Utility = INTEG(Discounted_Utility, 0)`
utiles
Cumulative Discounted Utility
(464)Discounted_Utility

(462) `Discount_Factor = exp(-Rate_of_Time_Pref * (Time-Base_Year))`
dmnl
Discount applied to utility from pure time preference (impatience).
(000)Time
(459)Base_Year
(472)Rate_of_Time_Pref
(463)Discounted_Marginal_Utility
(464)Discounted_Utility

(463) `Discounted_Marginal_Utility = Marginal_Utility * Discount_Factor`
utiles/$
Marginal utility of consumption, discounted to the base year.
(462)Discount_Factor
(470)Marginal_Utility
(467)Log_Discounted_Marginal_Utility

(464) `Discounted_Utility = Total_Utility * Discount_Factor`
utiles/year
The flow of utility, discounted to the base year.
(462)Discount_Factor
(477)Total_Utility
(461)Cum_Disc_Utility
(483)Net_Discounted_Utility

(465) `Environmental_Services_per_Cap = Ref_Envir_Services_per_Cap * Climate_Damage_Effect[Intangible]`
dmnl
Level of environmental services per capita. Note that the environment is assumed to provide the same level of services per capita regardless of the population. Thus there are no crowding or degradation effects (other than climate change damages).
(404)Climate_Damage_Effect
(474)Ref_Envir_Services_per_Cap
(466)Equiv_Consumption_Index

(466) `Equiv_Consumption_Index = (Consumption_per_Cap / Ref_Cons_per_Cap) ^ Share_of_Consumption * (Environmental_Services_per_Cap / Ref_Envir_Services_per_Cap) ^ (1 - Share_of_Consumption)`
dmnl
Index of equivalent consumption; equals the consumption equivalent of tangible goods (consumption) and intangibles (environmental services). Assumes unit elasticity of substitution between tangibles and intangibles.
(460)Consumption_per_Cap
(465)Environmental_Services_per_Cap
(473)Ref_Cons_per_Cap
(474)Ref_Envir_Services_per_Cap
(476)Share_of_Consumption
(468)Marginal_Equiv_Consumption
(469)Marginal_Util_Equiv_Cons
(478)Utility

(467) `Log_Discounted_Marginal_Utility = LN(Discounted_Marginal_Utility / INIT(Discounted_Marginal_Utility))`
dmnl
Logarithm of discounted marginal utility (relative to initial value).
(463)Discounted_Marginal_Utility

(468) `Marginal_Equiv_Consumption = Share_of_Consumption * Equiv_Consumption_Index / Consumption_per_Cap`
*person*year/$*
Marginal change in equivalent consumption index per unit change in consumption per capita.
(460)Consumption_per_Cap
(466)Equiv_Consumption_Index
(476)Share_of_Consumption
(470)Marginal_Utility

(469) `Marginal_Util_Equiv_Cons = Ref_Utility * (Equiv_Consumption_Index) ^ (-Rate_of_Inequal_Aversion)`
utiles/person/year
Marginal utility per unit change in equivalent consumption index.
(466)Equiv_Consumption_Index
(471)Rate_of_Inequal_Aversion
(475)Ref_Utility
(470)Marginal_Utility

(470) `Marginal_Utility = Marginal_Equiv_Consumption * Marginal_Util_Equiv_Cons`
utiles/$
Marginal utility of a unit of consumption.
(468)Marginal_Equiv_Consumption
(469)Marginal_Util_Equiv_Cons
(463)Discounted_Marginal_Utility

(471) `Rate_of_Inequal_Aversion = 2.5`
dmnl
Rate of Inequality Aversion in utility calculation.
(469)Marginal_Util_Equiv_Cons
(478)Utility

(472) `Rate_of_Time_Pref = 0`
1/year
Pure Rate of Social Time Preference in utility calculation.
(462)Discount_Factor

(473) `Ref_Cons_per_Cap = 1502`
$/person/year
Reference rate of consumption per capita.
(466)Equiv_Consumption_Index

(474) `Ref_Envir_Services_per_Cap = 1`
dmnl
Reference level of environmental services per capita.
(465)Environmental_Services_per_Cap
(466)Equiv_Consumption_Index

(475) `Ref_Utility = 1`
utiles/person/year
Reference Rate of Utility Generation.
(469)Marginal_Util_Equiv_Cons
(478)Utility

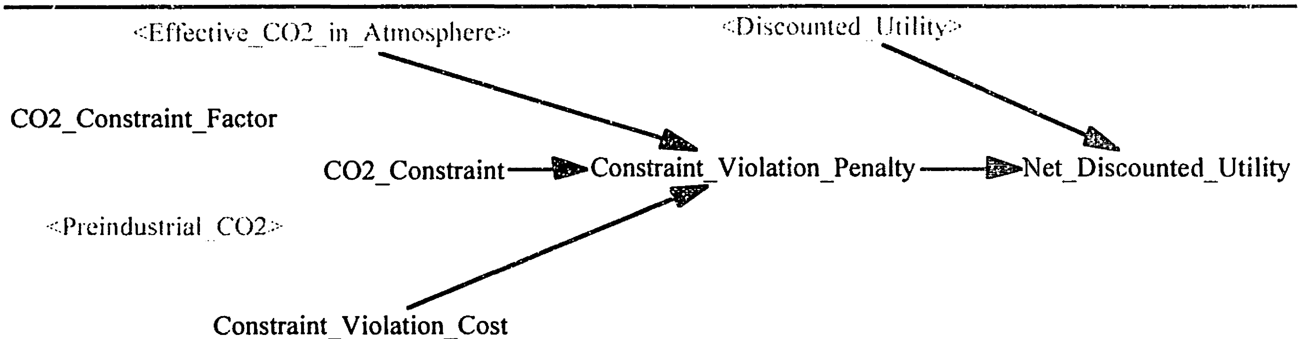
(476) Share_of_Consumption = 1
dmnl
Value share of consumption in equivalent consumption index. The default value of 1 means intangible (environmental) services have zero importance.
(407)Consumption_Equiv_Loss
(466)Equiv_Consumption_Index
(468)Marginal_Equiv_Consumption

(477) Total_Utility = Population * Utility
utiles/year
Flow of utility, weighted by population; i.e. total utility of all individuals.
(458)Population
(478)Utility
(464)Discounted_Utility

(478) Utility = Ref_Utility * IF_THEN_ELSE(Rate_of_Inequal_Aversion = 1,
LN(Equiv_Consumption_Index), (Equiv_Consumption_Index ^ (1 -
Rate_of_Inequal_Aversion) - 1) / (1 - Rate_of_Inequal_Aversion))
utiles/person/year
Utility of a representative individual. Reduces to logarithmic utility function: LN(Consumption_per_Cap) when the Rate of Inequality Aversion -> 1
(466)Equiv_Consumption_Index
(471)Rate_of_Inequal_Aversion
(475)Ref_Utility
(477)Total_Utility

.Welfare.Constrained

Calculation of discounted utility, modified for inclusion of a hard constraint on atmospheric CO2.



(479) CO2_Constraint = INITIAL (Preindustrial_CO2 * CO2_Constraint_Factor)
TonC
Constraint on CO2 content of atmosphere.
(480)CO2_Constraint_Factor
(073)Preindustrial_CO2
(482)Constraint_Violation_Penalty

(480) CO2_Constraint_Factor = 2
dmnl
CO2 constraint, expressed as a multiple of the preindustrial CO2 concentration.
(479)CO2_Constraint

(481) Constraint_Violation_Cost = 0
utiles/year/TonC

Unit cost of violating CO2 constraint. For constrained scenarios, set to a very high value in order to ensure a hard constraint.

(482)Constraint_Violation_Penalty

```
(482) Constraint_Violation_Penalty = Constraint_Violation_Cost * max(0,
        Effective_CO2_in_Atmosphere-CO2_Constraint)
```

utiles/year

Total cost of violation of CO2 constraint.

(479)CO2_Constraint
(481)Constraint_Violation_Cost
(002)Effective_CO2_in_Atmosphere

(483)Net_Discounted_Utility

```
(483) Net_Discounted_Utility = Discounted_Utility-Constraint_Violation_Penalty
```

utiles/year

Discounted utility, net of cost of constraint violation.

(482)Constraint_Violation_Penalty
(464)Discounted_Utility

FREE Model Control Files

The following control files automate the replication of most of the simulation runs presented in the text. For details of the Vensim language, refer to (Ventana Systems 1994).

General

PREP.CMD

Creates default data files and normal model simulation control settings.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION

MENU>DAT2VDF|all_data.dat|all_data.vdf
MENU>DAT2VDF|techdata.dat|techdata.vdf

SIMULATE>DATA|all_data.vdf techdata.vdf
SIMULATE>SENSITIVITY|
SIMULATE>PAYOFF|payoff.prm
SIMULATE>OPTPARM|conc_tax.prm
SIMULATE>OPTIMIZE|0
SIMULATE>SAVELIST|
```

CONST_TAX.PRM

Identifies optimal constant carbon tax.

```
:OPTIMIZER=Powell
:SENSITIVITY=Off
:MULTIPLE_START=Off
:RANDOM_NUMER=Linear
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.01
:TOLERANCE_MULTIPLIER=21
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
-1000<=CONSTANT TAX<=2000
```

CONC_TAX.PRM

Identifies optimal carbon tax policy with constant and atmospheric CO2 concentration terms.

```
:OPTIMIZER=Powell
:SENSITIVITY=Off
:MULTIPLE_START=Off
:RANDOM_NUMER=Linear
:OUTPUT_LEVEL=On
```

```
:TRACE=Off
:MAX_ITERATIONS=1000
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.05
:TOLERANCE_MULTIPLIER=2
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
-2000<=CONCENTRATION COEFF<=10000
-2000<=CONSTANT TAX<=10000
```

CONC_EMISS_TAX.PRM

Identifies optimal carbon tax policy with constant, atmospheric CO2 concentration, and emissions rate terms.

```
:OPTIMIZER=Powell
:SENSITIVITY=Off
:MULTIPLE_START=Off
:RANDOM_NUMER=Linear
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.01
:TOLERANCE_MULTIPLIER=2
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
-2000<=CONCENTRATION COEFF<=10000
-2000<=CONSTANT TAX<=10000
-2000<=Emissions Coeff<=10000
```

PAYOFF.PRM

Objective function for optimization.

```
*P
Discounted_Utility/1
```

SHORT.LST

Parameter list for reporting in sensitivity runs.

```
Total Energy Carbon Emissions
Gross Output
Cum Disc Utility
Energy Production
Atmos UOcean Temp
Discounted Utility
consumption
Effective CO2 in Atmosphere
Carbon Tax
Total Energy Cost
Output Loss
Total Energy Investment
Depletion Rent[oilgas]
```

```
Marginal Utility
```

DISCUTILITY.LST

Parameter list for reporting in sensitivity runs.

```
Discounted Utility
Cum Disc Utility
```

Equilibrium Tests

EQUIL.CMD

Tests equilibrium response to energy price changes (implemented using taxes).

```
{Sensitivity command file - equilibrium responses to step-input tax policies}
SPECIAL>NOINTERACTION

SIMULATE>SENSITIVITY|
SIMULATE>OPTIMIZE|0
SIMULATE>SAVELIST|

{base equilibrium run}
SIMULATE>RUNNAME|j+equil.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|equil.cin
SIMULATE>SETVAL|price adjustment time=1e9
MENU>RUN

{equilibrium run + tax step}
SIMULATE>RUNNAME|j+equil2.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|equil.cin
SIMULATE>SETVAL|price adjustment time=1e9
SIMULATE>SETVAL|constant tax=100
MENU>RUN

{equilibrium run + tax step + full adjustment in new energy intensity}
SIMULATE>RUNNAME|j+equil3.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|equil.cin
SIMULATE>SETVAL|price adjustment time=1e9
SIMULATE>SETVAL|constant tax=100
SIMULATE>SETVAL|energy adj coeff=1
MENU>RUN

{equilibrium run + tax step + full adjustment in new energy intensity + short
      delays}
SIMULATE>RUNNAME|j+equil4.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|equil.cin
SIMULATE>SETVAL|price adjustment time=1e9
SIMULATE>SETVAL|constant tax=100
SIMULATE>SETVAL|energy adj coeff=1
SIMULATE>SETVAL|Energy Intensity Adjustment Time=1
```

```
SIMULATE>SETVAL|Energy Price Perc Time=1
SIMULATE>SETVAL|Energy Forecast Time=0
MENU>RUN
```

EQUIL.CIN

Initializes model for equilibrium testing by eliminating exogenous growth trends and data drivers.

```
Investment Switch = 2
Low Lim Energy Tech[coal] = 1
Low Lim Energy Tech[oilgas] = 1
Low Lim Energy Tech[hn] = 1
Low Lim Energy Tech[new] = 1
Reference Resource[hn] = 1e30
Reference Resource[new] = 1e30
Initial Resource[coal] = 1e30
Initial Resource[oilgas] = 1e30
Initial_Pop_Growth_Rt = 0
Init_Frac_Factor_Prod_Gr_Rt = 0
Frac_Auton_Energy_Eff_Improvement_Rate = 0
Climate_Damage_Scale[tangible] = 0
Hist_Energy_Growth_Rate[coal] = 1e-6
Hist_Energy_Growth_Rate[oilgas] = 1e-6
Hist_Energy_Growth_Rate[hn] = 1e-6
Hist_Energy_Growth_Rate[new] = 1e-6
Final Time = 2300
Initial Tax Time = 2210
Tax Adj Time = .25
Const Interest Rate = 0
Asymptotic Frac Factor Prod Gr Rt = 0
Price Switch[coal] = 0
Price Switch[oilgas] = 0
Interest Rate Switch = 1
```

Scenarios

SCENARIO.CMD

Runs a variety of model scenarios.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION

SIMULATE>BASED|
SIMULATE>READCIN|
SIMULATE>SAVELIST|
SIMULATE>SENSITIVITY|
SIMULATE>OPTIMIZE|0

SIMULATE>RUNNAME|a.vdf
SIMULATE>READCIN|a.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN
```

```
SIMULATE>RUNNAME|b.vdf
SIMULATE>READCIN|b.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|c.vdf
SIMULATE>READCIN|c.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|d.vdf
SIMULATE>READCIN|d.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|e.vdf
SIMULATE>READCIN|e.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|f.vdf
SIMULATE>READCIN|f.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|g.vdf
SIMULATE>READCIN|g.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|h.vdf
SIMULATE>READCIN|h.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|i.vdf
SIMULATE>READCIN|i.cin
SIMULATE>ADDCIN|scenario.cin
MENU>RUN

SIMULATE>RUNNAME|j.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|SAVEPER=1
MENU>RUN
```

SCENARIOS+100.CMD

Runs scenarios with constant 100 $/TonC carbon tax implemented in 1995.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION

SIMULATE>BASED|
```

```
SIMULATE>READCIN|
SIMULATE>SAVELIST|
SIMULATE>SENSITIVITY|
SIMULATE>OPTIMIZE|0

SIMULATE>RUNNAME|a+100.vdf
SIMULATE>READCIN|a.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|b+100.vdf
SIMULATE>READCIN|b.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|c+100.vdf
SIMULATE>READCIN|c.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|d+100.vdf
SIMULATE>READCIN|d.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|e+100.vdf
SIMULATE>READCIN|e.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|f+100.vdf
SIMULATE>READCIN|f.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|g+100.vdf
SIMULATE>READCIN|g.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|h+100.vdf
SIMULATE>READCIN|h.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|i+100.vdf
```

```
SIMULATE>READCIN|i.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN

SIMULATE>RUNNAME|j+100.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|scenario.cin
SIMULATE>SETVAL|Constant Tax=100
MENU>RUN
```

SCENARIOS+CONST.CMD

Runs scenarios, with search for optimal constant carbon tax.

```
{Sensitivity command file - best constant tax in each scenario, with slow
      implementation to prevent adjustment costs from dominating}
SPECIAL>NOINTERACTION

SIMULATE>BASED|
SIMULATE>READCIN|
SIMULATE>SAVELIST|
SIMULATE>SENSITIVITY|
SIMULATE>OPTIMIZE|1
SIMULATE>OPTPARM|const_tax.prm
SIMULATE>PAYOFF|payoff.prm

SIMULATE>RUNNAME|a+const.vdf
SIMULATE>READCIN|a.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|b+const.vdf
SIMULATE>READCIN|b.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|c+const.vdf
SIMULATE>READCIN|c.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|d+const.vdf
SIMULATE>READCIN|d.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|e+const.vdf
SIMULATE>READCIN|e.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|f+const.vdf
SIMULATE>READCIN|f.cin
```

```
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|g+const.vdf
SIMULATE>READCIN|g.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|h+const.vdf
SIMULATE>READCIN|h.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|i+const.vdf
SIMULATE>READCIN|i.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|j+const.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN
```

SCENARIOS+CONST2.CMD

Runs scenarios, with search for optimal constant carbon taxes, depletion tax, optimization with limited horizon, and no-climate-change conditions.

```
{Sensitivity command file - best taxes for various scenarios}
SPECIAL>NOINTERACTION

SIMULATE>BASED|
SIMULATE>READCIN|
SIMULATE>SAVELIST|
SIMULATE>SENSITIVITY|
SIMULATE>PAYOFF|payoff.prm

{correction for depletion}

SIMULATE>OPTIMIZE|0

SIMULATE>RUNNAME|j+shad.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

{best constant taxes for selected scenarios, implemented over 20 years}

SIMULATE>OPTIMIZE|1
SIMULATE>OPTPARM|const_tax.prm

SIMULATE>RUNNAME|a+const.vdf
SIMULATE>READCIN|a.cin
```

```
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

SIMULATE>RUNNAME|d+const.vdf
SIMULATE>READCIN|d.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

SIMULATE>RUNNAME|j+const.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

SIMULATE>RUNNAME|j+const+nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|Minimum Carbon Tax=-100
SIMULATE>SETVAL|climate damage scale[tangible]=0
MENU>RUN

{limited horizon}
SIMULATE>RUNNAME|j+const+2100.vdf
SIMULATE>BASED|j+const.vdf
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|final time=2100
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

{correction for depletion}
SIMULATE>RUNNAME|j+shad+const.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

SIMULATE>RUNNAME|j+shad+const+nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|Minimum Carbon Tax=-100
SIMULATE>SETVAL|climate damage scale[tangible]=0
MENU>RUN

{best taxes with constant and atmospheric concentration terms}

SIMULATE>OPTPARM|conc_tax.prm

SIMULATE>RUNNAME|j+conc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|Minimum Carbon Tax=-100
```

```
MENU>RUN

{same, without climate change}
SIMULATE>RUNNAME|j+conc+nocc
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|climate damage scale[tangible]=0
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

{best tax with constant and atmospheric concentration terms, after correction
      for depletion}
SIMULATE>RUNNAME|j+shad+conc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN

{same, without climate change}
SIMULATE>RUNNAME|j+shad+conc+nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|climate damage scale[tangible]=0
SIMULATE>SETVAL|Minimum Carbon Tax=-100
MENU>RUN
```

SCENARIO.CIN

Sets default parameters for running scenarios.

```
FINAL TIME = 2100
SAVEPER = 1
```

A.CIN

Scenario A

```
 {A}
 {DICE-like}
{exogenous drivers}
Asymptotic_Frac_Factor_Prod_Gr_Rt = 0
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
SR_Elasticity = 0.5
SR_Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
Energy_Construction_Delay[Coal] = 1
Energy_Construction_Delay[OilGas] = 1
Energy_Construction_Delay[HN] = 1
Energy_Construction_Delay[New] = 1
Capital_Share[Coal] = 0.1
Capital_Share[OilGas] = 0.1
Capital_Share[HN] = 0.1
Capital_Share[New] = 0.1
Supply_Line_Correction_Time = 1
Capital_Corr_Time = 1
{energy req. embodiment}
Energy_Intensity_Adjustment_Time = 1
{retrofits}
Retrofit_Rate = 1
{depletion}
Reference_Resource[hn] =  1E+30
Reference_Resource[new] =  1E+30
Initial_Resource[coal] =  1E+30
Initial_Resource[oilgas] =  1E+30
{energy technology}
Low_Lim_Energy_Tech[coal] = 1
```

```
Low_Lim_Energy_Tech[oilgas] = 1
Low_Lim_Energy_Tech[hn] = 1
Low_Lim_Energy_Tech[new] =  1
Endogenous_Tech_Fraction = 0
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

B.CIN

Scenario B

```
 {B}
 {More Growth}
{exogenous drivers}
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
SR_Elasticity = 0.5
SR_Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
Energy_Construction_Delay[Coal] = 1
Energy_Construction_Delay[OilGas] = 1
Energy_Construction_Delay[HN] = 1
Energy_Construction_Delay[New] = 1
Capital_Share[Coal] = 0.1
Capital_Share[OilGas] = 0.1
Capital_Share[HN] = 0.1
Capital_Share[New] = 0.1
Supply_Line_Correction_Time = 1
Capital_Corr_Time = 1
{energy req. embodiment}
Energy_Intensity_Adjustment_Time = 1
{retrofits}
Retrofit_Rate = 1
{depletion}
Reference_Resource[hn] =  1E+30
Reference_Resource[new] =  1E+30
Initial_Resource[coal] =  1E+30
Initial_Resource[oilgas] =  1E+30
{energy technology}
Low_Lim_Energy_Tech[coal] = 1
Low_Lim_Energy_Tech[oilgas] = 1
Low_Lim_Energy_Tech[hn] = 1
Low_Lim_Energy_Tech[new] =  1
Endogenous_Tech_Fraction = 0
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

C.CIN

Scenario C

```
 {C}
 {Depletion}
{exogenous drivers}
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
SR_Elasticity = 0.5
SR_Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
Energy_Construction_Delay[Coal] = 1
Energy_Construction_Delay[OilGas] = 1
Energy_Construction_Delay[HN] = 1
Energy_Construction_Delay[New] = 1
Capital_Share[Coal] = 0.1
Capital_Share[OilGas] = 0.1
Capital_Share[HN] = 0.1
Capital_Share[New] = 0.1
Supply_Line_Correction_Time = 1
Capital_Corr_Time = 1
{energy req. embodiment}
Energy_Intensity_Adjustment_Time = 1
{retrofits}
Retrofit_Rate = 1
{depletion}
{energy technology}
Low_Lim_Energy_Tech[coal] = 1
Low_Lim_Energy_Tech[oilgas] = 1
```

```
Low_Lim_Energy_Tech[hn] = 1
Low_Lim_Energy_Tech[new] =  1
Endogenous_Tech_Fraction = 0
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

D.CIN

Scenario D

```
{D}
{Auton. Energy Tech.}
{exogenous drivers}
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
SR_Elasticity = 0.5
SR_Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
Energy_Construction_Delay[Coal] = 1
Energy_Construction_Delay[OilGas] = 1
Energy_Construction_Delay[HN] = 1
Energy_Construction_Delay[New] = 1
Capital_Share[Coal] = 0.1
Capital_Share[OilGas] = 0.1
Capital_Share[HN] = 0.1
Capital_Share[New] = 0.1
Supply_Line_Correction_Time = 1
Capital_Corr_Time = 1
{energy req. embodiment}
Energy_Intensity_Adjustment_Time = 1
{retrofits}
Retrofit_Rate = 1
{depletion}
{energy technology}
Endogenous_Tech_Fraction = 0
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

E.CIN

Scenario E

```
{E}
{Endog. Energy Tech.}
{exogenous drivers}
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
SR_Elasticity = 0.5
SR_Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
Energy_Construction_Delay[Coal] = 1
Energy_Construction_Delay[OilGas] = 1
Energy_Construction_Delay[HN] = 1
Energy_Construction_Delay[New] = 1
Capital_Share[Coal] = 0.1
Capital_Share[OilGas] = 0.1
Capital_Share[HN] = 0.1
Capital_Share[New] = 0.1
Supply_Line_Correction_Time = 1
Capital_Corr_Time = 1
{energy req. embodiment}
Energy_Intensity_Adjustment_Time = 1
{retrofits}
Retrofit_Rate = 1
{depletion}
{energy technology}
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

F.CIN

Scenario F

```
{F}
{Energy Capac}
{exogenous drivers}
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
SR_Elasticity = 0.5
SR_Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
{energy req. embodiment}
Energy_Intensity_Adjustment_Time = 1
{retrofits}
Retrofit_Rate = 1
{depletion}
{energy technology}
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

G.CIN

Scenario G

```
{G}
{Embodiment}
{exogenous drivers}
{production structure}
Capital_Energy_Subst_Elast = 0.5
Energy_Subst_Elast = 0.7
{behavior}
Energy_Forecast_Time = 0
Energy_Price_Perc_Time = 2
Output_Perc_Time = 1
Energy_Adj_Coeff = 1
Return_Perc_Time = 1
Tax_Adj_Time = 1
{energy capacitation}
{energy req. embodiment}
{retrofits}
{depletion}
{energy technology}
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

H.CIN

Scenario H

```
{H}
{Behavior}
{exogenous drivers}
{production structure}
{behavior}
{energy capacitation}
{energy req. embodiment}
{retrofits}
{depletion}
{energy technology}
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch =  0
```

I.CIN

Scenario I

```
{I}
{Carbon Cycle}
{exogenous drivers}
{production structure}
{behavior}
{energy capacitation}
```

```
{energy req. embodiment}
{retrofits}
{depletion}
{energy technology}
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
```

J.CIN

Scenario J

```
 {J}
 {Fair Discount}
{exogenous drivers}
{production structure}
{behavior}
{energy capacitation}
{energy req. embodiment}
{retrofits}
{depletion}
{energy technology}
{welfare evaluation}
{carbon cycle}
```

Depletion and Perception Bias

CONST_TAX_SENSI.CMD

Evaluates sensitivity to constant carbon taxes, with and without climate change, depletion tax, and energy price perception bias.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION

SIMULATE>BASED|
SIMULATE>SAVELIST|discutility.lst
SIMULATE>OPTIMIZE|0

{constant tax sensitivity}

SIMULATE>SENSITIVITY|const_tax_sensi_100.prm
SIMULATE>RUNNAME|j+const_sensi_100.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|minimum carbon tax=-100
MENU>RUN

SIMULATE>SENSITIVITY|const_tax_sensi_1000.prm
SIMULATE>RUNNAME|j+const_sensi_1000.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

{same, no climate change}

SIMULATE>SENSITIVITY|const_tax_sensi_100.prm
SIMULATE>RUNNAME|j+const_sensi_100_nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|minimum carbon tax=-100
SIMULATE>SETVAL|climate damage scale[tangible]=0
```

```
MENU>RUN

SIMULATE>SENSITIVITY|const_tax_sensi_1000.prm
SIMULATE>RUNNAME|j+const_sensi_1000_nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|climate damage scale[tangible]=0
MENU>RUN

{constant tax sensitivity, with depletion tax}

SIMULATE>SENSITIVITY|const_tax_sensi_100.prm
SIMULATE>RUNNAME|j+shad+const_sensi_100.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|minimum carbon tax=-100
MENU>RUN

SIMULATE>SENSITIVITY|const_tax_sensi_1000.prm
SIMULATE>RUNNAME|j+shad+const_sensi_1000.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

{same, no climate change}

SIMULATE>SENSITIVITY|const_tax_sensi_100.prm
SIMULATE>RUNNAME|j+shad+const_s_100_nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|minimum carbon tax=-100
SIMULATE>SETVAL|climate damage scale[tangible]=0
MENU>RUN

SIMULATE>SENSITIVITY|const_tax_sensi_1000.prm
SIMULATE>RUNNAME|j+shad+const_s_1000_nocc.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|climate damage scale[tangible]=0
MENU>RUN

{constant tax sensitivity, with biased energy price perception}

SIMULATE>SENSITIVITY|const_tax_sensi_200.prm
SIMULATE>RUNNAME|j+bias0+const_sensi_200.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|energy price discount=1
MENU>RUN
```

```
SIMULATE>SENSITIVITY|const_tax_sensi_200.prm
SIMULATE>RUNNAME|j+bias9+const_sensi_200.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|energy price discount=.9
MENU>RUN

SIMULATE>SENSITIVITY|const_tax_sensi_200.prm
SIMULATE>RUNNAME|j+bias8+const_sensi_200.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|energy price discount=.8
MENU>RUN

SIMULATE>SENSITIVITY|const_tax_sensi_200.prm
SIMULATE>RUNNAME|j+bias7+const_sensi_200.vdf
SIMULATE>READCIN|j.cin
SIMULATE>ADDCIN|shadow.cin
SIMULATE>SETVAL|tax adj time=20
SIMULATE>SETVAL|energy price discount=.7
MENU>RUN
```

CONST_TAX_SENSI_100.PRM

Sensitivity control file for taxes in the interval -100 to 200 $/TonC.

```
9,U,1234
Constant Tax=VECTOR(-100,200,10)
```

CONST_TAX_SENSI_200.PRM

Sensitivity control file for taxes in the interval 0 to 400 $/TonC.

```
9,U,1234
Constant Tax=VECTOR(0,400,20)
```

CONST_TAX_SENSI_1000.PRM

Sensitivity control file for taxes in the interval 250 to 1250 $/TonC.

```
9,U,1234
Constant Tax=VECTOR(250,1250,50)
```

INIT_DEPL.PRM

Optimization control file for initial depletion tax.

```
:OPTIMIZER=Powell
:SENSITIVITY=Off
:MULTIPLE_START=Off
:RANDOM_NUMER=Linear
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
```

```
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.01
:TOLERANCE_MULTIPLIER=21
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
0<=INITIAL DEPLETION TAX[OILGAS]=.3<=1
```

SHADOW.CIN

Switches depletion tax on.

```
Frac Depletion Recovered = 1
```

Meeting Constraints

CONSTRAIN.CMD

Finds optimal carbon taxes with various initiation times, with and without CO2 concentration constraints.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION
SIMULATE>SENSITIVITY|
SIMULATE>SAVELIST|
SIMULATE>OPTIMIZE|1
SIMULATE>PAYOFF|cpayoff.prm
SIMULATE>OPTPARM|conc_tax.prm
SIMULATE>SAVELIST|
SIMULATE>BASED|

{Group 1 - no constraint}
SIMULATE>RUNNAME|constrain095.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=0
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=1995
MENU>RUN

SIMULATE>RUNNAME|constrain005.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=0
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2005
MENU>RUN

SIMULATE>RUNNAME|constrain015.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=0
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2015
MENU>RUN
```

```
SIMULATE>RUNNAME|constrain025.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=0
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2025
MENU>RUN

SIMULATE>RUNNAME|constrain035.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=0
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2035
MENU>RUN

SIMULATE>RUNNAME|constrain045.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=0
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2045
MENU>RUN

{Group 2 - 2xCO2}
SIMULATE>RUNNAME|constrain295.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=1995
MENU>RUN

SIMULATE>RUNNAME|constrain205.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2005
MENU>RUN

SIMULATE>RUNNAME|constrain215.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2015
MENU>RUN

SIMULATE>RUNNAME|constrain225.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
```

```
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2025
MENU>RUN

SIMULATE>RUNNAME|constrain235.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2035
MENU>RUN
SIMULATE>RUNNAME|constrain245.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=2
SIMULATE>SETVAL|Initial_Tax_Time=2045
MENU>RUN

{Group 3 - 3xCO2}
SIMULATE>RUNNAME|constrain395.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=3
SIMULATE>SETVAL|Initial_Tax_Time=1995
MENU>RUN

SIMULATE>RUNNAME|constrain305.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=3
SIMULATE>SETVAL|Initial_Tax_Time=2005
MENU>RUN

SIMULATE>RUNNAME|constrain315.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=3
SIMULATE>SETVAL|Initial_Tax_Time=2015
MENU>RUN

SIMULATE>RUNNAME|constrain325.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=3
SIMULATE>SETVAL|Initial_Tax_Time=2025
MENU>RUN

{Group 4 - 4xCO2}
SIMULATE>RUNNAME|constrain495.vdf
```

```
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=4
SIMULATE>SETVAL|Initial_Tax_Time=1995
MENU>RUN

SIMULATE>RUNNAME|constrain405.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=4
SIMULATE>SETVAL|Initial_Tax_Time=2005
MENU>RUN

SIMULATE>RUNNAME|constrain415.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=4
SIMULATE>SETVAL|Initial_Tax_Time=2015
MENU>RUN

SIMULATE>RUNNAME|constrain425.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|FINAL TIME=2200
SIMULATE>SETVAL|Constraint Violation Cost=1e12
SIMULATE>SETVAL|CO2_Constraint_Factor=4
SIMULATE>SETVAL|Initial_Tax_Time=2025
MENU>RUN
```

CPAYOFF.PRM

Constrained objective function.

```
*P
Net_Discounted_Utility/1
```

E_CAPAC.CIN

Relaxes capacity constraints in energy system.

```
{relaxes energy system capacitation assumption}
Energy_Construction_Delay[Coal] =                    1
Energy_Construction_Delay[OilGas] =                  1
Energy_Construction_Delay[HN] =                      1
Energy_Construction_Delay[New] =                     1
Capital_Share[Coal] =                                0.1
Capital_Share[OilGas] =                              0.1
Capital_Share[HN] =                                  0.1
Capital_Share[New] =                                 0.1
Supply_Line_Correction_Time =                        1
Capital_Corr_Time =                                  1
```

FLEXI2.CIN

Raises short run substitution elasticities and removes delays in adjustment to create a more flexible production structure.

```
{implements a production structure with high short-run flexibility}

{production structure}
SR_Elasticity =                                                  0.5
SR_Energy_Subst_Elast =                                          0.7

{behavior}
Energy_Forecast_Time =                                           0
Energy_Price_Perc_Time =                                         2

Output_Perc_Time =                                               1
Energy_Adj_Coeff =                                               1
Return_Perc_Time =                                               1

{energy req. embodiment}
Energy_Intensity_Adjustment_Time =                               1

{retrofits}
Retrofit_Rate =                                                  1
```

Technology

TECH_DATA.CMD

Compares endogenous and exogenous technology trajectories.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION
SIMULATE>OPTIMIZE|0
SIMULATE>SENSITIVITY|
SIMULATE>SAVELIST|
SIMULATE>BASED|
SIMULATE>OPTPARM|const_tax.prm

{run base cases}
SIMULATE>RUNNAME|j+t.vdf
SIMULATE>READCIN|shadow.cin
MENU>RUN

SIMULATE>RUNNAME|j+t+100.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|Constant_Tax=100
MENU>RUN

SIMULATE>RUNNAME|j+s.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|scale.cin
MENU>RUN
```

```
SIMULATE>RUNNAME|j+s+100.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|scale.cin
SIMULATE>SETVAL|Constant_Tax=100
MENU>RUN

SIMULATE>OPTIMIZE|1
SIMULATE>RUNNAME|j+s+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|scale.cin
SIMULATE>SETVAL|Constant_Tax=100
SIMULATE>SETVAL|tax adj time=20
MENU>RUN

SIMULATE>RUNNAME|j+t+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|Constant_Tax=100
SIMULATE>SETVAL|tax adj time=20
MENU>RUN
SIMULATE>OPTIMIZE|0

{convert technology trajectories to data drivers}
SPECIAL>LOADMODEL|tech_data.mdl

SIMULATE>DATA|j+t.vdf
SIMULATE>RUNNAME|tech_data.vdf
MENU>RUN

SIMULATE>DATA|j+s.vdf
SIMULATE>RUNNAME|scale_data.vdf
MENU>RUN

{run with exogenous technology}
SPECIAL>LOADMODEL|free 6.mdl
SIMULATE>OPTIMIZE|0
SIMULATE>OPTPARM|const_tax.prm
SIMULATE>SENSITIVITY|
SIMULATE>SAVELIST|
SIMULATE>BASED|

SIMULATE>RUNNAME|j+exs+100.vdf
SIMULATE>DATA|all_data.vdf scale_data.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|scale.cin
SIMULATE>ADDCIN|tech_data.cin
SIMULATE>SETVAL|Constant_Tax=100
MENU>RUN

SIMULATE>OPTIMIZE|1
SIMULATE>RUNNAME|j+exs+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|scale.cin
SIMULATE>ADDCIN|tech_data.cin
SIMULATE>SETVAL|Constant_Tax=100
```

```
SIMULATE>SETVAL|tax adj time=20
MENU>RUN
SIMULATE>OPTIMIZE|0

SIMULATE>RUNNAME|j+ext+100.vdf
SIMULATE>DATA|all_data.vdf tech_data.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|tech_data.cin
SIMULATE>SETVAL|Constant_Tax=100
MENU>RUN

SIMULATE>OPTIMIZE|1
SIMULATE>RUNNAME|j+ext+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|tech_data.cin
SIMULATE>SETVAL|Constant_Tax=100
SIMULATE>SETVAL|tax adj time=20
MENU>RUN
SIMULATE>OPTIMIZE|0
```

TECH_DATA.CIN

Switches technology trajectory to exogenous data series.

```
Tech Data Switch = 1
```

TECH_DATA.MDL

Data model, used to make the technology trajectory from one simulation run usable as an exogenous input to another simulation run.

`Energy Technology[source]`

dmnl

Energy technology level, extracted from a simulation run of full model.

`source: Coal,OilGas,HN,New`

dmnl

Energy sources.

`Technology Data[source]= Energy Technology[source]`

dmnl

Technology data, for input as data driver to full model.

:SUPPLEMENTARY

.Control

Simulation Control Paramaters

`FINAL TIME  = 2300`

Year

The final time for the simulation.

`INITIAL TIME  = 1960`

Year

The initial time for the simulation.

```
SAVEPER  = TIME STEP
```
Year
The frequency with which output is stored.

```
TIME STEP  = 1
```
Year
The time step for the simulation.

Discounting and Growth

DISC_GROWTH.CMD

Compares optimal carbon taxes with different growth and discounting assumptions.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION
SIMULATE>SENSITIVITY|
SIMULATE>SAVELIST|
SIMULATE>OPTIMIZE|1
SIMULATE>PAYOFF|payoff.prm
SIMULATE>OPTPARM|const_tax.prm
SIMULATE>BASED|

{run 1 is j+shad+const}

{run 2 - low growth}
SIMULATE>RUNNAME|j+shad+logrow+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>SETVAL|Tax Adj Time=20
SIMULATE>SETVAL|Asymptotic Frac Factor Prod Gr Rt=0
MENU>RUN

{run 3 - conventional discounting (scenario I)}
SIMULATE>RUNNAME|i+shad+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|i.cin
SIMULATE>SETVAL|Tax Adj Time=20
MENU>RUN

{run 4 - low growth and conventional discounting}
SIMULATE>RUNNAME|i+shad+logrow+const.vdf
SIMULATE>READCIN|shadow.cin
SIMULATE>ADDCIN|i.cin
SIMULATE>SETVAL|Tax Adj Time=20
SIMULATE>SETVAL|Asymptotic Frac Factor Prod Gr Rt=0
MENU>RUN
```

Intangibles

Resets damage functions to incorporate intangible damages.

INTANG.CIN

```
Climate_Damage_Scale[Tangible]=.0055
```

```
Climate_Damage_Scale[InTangible]=.0075
Share of Consumption=.5
```

Parameter Sensitivity

SENSI_ALL_CONST.CMD

Evaluates of model behavior to 10% perturbations of selected model parameters.

```
{Sensitivity command file, for evaluating parameter senstivity to all
      constants}
SPECIAL>NOINTERACTION

{rerun base scenarios for comparison}
SIMULATE>RUNNAME|ad.vdf
SIMULATE>READCIN|a.cin
MENU>RUN

SIMULATE>RUNNAME|jd.vdf
SIMULATE>READCIN|j.cin
MENU>RUN

SIMULATE>OPTIMIZE|1
SIMULATE>OPTPARM|sel_const.prm
SIMULATE>BASED|
SIMULATE>READRUNCHG|
SIMULATE>RUNNAME|param_sensi.vdf

SIMULATE>READCIN|j.cin
SIMULATE>DATA|all_data.vdf tech_data.vdf jd.vdf

SIMULATE>PAYOFF|util_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_j_util.tab
FILE>RENAME|sensitiv.tab|sensitiv_j_util.tab

SIMULATE>PAYOFF|output_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_j_out.tab
FILE>RENAME|sensitiv.tab|sensitiv_j_out.tab

SIMULATE>PAYOFF|temp_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_j_temp.tab
FILE>RENAME|sensitiv.tab|sensitiv_j_temp.tab

SIMULATE>PAYOFF|emiss_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_j_emiss.tab
FILE>RENAME|sensitiv.tab|sensitiv_j_emiss.tab

SIMULATE>READCIN|a.cin
SIMULATE>DATA|all_data.vdf tech_data.vdf ad.vdf
```

```
SIMULATE>PAYOFF|util_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_a_util.tab
FILE>RENAME|sensitiv.tab|sensitiv_a_util.tab

SIMULATE>PAYOFF|output_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_a_out.tab
FILE>RENAME|sensitiv.tab|sensitiv_a_out.tab

SIMULATE>PAYOFF|temp_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_a_temp.tab
FILE>RENAME|sensitiv.tab|sensitiv_a_temp.tab

SIMULATE>PAYOFF|emiss_pay.prm
MENU>RUN
FILE>RENAME|sortsens.tab|sortsens_a_emiss.tab
FILE>RENAME|sensitiv.tab|sensitiv_a_emiss.tab
```

ALL_CONST.PRM

Optimization control file for evaluating sensitivity to all parameters.

```
:OPTIMIZER=Off
:SENSITIVITY=All Constants=10
:MULTIPLE_START=Off
:RANDOM_NUMER=Linear
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.0003
:TOLERANCE_MULTIPLIER=21
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
```

SEL_CONST.PRM

Optimization control file for evaluating sensitivity to the listed subset of model parameters.

```
:OPTIMIZER=Off
:SENSITIVITY=Parameter Percent=10
:MULTIPLE_START=Off
:RANDOM_NUMER=Linear
:OUTPUT_LEVEL=On
:TRACE=Off
:MAX_ITERATIONS=1000
:PASS_LIMIT=2
:FRACTIONAL_TOLERANCE=0.0003
:TOLERANCE_MULTIPLIER=21
:ABSOLUTE_TOLERANCE=1
:SCALE_ABSOLUTE=1
A UO Heat Cap                        Asymptotic AEEI
```

Asymptotic Frac Factor Prod Gr Rt
Biomass Res Time
Biostim Coeff
Buff CO2 Coeff
Capital Corr Time
Capital Energy Subst Elast
Capital Lifetime
Capital Share[coal]
Capital Share[hn]
Capital Share[new]
Capital Share[oilgas]
Climate Damage Nonlinearity[tangible]
Climate Damage Scale[tangible]
Climate Sensitivity
CO2 Rad Force Coeff
Consumer Discount Rate
Consumer Inequal Aversion
Eddy Diff Coeff
Endogenous Tech Fraction
Energy Adj Coeff
Energy Capital Lifetime[coal]
Energy Capital Lifetime[hn]
Energy Capital Lifetime[new]
Energy Capital Lifetime[oilgas]
Energy Construction Delay[coal]
Energy Construction Delay[hn]
Energy Construction Delay[new]
Energy Construction Delay[oilgas]
Energy Delivery Delay
Energy Forecast Time
Energy Intensity Adjustment Time
Energy Learning Rate
Energy Order Adj Coeff
Energy Price Discount
Energy Price Perc Time
Energy Scale Effect
Energy Subst Elast
Energy Trend Time
Forecast Pop Growth Rt Decline Rt
Frac Auton Energy Eff Improvement Rate
Frac Depletion Recovered
Frac Factor Prod Gr Rt Decline Rt
Fractional Adaptation Rate[tangible]
Growth Trend Time
Heat Capacity Ratio
Heat Trans Coeff
Hist Energy Growth Rate[coal]
Hist Energy Growth Rate[hn]
Hist Energy Growth Rate[new]
Hist Energy Growth Rate[cilgas]
Humification Fraction
Humus Res Time
Init Atmos UOcean Temp
init co2 in atm
Init CO2 in Biomass
Init CO2 in Deep Ocean[layer10]
Init CO2 in Deep Ocean[layer1]
Init CO2 in Deep Ocean[layer2]
Init CO2 in Deep Ocean[layer3]
Init CO2 in Deep Ocean[layer4]
Init CO2 in Deep Ocean[layer5]
Init CO2 in Deep Ocean[layer6]
Init CO2 in Deep Ocean[layer6]
Init CO2 in Deep Ocean[layer7]
Init CO2 in Deep Ocean[layer8]
Init CO2 in Deep Ocean[layer9]
Init CO2 in Humus
Init CO2 in Mixed Ocean
Init Frac Factor Prod Gr Rt
Init NPP
Initial Cost Trend
Initial Energy Requirement[coal]
Initial Energy Requirement[hn]
Initial Energy Requirement[new]
Initial Energy Requirement[oilgas]
Initial Producer Price[coal]
Initial Producer Price[hn]
Initial Producer Price[new]
Initial Producer Price[oilgas]
Initial Resource[Coal]
Initial Resource[OilGas]
Labor Force Fraction
Low Lim Energy Tech[coal]
Low Lim Energy Tech[hn]
Low Lim Energy Tech[new]
Low Lim Energy Tech[oilgas]
LR Order Trend Time
LR Output Trend Time
Marginal Atmos Retention
Max Input Ratio
Min Depletion Time
Mixed Depth
Mixing Time
Output Perc Time
Output Trend Establishment Time
Preind CO2 in Mixed Layer
Preindustrial CO2
Price Adjustment Time
Rate of CO2 Transfer
Rate of Inequal Aversion
Rate of Time Pref
Ref Buffer Factor
Ref Energy Value Share[Coal]
Ref Energy Value Share[hn]
Ref Energy Value Share[new]
Reference Resource[HN]
Reference Resource[New]
Retrofit Rate

```
Return Coeff
Return Perc Time
Resource Elasticity[coal]
Resource Elasticity[hn]
Resource Elasticity[new]
Resource Elasticity[oilgas]
SR Elasticity
SR Energy Price Perc Time
SR Energy Subst Elast
Supply Demand Coeff
Supply Line Correction Time
Time to Correct Rent
Trend Time
Value Share of Labor
Weight to Average Cost
Weight to Marg Cost
```

EMISS_PAY.PRM

Objective function for measuring sum-of-squares variation in emissions.

```
*C
Total_Carbon_Emissions/1
```

OUTPUT_PAY.PRM

Objective function for measuring sum-of-squares variation in output.

```
*C
Gross_Output/1
```

TEMP_PAY.PRM

Objective function for measuring sum-of-squares variation in temperature.

```
*C
Atmos UOcean Temp/1
```

UTIL_PAY.PRM

Objective function for measuring sum-of-squares variation in utility.

```
*C
Discounted_Utility/1
```

Multivariate Sensitivity

STOCH_OPT.CMD

Performs grid search for optimal carbon tax policy (with constant and atmospheric concentration terms) under uncertainty.

```
{Sensitivity command file - for stochastic evaluation of carbon tax policy}
SPECIAL>NOINTERACTION
SIMULATE>SENSITIVITY|uncertain_sensi2.prm
SIMULATE>OPTIMIZE|0
SIMULATE>SAVELIST|discutility.lst

{Group 1 - varying all variables}

SIMULATE>RUNNAME|stoch_opt_6.vdf
SIMULATE>SETVAL|Constant_Tax= -1000
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_7.vdf
SIMULATE>SETVAL|Constant_Tax= -1000
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|
```

```
SIMULATE>RUNNAME|stoch_opt_8.vdf
SIMULATE>SETVAL|Constant_Tax= -1000
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_9.vdf
SIMULATE>SETVAL|Constant_Tax= -1000
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_26.vdf
SIMULATE>SETVAL|Constant_Tax= -300
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_27.vdf
SIMULATE>SETVAL|Constant_Tax= -300
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_28.vdf
SIMULATE>SETVAL|Constant_Tax= -300
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_29.vdf
SIMULATE>SETVAL|Constant_Tax= -300
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_36.vdf
SIMULATE>SETVAL|Constant_Tax= -100
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_37.vdf
SIMULATE>SETVAL|Constant_Tax= -100
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_38.vdf
SIMULATE>SETVAL|Constant_Tax= -100
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_39.vdf
SIMULATE>SETVAL|Constant_Tax= -100
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_46.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_47.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_48.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_49.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_55.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_56.vdf
SIMULATE>SETVAL|Constant_Tax= 0
```

```
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_57.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_58.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_59.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_61.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff= -
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_62.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff= -
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_63.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff= -
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_64.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff= -
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_65.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_66.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_67.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_68.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_69.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_71.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff= -
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_72.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff= -
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_73.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff= -
      100
MENU>RUN
SIMULATE>READRUNCHG|
```

```
SIMULATE>RUNNAME|stoch_opt_74.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff= -
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_75.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_76.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_77.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_78.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_79.vdf
SIMULATE>SETVAL|Constant_Tax= 100
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_81.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff= -
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_82.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff= -
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_83.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff= -
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_84.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff= -
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_85.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_86.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_87.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_88.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_89.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_91.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff= -
      1000
```

```
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_92.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff= -
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_93.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff= -
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_94.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff= -
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_95.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_96.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_97.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff=
      100
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_98.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff=
      300
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_99.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff=
      1000
MENU>RUN
SIMULATE>READRUNCHG|
```

STOCH_OPT_ZOOM3.CMD

Performs grid search over a restricted region for optimal carbon tax policy (with constant and atmospheric concentration terms) under uncertainty.

```
{Sensitivity command file}
SPECIAL>NOINTERACTION
SIMULATE>SENSITIVITY|uncertain_sensi2.prm
SIMULATE>OPTIMIZE|0
SIMULATE>SAVELIST|discutility.lst
SIMULATE>BASED|
SIMULATE>READCIN|

{Group 1 - combinatorial}
SIMULATE>RUNNAME|stoch_opt_zoom301.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom302.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom303.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|
```

```
SIMULATE>RUNNAME|stoch_opt_zoom304.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom305.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff=
      120
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom306.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom307.vdf
SIMULATE>SETVAL|Constant_Tax= -60
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom308.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom309.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom310.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom311.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom312.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      120
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom313.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom314.vdf
SIMULATE>SETVAL|Constant_Tax= -30
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom315.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom316.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom317.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom318.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom319.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      120
```

```
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom320.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom321.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom322.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom323.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom324.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom325.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom326.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      120
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom327.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom328.vdf
SIMULATE>SETVAL|Constant_Tax= 30
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom329.vdf
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom330.vdf
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom331.vdf
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom332.vdf
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom333.vdf
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff=
      120
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom334.vdf
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom335.vdf
```

```
SIMULATE>SETVAL|Constant_Tax= 60
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom336.vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom337 vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom338.vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom339.vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom340.vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff=
      120
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom341.vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom342.vdf
SIMULATE>SETVAL|Constant_Tax= 90
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom343.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom344.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff=
      30
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom345.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff=
      60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom346.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff=
      90
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom347.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff=
      120
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom348.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff=
      150
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_zoom349.vdf
SIMULATE>SETVAL|Constant_Tax= 120
SIMULATE>SETVAL|Concentration_Coeff=
      180
MENU>RUN
SIMULATE>READRUNCHG|
```

UNCERTAIN_SENSI2.PRM

Sensitivity command file for uncertainty analysis over subjective probability distributions.

```
20,L,456
Forecast Pop Growth Rt Decline Rt=RANDOM_NORMAL(.0027,.033,.019,.0106)
Climate Sensitivity=RANDOM_NORMAL(1.5,4.4,2.93,1.04)
Biostim Coeff=RANDOM_NORMAL(0,.7,.4,.1)
Climate Damage Scale[tangible]=RANDOM_NORMAL(0,.032,.013,.011)
Initial Resource[OilGas]=RANDOM_NORMAL(2e13,4e13,3e13,3e12)
Eddy Diff Coeff=RANDOM_NORMAL(3300,5000,4000,300)
Frac Auton Energy Eff Improvement Rate=RANDOM_NORMAL(.001,.023,.011,.0076)
Capital Energy Subst Elast=RANDOM_NORMAL(.4,.95,.7,.1)
Energy Subst Elast=RANDOM_NORMAL(1.05,3,2,.33)
Frac Depletion Recovered=RANDOM_UNIFORM(0,1)
Frac Factor Prod Gr Rt Decline Rt=RANDOM_NORMAL(0.002,.024,.011,.0077)
```

MEDIAN.CIN

Sets model parameters to median values of subjective probability distributions.

```
Forecast Pop Growth Rt Decline Rt=.019
Climate Sensitivity=2.93
Biostim Coeff=.4
Climate Damage Scale[tangible]=.013
Initial Resource[OilGas]=3e13
Eddy Diff Coeff=4000
Frac Auton Energy Eff Improvement Rate=.011
Capital Energy Subst Elast=.7
Energy Subst Elast=2
Frac Depletion Recovered=.5
Frac Factor Prod Gr Rt Decline Rt=.011
```

Emissions Pulse Test

EMISS_PULSE.CIN

Sets volume of test pulse of emissions.

```
Emissions Pulse Volume = 5e+011
```

EMISS_PULSE_SENSI.CIN

Tests impact of emissions pulse at decadal intervals from 2000 to 2100.

```
5,U,1234
Emissions Pulse Time=VECTOR(2000,2100,10)
```

Data

Exogenous data series for calibration and comparison. Only coal and oil/gas prices influence model behavior.

Elect Price (Jenkins 1989)
1960 6.64784
1961 6.95902
1962 6.8534
1963 6.95924
1964 6.77416
1965 6.96237
1966 6.94241
1967 6.50688
1968 5.72611
1969 5.45512
1970 5.2703
1971 5.75105
1972 5.[illegible]6886
1973 5.06676
1975 6.14003
1976 5.44883
1977 6.49034
1978 7.17429
1979 7.87244
1980 9.20048
1981 7.35384
1982 6.44922
1983 5.44273
1984 4.3131
1985 5.27546
1986 4.99998
1987 5.78054
1988 5.65552
Hydro Electricity (Guyol 1969; Energy Information Administration 1995)
1958 5.74306e+009
1959 5.90702e+009
1960 6.40238e+009
1961 6.77396e+009
1962 7.12661e+009
1963 7.47073e+009
1964 7.72361e+009
1980 1.62e+010
1985 1.85e+010
1986 1.88e+010
1987 1.89e+010
1988 1.96e+010
1989 1.95e+010
1990 2.02e+010
1991 2.05e+010
1992 2.04e+010
1993 2.12e+010
Nuclear Electricity (Guyol 1969; Energy Information Administration 1995)
1958 4.43664e+006
1959 1.34129e+007
1960 2.56183e+007
1961 4.09594e+007
1962 6.09336e+007
1963 1.09025e+008
1964 1.59522e+008
1980 6.40598e+009
1985 1.33e+010
1986 1.42e+010
1987 1.55e+010
1988 1.68e+010
1989 1.73e+010
1990 1.77e+010
1991 1.86e+010
1992 1.88e+010
1993 1.95e+010
Other Electricity (Guyol 1969; Energy Information Administration 1995)
1958 1.8121e+007
1959 2.10413e+007
1960 2.35966e+007
1961 2.69287e+007
1962 3.00175e+007
1963 3.36866e+007
1964 3.6738e+007
1980 1.79712e+008
1985 2.78928e+008
1986 3.33216e+008
1987 3.43512e+008
1988 3.49128e+008
1989 3.54744e+008
1990 3.58488e+008
1991 3.66912e+008
1992 3.76272e+008
1993 3.80952e+008
Thermal Electricity (Guyol 1969; Energy Information Administration 1995)
1958 1.22e+010
1959 1.38e+010
1960 1.5e+010
1961 1.62e+010
1962 1.77e+010
1963 1.94e+010
1964 2.14e+010
1980 5.23e+010
1985 5.67e+010
1986 5.76e+010
1987 6.05e+010
1988 6.23e+010
1989 6.55e+010
1990 6.63e+010
1991 6.72e+010
1992 6.76e+010
1993 6.76e+010
Total Electricity (Guyol 1969; Energy Information Administration 1995)
1958 1.79e+010
1959 1.97e+010
1960 2.15e+010
1961 2.3e+010
1962 2.49e+010
1963 2.7e+010
1964 2.93e+010
1980 6.93e+010
1985 8.22e+010
1986 8.44e+010
1987 8.83e+010
1988 9.18e+010
1989 9.5e+010
1990 9.72e+010
1991 9.91e+010
1992 9.95e+010
1993 1.01e+011
Nonenergy Carbon Emissions(IPCC 1991)
1985 8e+008
2000 1.2e+009
2025 1.6e+009
2050 1.7e+009
2075 1e+009
2100 7e+008
Other GHG Rad Forcing (Goudriaan and Ketner 1984; Nordhaus 1994)
1900 0.16
1960 0.37
1970 0.45
1980 0.55
1990 0.66
2000 0.73
2025 0.96
2050 1.18
2075 1.29
2100 1.36
World Coal Price (Congressional Research Service 1980; International Energy Agency 1986;

International Energy Agency 1995)
1950 1.83396
1955 1.41089
1960 1.27833
1961 1.30591
1962 1.2377
1963 1.32293
1964 1.34327
1965 1.25054
1966 1.14891
1967 1.12912
1968 1.15165
1969 1.23422
1970 1.30961
1971 1.35557
1972 1.31991
1973 1.38164
1974 2.07008
1975 2.7321
1976 2.69816
1977 2.62197
1978 2.46015
1979 2.40371
1980 2.83163
1981 3.09668
1982 2.878
1983 2.31532
1984 1.99282
1985 1.93236
1986 1.80543
1987 1.58402
1988 1.63258
1989 1.71791
1990 1.73208
1991 1.62826
1992 1.52719
1993 1.35947
World Crude Price (Jenkins 1989; Energy Information Administration 1995)
1925 2.09445
1930 1.55743
1938 1.75307
1950 1.55436
1955 1.5757
1960 1.14513
1961 1.06124
1962 1.00394
1963 0.992351
1964 0.940067
1965 0.918364
1966 0.888632
1967 0.865822
1968 0.789375
1969 0.720679
1970 0.687051
1971 0.909092
1972 1.13335
1973 2.44126
1974 4.71159
1975 4.38317
1976 4.47406
1977 4.61001
1978 4.29258
1979 5.9554
1980 8.77039
1981 8.69359
1982 7.45944
1983 6.21932
1984 5.9337
1985 5.36751
1986 2.53951
1987 3.28076
1988 2.50756
1989 3.06418
1990 3.5476
1991 2.84308
1992 2.75598
1993 2.37094
World Gas Price (Congressional Research Service 1980; International Energy Agency 1995)
1960 1.69
1961 1.67
1962 1.66
1963 1.64
1964 1.62
1965 1.61
1966 1.62
1967 1.64
1968 1.66
1969 1.68
1970 1.7
1971 1.73
1972 1.76
1973 1.8
1974 2.06
1975 2.47
1976 2.84
1977 3.27
1978 3.38
1979 3.99
1980 4.59608
1981 5.09324
1982 5.09938
1983 4.40839
1984 4.48125
1985 4.40583
1986 4.10606
1987 2.81703
1988 2.48003
1989 2.10342
1990 2.71898
1991 2.96603
1992 2.51092
1993 2.26163
Coal EIA (Energy Information Administration 1995)
2000 1.061e+011
2005 1.155e+011
2010 1.246e+011
Gas EIA (Energy Information Administration 1995)
2000 9.41e+010
2005 1.035e+011
2010 1.127e+011
Oil EIA (Energy Information Administration 1995)
2000 1.651e+011
2005 1.793e+011
2010 1.913e+011
Primary EIA (Energy Information Administration 1995)
2000 4.248e+011
2005 4.628e+011
2010 4.977e+011
Primary Trabalka (Trabalka 1986)
2000 4.62e+011
2025 6.73e+011
2050 9.09e+011
2075 1.196e+012
Primary WEC (World Energy Council 1989)
2000 4.5671e+011
2020 6.1585e+011
CO2 Concentration A (IPCC 1991)
1970 437
1990 679
CO2 Concentration B (IPCC 1991)
1970 398
1990 492

CO2 Concentration C (IPCC 1991)
1970 398
1990 469
CO2 Concentration D (IPCC 1991)
1970 393
1990 413
CO2 Concentration E (IPCC 1991)
1970 381
1990 407
CO2 Emissions A (IPCC 1991)
1985 6e+009
2000 7.7e+009
2025 1.15e+010
2050 1.52e+010
2075 1.87e+010
2100 2.24e+010
CO2 Emissions B (IPCC 1991)
1985 5.9e+009
2000 5.5e+009
2025 6.4e+009
2050 7.5e+009
2075 8.8e+009
2100 1.03e+010
CO2 Emissions C (IPCC 1991)
1985 5.9e+009
2000 5.6e+009
2025 6.3e+009
2050 7.1e+009
2075 5.1e+009
2100 3.5e+009
CO2 Emissions D (IPCC 1991)
1985 6e+009
2000 5.6e+009
2025 5.1e+009
2050 2.9e+009
2075 3e+009
2100 2.7e+009
CO2 Emissions E (IPCC 1991)
1985 6e+009
2000 4.6e+009
2025 3.8e+009
2050 3.7e+009
2075 3.5e+009
2100 2.6e+009
DICE IPCC CO2 Rad Forcing (Nordhaus 1994)
1900 0.37
1960 0.81
1970 1.03
1980 1.36
1990 1.79
2000 2.22
2025 3.4
2050 4.82
2075 6.25
2100 7.6
DICE IPCC Other Rad Forcing (Nordhaus 1994)
1900 0.16
1960 0.37
1970 0.45
1980 0.55
1990 0.66
2000 0.73
2025 0.96
2050 1.18
2075 1.29
2100 1.36
EMF GDP (Weyant 1995)
1990 2.195e+013
2000 2.8553e+013
2025 5.8077e+013
2050 1.0244e+014
2075 1.6638e+014
2100 2.8196e+014
2150 6.2751e+014
2200 9.8414e+014
EMF Population (Weyant 1995)
1990 5.252e+009
2000 6.205e+009
2025 8.414e+009
2050 1.0031e+010
2075 1.0849e+010
2100 1.1312e+010
2150 1.1312e+010
2200 1.1312e+010
Energy CO2 Emissions A (IPCC 1991)
1985 5.1e+009
2000 6.5e+009
2025 9.9e+009
2050 1.35e+010
2075 1.77e+010
2100 2.17e+010
Energy CO2 Emissions B (IPCC 1991)
1985 5.1e+009
2000 5.6e+009
2025 6.6e+009
2050 7.6e+009
2075 8.7e+009
2100 1.03e+010
Energy CO2 Emissions C (IPCC 1991)
1985 5.1e+009
2000 5.6e+009
2025 6.5e+009
2050 7.2e+009
2075 5e+009
2100 3.5e+009
Energy CO2 Emissions D (IPCC 1991)
1985 5.1e+009
2000 5.7e+009
2025 5.4e+009
2050 3e+009
2075 2.9e+009
2100 2.7e+009
Coal Production (International Energy Agency 1989; World Energy Council 1989; Energy Information Administration 1995)
1960 5.6692e+010
1961 5.6801e+010
1962 5.691e+010
1963 5.7019e+010
1964 5.7129e+010
1965 5.7239e+010
1966 5.7349e+010
1967 5.7459e+010
1968 5.757e+010
1969 5.7681e+010
1970 5.7792e+010
1971 5.7903e+010
1972 5.871e+010
1973 5.9342e+010
1974 5.9802e+010
1975 6.3799e+010
1976 6.5086e+010
1977 6.746e+010
1978 6.8822e+010
1979 7.2131e+010
1980 7.3438e+010
1981 7.3681e+010
1982 7.6628e+010
1983 7.6845e+010
1984 8.054e+010
1985 8.4819e+010
1986 8.6875e+010
1987 8.9057e+010

1988 9.0991e+010
1990 9.69e+010
1992 9.38e+010
Commercial Energy (Jenkins 1989; International Energy Agency 1990)
1870 5.88e+009
1890 1.4196e+010
1910 3.2844e+010
1925 4.2042e+010
1930 4.5696e+010
1938 4.977e+010
1950 7.1946e+010
1960 1.2597e+011
1961 1.3164e+011
1962 1.3756e+011
1963 1.4374e+011
1964 1.502e+011
1965 1.5696e+011
1966 1.6401e+011
1967 1.7139e+011
1968 1.7909e+011
1969 1.8715e+011
1970 1.9556e+011
1971 2.0435e+011
1972 2.1501e+011
1973 2.2739e+011
1974 2.2898e+011
1975 2.3082e+011
1976 2.4482e+011
1977 2.538e+011
1978 2.6467e+011
1979 2.7319e+011
1980 2.7125e+011
1981 2.6868e+011
1982 2.6715e+011
1983 2.7155e+011
1984 2.8373e+011
1985 2.9263e+011
1986 2.9891e+011
1987 3.1047e+011
1988 3.2111e+011
1989 3.272e+011
1990 3.2567e+011
Gas Production (International Energy Agency 1989; World Energy Council 1989; Energy Information Administration 1995)
1960 1.7539e+010
1961 1.8806e+010
1962 2.0165e+010
1963 2.1622e+010
1964 2.3184e+010
1965 2.4859e+010
1966 2.6655e+010
1967 2.8581e+010
1968 3.0645e+010
1969 3.286e+010
1970 3.5234e+010
1971 3.7779e+010
1972 3.9623e+010
1973 4.142e+010
1974 4.2353e+010
1975 4.2412e+010
1976 4.426e+010
1977 4.6032e+010
1978 4.7578e+010
1979 5.1005e+010
1980 5.1576e+010
1981 5.2769e+010
1982 5.2643e+010
1983 5.3122e+010
1984 5.7716e+010
1985 5.9892e+010
1986 6.14e+010
1987 6.4814e+010
1988 6.7544e+010
1990 7.6e+010
1992 7.84e+010
Oil Production (Jenkins 1989; United Nations 1991; Energy Information Administration 1995)
1870 3.3432e+007
1890 4.10823e+008
1910 1.76226e+009
1925 5.89281e+009
1930 7.85767e+009
1938 1.0966e+010
1950 2.0835e+010
1955 3.3113e+010
1960 4.529e+010
1961 4.9277e+010
1962 5.3464e+010
1963 5.7435e+010
1964 6.1858e+010
1965 6.6521e+010
1966 7.2085e+010
1967 7.7524e+010
1968 8.4545e+010
1969 9.1461e+010
1970 1.0005e+011
1971 1.06e+011
1972 1.1221e+011
1973 1.2263e+011
1974 1.2283e+011
1975 1.1669e+011
1976 1.2589e+011
1977 1.311e+011
1978 1.3217e+011
1979 1.3784e+011
1980 1.3147e+011
1981 1.2415e+011
1982 1.1959e+011
1983 1.1881e+011
1984 1.2177e+011
1985 1.2071e+011
1986 1.2643e+011
1987 1.2617e+011
1988 1.2863e+011
1989 1.3027e+011
1990 1.428e+011
1992 1.438e+011
Primary Energy (Goldemberg, Johansson et al. 1987; World Energy Council 1989; Schipper and Meyers 1992)
1850 2.1444e+010
1870 2.5229e+010
1890 3.1536e+010
1910 5.0458e+010
1930 7.1587e+010
1950 1.0281e+011
1960 1.5539e+011
1966 1.9458e+011
1967 1.9931e+011
1968 2.0561e+011
1969 2.1949e+011
1970 2.3147e+011
1971 2.4125e+011
1972 2.5197e+011
1973 2.6522e+011
1974 2.6679e+011
1975 2.6711e+011
1976 2.8162e+011
1977 2.9045e+011
1978 2.9991e+011
1979 3.1063e+011
1980 3.0874e+011
1981 3.0685e+011
1984 3.3617e+011
Traditional Energy (Jenkins 1989; World Energy Council 1989; Schipper and Meyers 1992)

1870 1.9349e+010
1890 1.734e+010
1910 1.7614e+010
1930 2.5891e+010
1950 3.0861e+010
1960 2.94e+010
1973 2.7636e+010
1980 3.2789e+010
1984 3.6565e+010
1990 4.8565e+010

Cons Frac GDP (World Bank 1995)

1960 0.636
1961 0.638
1962 0.637
1963 0.634
1964 0.629
1965 0.624
1966 0.617
1967 0.619
1968 0.616
1969 0.612
1970 0.608
1971 0.607
1972 0.604
1973 0.593
1974 0.593
1975 0.601
1976 0.597
1977 0.597
1978 0.594
1979 0.592
1980 0.593
1981 0.596
1982 0.607
1983 0.612
1984 0.607
1985 0.615
1986 0.617
1987 0.615
1988 0.612
1989 0.61
1990 0.612
1991 0.612
1992 0.618
1993 0.62

GDP Deflator (World Bank 1995)

1960 0.2357
1961 0.238
1962 0.2429
1963 0.2457
1964 0.2501
1965 0.256
1966 0.2646
1967 0.2715
1968 0.2868
1969 0.3021
1970 0.3169
1971 0.3353
1972 0.3534
1973 0.3717
1974 0.4033
1975 0.4442
1976 0.473
1977 0.5002
1978 0.5392
1979 0.5869
1980 0.6428
1981 0.7042
1982 0.7476
1983 0.7788
1984 0.8101
1985 0.8384
1986 0.8586
1987 0.886
1988 0.9203
1989 0.96
1990 1
1991 1.0346
1992 1.0597
1993 1.0805

Invest Frac GDP (World Bank 1995)

1960 0.216
1961 0.208
1962 0.207
1963 0.211
1964 0.22
1965 0.225
1966 0.227
1967 0.221
1968 0.223
1969 0.229
1970 0.23
1971 0.231
1972 0.233
1973 0.249
1974 0.252
1975 0.233
1976 0.24
1977 0.244
1978 0.247
1979 0.246
1980 0.241
1981 0.238
1982 0.222
1983 0.214
1984 0.225
1985 0.223
1986 0.222
1987 0.225
1988 0.233
1989 0.24
1990 0.232
1991 0.225
1992 0.217
1993 0.215

World GDP (World Bank 1995)

1960 6124
1961 6394
1962 6735
1963 7086
1964 7555
1965 7949
1966 8414
1967 8790
1968 9287
1969 9822
1970 10254
1971 10636
1972 11174
1973 11910
1974 12090
1975 12548
1976 13171
1977 13742
1978 14311
1979 14857
1980 15111
1981 15352
1982 15414
1983 15874
1984 16566
1985 17111
1986 17635
1987 18261
1988 19046
1989 19695
1990 20119
1991 20284
1992 20541
1993 20911

World Pop Growth Rt (World Bank 1995)

1961 0.0132
1962 0.0173
1963 0.021
1964 0.0207
1965 0.0209
1966 0.0209

1967 0.0205
1968 0.0207
1969 0.021
1970 0.0211
1971 0.0208
1972 0.0202
1973 0.0199
1974 0.0195
1975 0.0189
1976 0.0174
1977 0.0171
1978 0.0171
1979 0.0172
1980 0.017
1981 0.0164
1982 0.0169
1983 0.017
1984 0.0167
1985 0.0169
1986 0.017
1987 0.0173
1988 0.0173
1989 0.0172
1990 0.0173
1991 0.0167
1992 0.0164
1993 0.0166
1994 0.0153
World Population (World Bank 1995)
1960 3041
1961 3082
1962 3135
1963 3201
1964 3267
1965 3335
1966 3405
1967 3475
1968 3546
1969 3621
1970 3697
1971 3775
1972 3851
1973 3928
1974 4004
1975 4080
1976 4151
1977 4222
1978 4294
1979 4368
1980 4442
1981 4515
1982 4591
1983 4669
1984 4747
1985 4828
1986 4910
1987 4995
1988 5081
1989 5168
1990 5258
1991 5345
1992 5433
1993 5523
1994 5608

Carbon Cycle Models Documentation

This appendix documents the replicated carbon cycle models discussed in the Feedback Structure in Integrated Models and Model Description.

Model Equations

Citations are provided in the header for each subsystem. The model listing is cross-referenced for easy perusal of the equations. The listing was generated by the Vensim documentation tool. For details of the Vensim language, refer to (Ventana Systems 1994). The format is as follows:

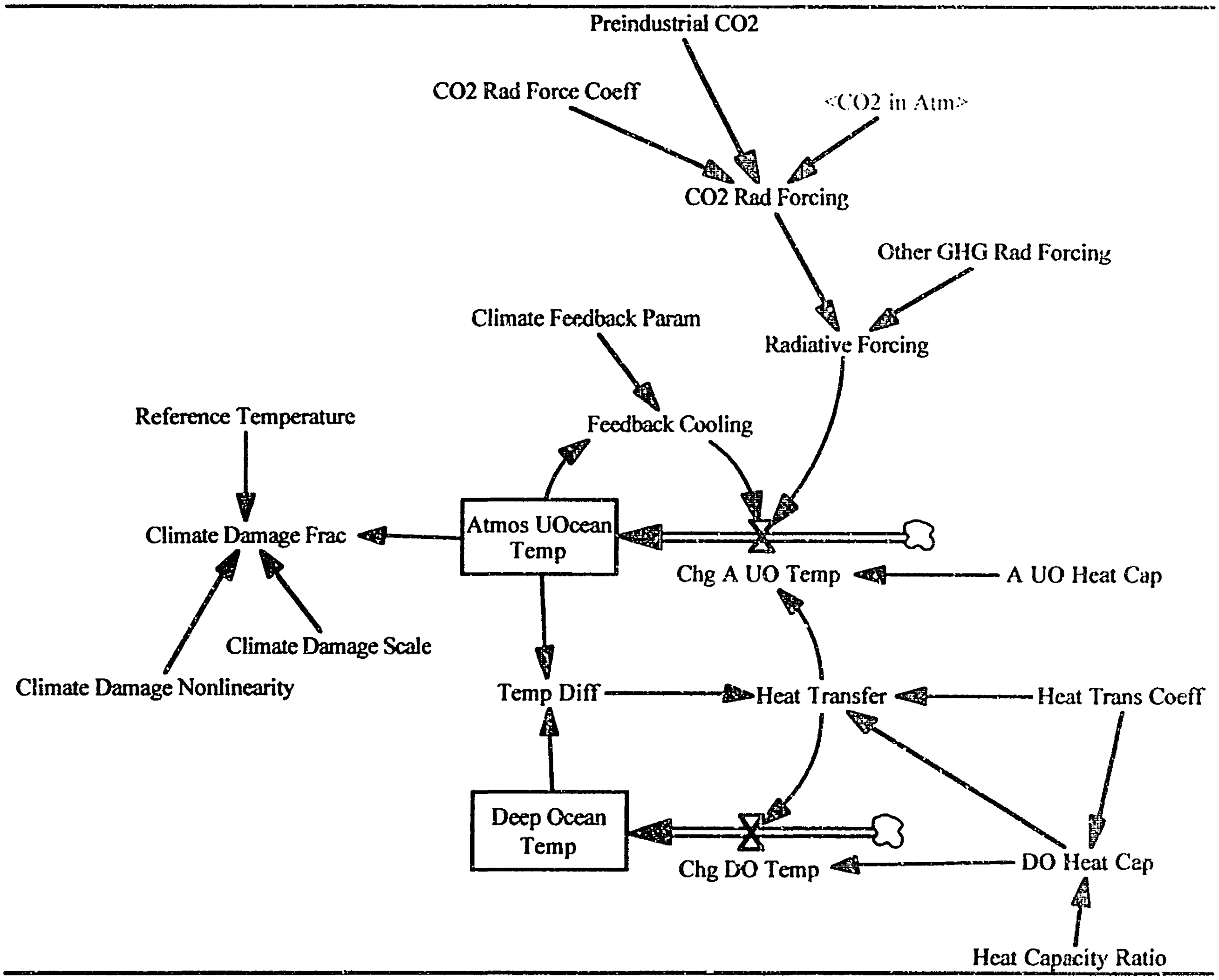
```
(###) Variable = equation
      units
      Comment
                          (###) Causes (inputs to this variable)
                                          (###) Uses (dependent variables)
```

The model is normaly simulated using Euler integration.

.Climate

Drawn from Nordhaus' DICE model. See:

Nordhaus, W. D. 1994. Managing the Global Commons. Cambridge, MA: MIT Press.



(001) `A_UO_Heat_Cap = 44.248`
*watt * year / DegreesC / (meter * meter)*
Atmosphere & Upper Ocean Heat Capacity per Unit Area
(003)Chg_A_UO_Temp

(002) `Atmos_UOcean_Temp[model] = INTEG ( Chg_A_UO_Temp[model], Init_Atmos_UOcean_Temp)`
DegreesC
Temperature of the Atmosphere and Upper Ocean
(003)Chg_A_UO_Temp
(017)Init_Atmos_UOcean_Temp
(005)Climate_Damage_Frac
(013)Feedback_Cooling
(021)Temp_Diff

(003) `Chg_A_UO_Temp[model] = (Radiative_Forcing[model] - Feedback_Cooling[model] - Heat_Transfer[model]) / A_UO_Heat_Cap`
DegreesC / year
Rate of Change in the Atmosphere & Upper Ocean Temperature.
(001)A_UO_Heat_Cap
(013)Feedback_Cooling
(016)Heat_Transfer

(019)Radiative_Forcing
(002)Atmos_UOcean_Temp

(004) `Chg_DO_Temp[model] = Heat_Transfer[model] / DO_Heat_Cap`
DegreesC / year
Rate of Change in the Deep Ocean Temperature
(012)DO_Heat_Cap
(016)Heat_Transfer
(011)Deep_Ocean_Temp

(005) `Climate_Damage_Frac[model] = 1 - 1 / (1 + Climate_Damage_Scale * (Atmos_UOcean_Temp[model] / Reference_Temperature)^Climate_Damage_Nonlinearity)`
dmnl
Fraction of output lost to climate damages.
(002)Atmos_UOcean_Temp
(006)Climate_Damage_Nonlinearity
(007)Climate_Damage_Scale
(020)Reference_Temperature

(006) `Climate_Damage_Nonlinearity = 2`
dmnl
Nonlinearity of Climate Damage Cost Fraction.
(005)Climate_Damage_Frac

(007) `Climate_Damage_Scale = 0.013`
dmnl
Climate Damage Fraction at Reference Temperature
(005)Climate_Damage_Frac

(008) `Climate_Feedback_Param = 1.41`
watt / meter / meter / DegreesC
Climate Feedback Parameter - determines feedback effect from temperature increase.
(013)Feedback_Cooling

(009) `CO2_Rad_Force_Coeff = 4.1`
watt / meter / meter
Coefficient of Radiative Forcing from CO2
(010)CO2_Rad_Forcing

(010) `CO2_Rad_Forcing[model] = CO2_Rad_Force_Coeff * LOG(CO2_in_Atm[model] / Preindustrial_CO2 , 2)`
watt / meter / meter
Radiative forcing from accumulation of CO2.
(134)CO2_in_Atm
(009)CO2_Rad_Force_Coeff
(078)Preindustrial_CO2
(019)Radiative_Forcing

(011) `Deep_Ocean_Temp[model] = INTEG ( Chg_DO_Temp[model], 0.1)`
DegreesC
Temperature of the Deep Ocean
(004)Chg_DO_Temp
(021)Temp_Diff

(012) `DO_Heat_Cap = Heat_Capacity_Ratio * Heat_Trans_Coeff`
*watt * year / DegreesC / meter / meter*
Deep Ocean Heat Capacity per Unit Area

(014)Heat_Capacity_Ratio
(015)Heat_Trans_Coeff
(004)Chg_DO_Temp
(016)Heat_Transfer

```
(013) Feedback_Cooling[model] = Atmos_UOcean_Temp[model] *
        Climate_Feedback_Param
```
watt / meter / meter
Feedback cooling of atmosphere / upper ocean system due to blackbody radiation.
(002)Atmos_UOcean_Temp
(008)Climate_Feedback_Param
(003)Chg_A_UO_Temp

```
(014) Heat_Capacity_Ratio = 0.44
```
*watt / (meter * meter * DegreesC)*
Ratio of Thermal Capacity of Deep Ocean to Heat Transfer Time Constant
(012)DO_Heat_Cap

```
(015) Heat_Trans_Coeff = 500
```
year
Heat Transfer Coefficient [tau12] (years) Coefficient of heat transfer between the atmosphere & upper ocean and the deep ocean. May be interpreted as a mixing time constant.
(012)DO_Heat_Cap
(016)Heat_Transfer

```
(016) Heat_Transfer[model] = Temp_Diff[model] * DO_Heat_Cap / Heat_Trans_Coeff
```
watt / meter / meter
Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean
(012)DO_Heat_Cap
(015)Heat_Trans_Coeff
(021)Temp_Diff
(003)Chg_A_UO_Temp
(004)Chg_DO_Temp

```
(017) Init_Atmos_UOcean_Temp = 0.2
```
DegreesC
Initial Temperature of the Atmosphere and Upper Ocean
(002)Atmos_UOcean_Temp

```
(018) Other_GHG_Rad_Forcing = 0
```
watt / meter / meter
Radiative Forcing from Other GHGs Additional radiative forcing from accumulation of other GHGs (e.g. NOx and Methane).
(019)Radiative_Forcing

```
(019) Radiative_Forcing[model] = CO2_Rad_Forcing[model] +
        Other_GHG_Rad_Forcing
```
watt / meter / meter
Total Radiative Forcing from All GHGs
(010)CO2_Rad_Forcing
(018)Other_GHG_Rad_Forcing
(003)Chg_A_UO_Temp

```
(020) Reference_Temperature = 3
```
DegreesC
Reference Temperature for Calculation of Climate Damages.
(005)Climate_Damage_Frac

```
(021) Temp_Diff[model] = Atmos_UOcean_Temp[model] - Deep_Ocean_Temp[model]
```
DegreesC

Temperature Difference between Upper and Deep Ocean

(002)Atmos_UOcean_Temp

(011)Deep_Ocean_Temp

(016)Heat_Transfer

.Control

Simulation Control Parameters

```
(022) FINAL_TIME = 2305
```
year

The final time for the simulation.

```
(023) INITIAL_TIME = 1775
```
year

The initial time for the simulation.

(000)Time

```
(024) SAVEPER = 5
```
year

The frequency with which output is stored.

```
(025) TIME_STEP = 0.5
```
year

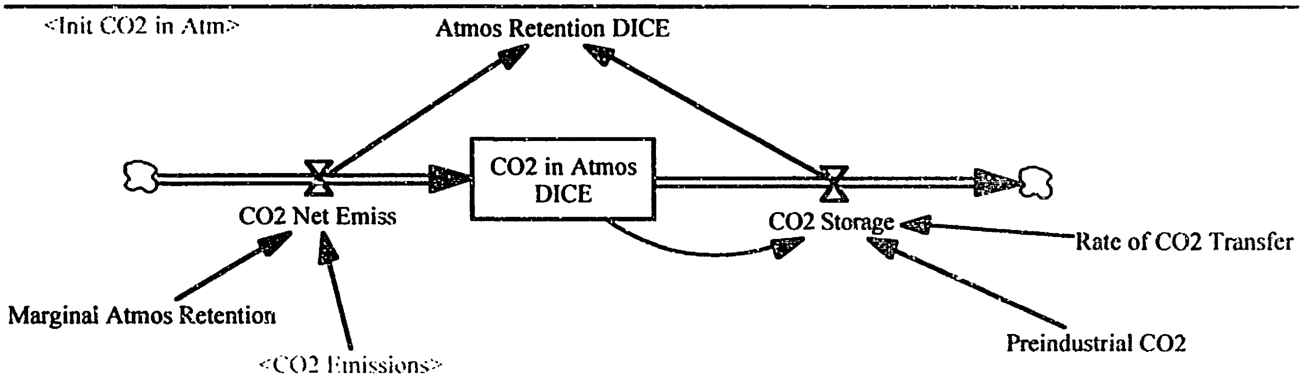
The time step for the simulation.

(035)Emiss_Pulse

.DICE

Carbon cycle model from Nordhaus' DICE model. See:

Nordhaus, W. D. 1994. Managing the Global Commons. Cambridge, MA: MIT Press.




```
(026) Atmos_Retention_DICE = zidz(CO2_Net_Emiss - CO2_Storage, CO2_Net_Emiss)
```
dmnl

Total (average) atmospheric retention in Nordhaus carbon cycle.

(028)CO2_Net_Emiss

(029)CO2_Storage

```
(027) CO2_in_Atmos_DICE = INTEG(CO2_Net_Emiss - CO2_Storage, Init_CO2_in_Atm)
```
TonC

Greenhouse Gases in Atmosphere

(028)CO2_Net_Emiss

(029)CO2_Storage
(077)Init_CO2_in_Atm
(134)CO2_in_Atm
(029)CO2_Storage

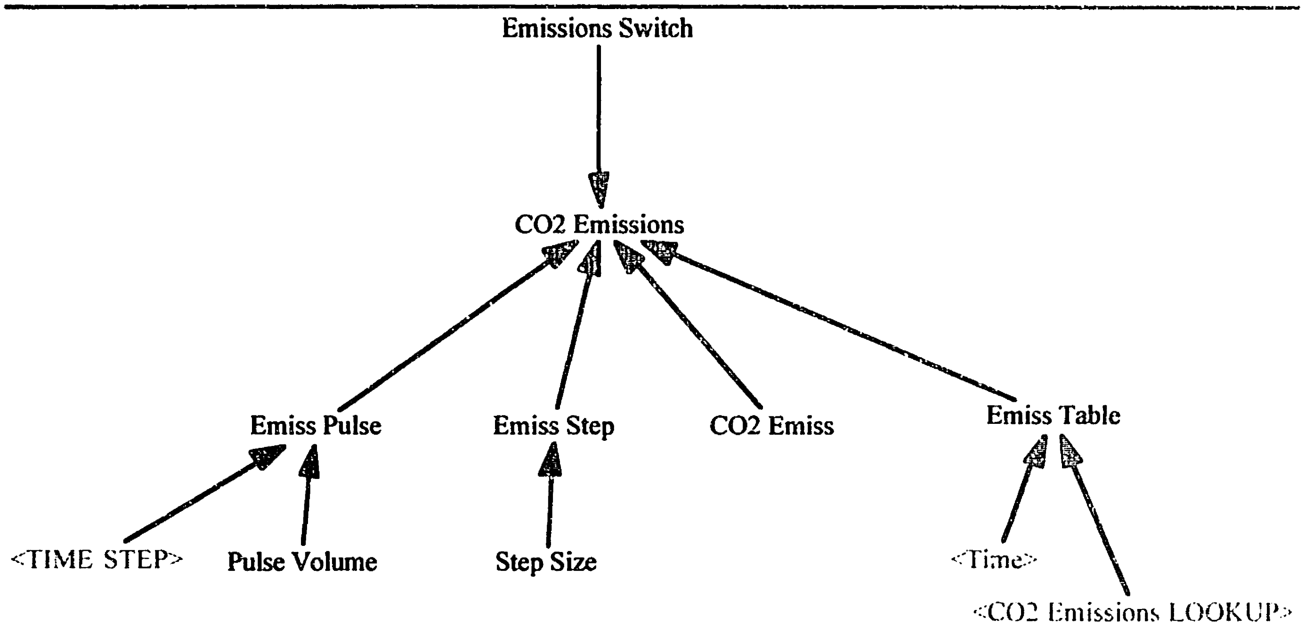
(028) `CO2_Net_Emiss = Marginal_Atmos_Retention * CO2_Emissions`
TonC / year
Net Greenhouse Gas Emissions (tons carbon equivalent / year) Greenhouse gas emissions less short - run uptake from the atmosphere.
(033)CO2_Emissions
(030)Marginal_Atmos_Retention
(027)CO2_in_Atmos_DICE
(026)Atmos_Retention_DICE

(029) `CO2_Storage = (CO2_in_Atmos_DICE - Preindustrial_CO2) * Rate_of_CO2_Transfer`
TonC / year
Greenhouse Gas removal from the atmosphere and storage by long - term processes.
(027)CO2_in_Atmos_DICE
(078)Preindustrial_CO2
(031)Rate_of_CO2_Transfer
(027)CO2_in_Atmos_DICE
(026)Atmos_Retention_DICE

(030) `Marginal_Atmos_Retention = 0.64`
dmnl
Atmospheric Retention Fraction Marginal fraction of Greenhouse Gas Emissions which accumulate in the atmosphere.
(028)CO2_Net_Emiss

(031) `Rate_of_CO2_Transfer = 0.008333`
1 / year
Rate of Storage of Atmospheric Greenhouse Gases Inverse yields average residence time of gases (120 years).
(029)CO2_Storage

.Emissions




```
(032) CO2_Emiss
```
Emissions from data from DICE reference model

(033)CO2_Emissions

```
(033) CO2_Emissions = if_then_else(Emissions_Switch = 0, CO2_Emiss,
        if_then_else(Emissions_Switch = 1, Emiss_Table,
        if_then_else(Emissions_Switch = 2, Emiss_Step, Emiss_Pulse)))
```
TonC / year

Total CO2 emissions. Switchable among test inputs. 0 = data; 1 = lookup; 2 = step; 3 = pulse

(032)CO2_Emiss
(035)Emiss_Pulse
(036)Emiss_Step
(037)Emiss_Table
(038)Emissions_Switch

(115)CO2_in_AtmMix
(046)CO2_in_Atmosphere_C
(093)CO2_in_Atmosphere_Oeschger
(071)Atmos_Reten_GLOCO
(080)Atmos_Reten_ICAM
(041)Atmospheric_Retention_C
(089)Atmospheric_Retention_Oeschger
(110)Atmospheric_Retention_S
(082)CO2_Emiss_to_Box
(072)CO2_Emiss_to_Box_0
(028)CO2_Net_Emiss

```
(034) CO2_Emissions_LOOKUP ([(1965, 0) - (2305, 4e+010)], (1965, 3e+009),
        (1990, 6e+009), (2025, 1.2e+010), (2075, 2.4e+010), (2100,
        2.4e+010), (2105, 1.2e+010), (2205, 1.2e+010) )
```
TonC / year

Emissions lookup table.

(037)Emiss_Table

```
(035) Emiss_Pulse = Pulse_Volume * PULSE(1965, TIME_STEP) / TIME_STEP
```

TonC / year
Emissions pulse for response testing.
(039)Pulse_Volume
(025)TIME_STEP
(033)CO2_Emissions

(036) `Emiss_Step = STEP(Step_Size, 1965)`
TonC / year
Emissions step for response testing.
(040)Step_Size
(033)CO2_Emissions

(037) `Emiss_Table = CO2_Emissions_LOOKUP(Time)`
TonC / year
Emissions from lookup table.
(000)Time
(034)CO2_Emissions_LOOKUP
(033)CO2_Emissions

(038) `Emissions_Switch = 0`
dmnl
Switches among emissions inputs. 0 = data; 1 = lookup; 2 = step; 3 = pulse
(033)CO2_Emissions

(039) `Pulse_Volume = 5.94e+011`
TonC
Volume of emissions pulse (set to double atmospheric stock)
(035)Emiss_Pulse
(137)Pulse_Retained

(040) `Step_Size = 6e+009`
TonC / year
Size of step emissions input.
(036)Emiss_Step

.FREE

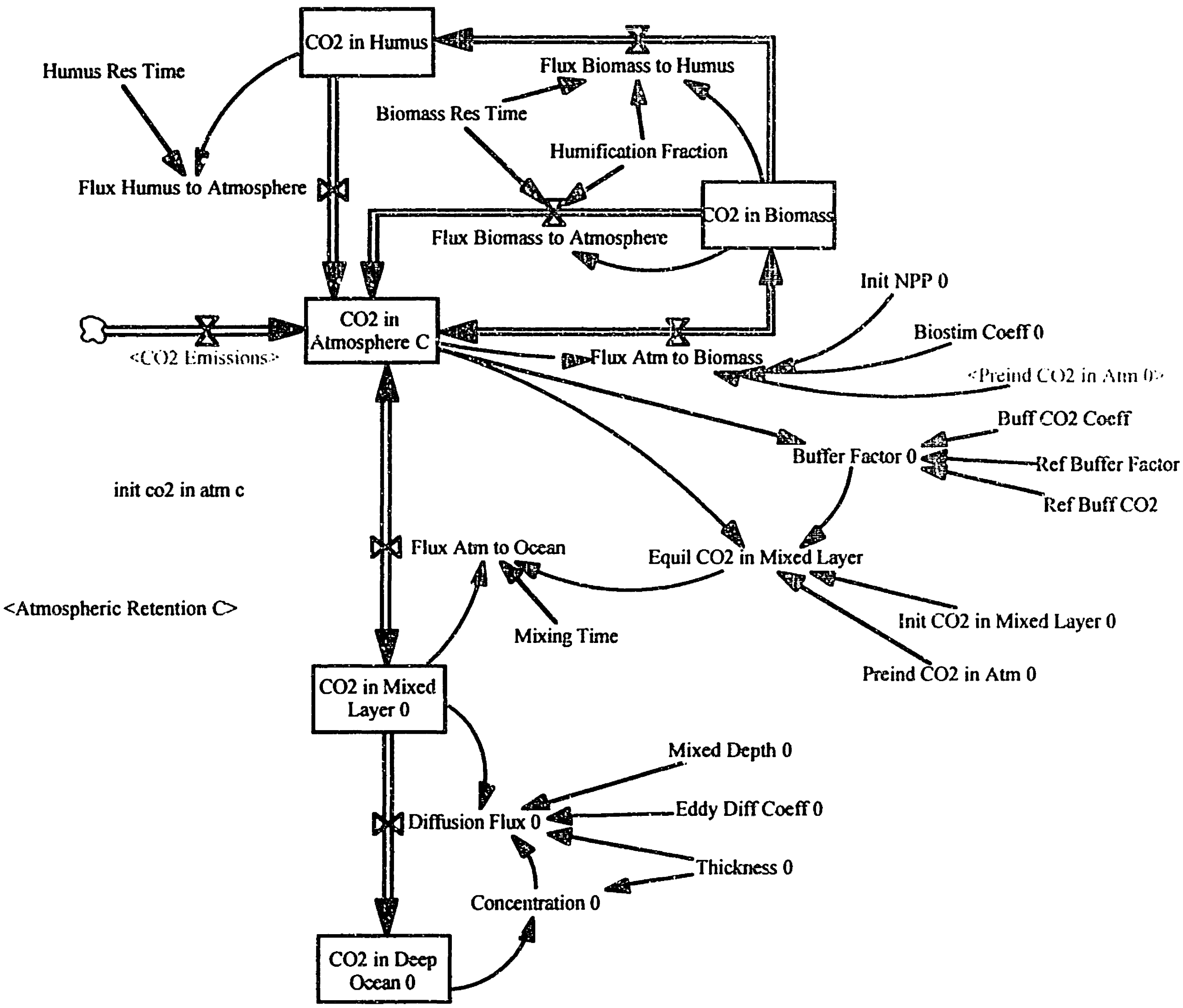
FREE carbon cycle model, coupling the atmosphere / mixed ocean interactions of the IMAGE 1.0 model to a simpler 10 - box eddy diffusion deep ocean and a 2 - box biosphere. See:

Fiddaman, T. 1997. Feedback Complexity in Integrated Climate - Economy Models. Ph.D. Dissertation. MIT Sloan School of Management.

Goudriaan, J. and P. Ketner. 1984. A Simulation Study for the Global Carbon Cycle, Including Man's Impact on the Biosphere. Climatic Change 6: 167 - 192.

Oeschger, H., U. Siegenthaler, et al. 1975. A Box Diffusion Model to Study the Carbon Dioxide Exchange in Nature. Tellus XXVII(2): 167 - 192.

Rotmans, J. 1990. IMAGE: An Integrated Model to Assess the Greenhouse Effect. Boston: Kluwer Academic Publishers.




```
(041) Atmospheric_Retention_C = zidz(CO2_Emissions - Flux_Atm_to_Ocean -
        Flux_Atm_to_Biomass + Flux_Biomass_to_Atmosphere +
        Flux_Humus_to_Atmosphere , CO2_Emissions )
```
dmnl
Atmospheric retention of emissions.
(033)CO2_Emissions
(055)Flux_Atm_to_Biomass
(056)Flux_Atm_to_Ocean
(057)Flux_Biomass_to_Atmosphere
(059)Flux_Humus_to_Atmosphere

```
(042) Biomass_Res_Time = 10.6
```
year
Average residence time of carbon in biomass.
(047)CO2_in_Biomass
(057)Flux_Biomass_to_Atmosphere
(058)Flux_Biomass_to_Humus

```
(043) Biostim_Coeff_0 = 0.4
```
dmnl

Coefficient for response of primary production to CO2 concentration.

(055)Flux_Atm_to_Biomass

```
(044) Buff_CO2_Coeff = 4.05
```
dmnl

(045)Buffer_Factor_0

```
(045) Buffer_Factor_0 = Ref_Buffer_Factor + Buff_CO2_Coeff *
        LN(CO2_in_Atmosphere_C / Ref_Buff_CO2)
```
dmnl

Buffer factor for atmosphere / mixed ocean carbon equilibration.

(046)CO2_in_Atmosphere_C
(044)Buff_CO2_Coeff
(068)Ref_Buff_CO2
(069)Ref_Buffer_Factor

(054)Equil_CO2_in_Mixed_Layer

```
(046) CO2_in_Atmosphere_C = INTEG ( CO2_Emissions - Flux_Atm_to_Ocean -
        Flux_Atm_to_Biomass + Flux_Biomass_to_Atmosphere +
        Flux_Humus_to_Atmosphere, init_co2_in_atm_c)
```
TonC

Carbon in atmosphere

(033)CO2_Emissions
(055)Flux_Atm_to_Biomass
(056)Flux_Atm_to_Ocean
(057)Flux_Biomass_to_Atmosphere
(059)Flux_Humus_to_Atmosphere
(062)init_co2_in_atm_c

(045)Buffer_Factor_0
(134)CO2_in_Atm
(054)Equil_CO2_in_Mixed_Layer
(055)Flux_Atm_to_Biomass

```
(047) CO2_in_Biomass = INTEG ( Flux_Atm_to_Biomass -
        Flux_Biomass_to_Atmosphere - Flux_Biomass_to_Humus, Init_NPP_0 *
        Biomass_Res_Time)
```
TonC

Carbon in biosphere (biomass, litter, and humus)

(042)Biomass_Res_Time
(055)Flux_Atm_to_Biomass
(057)Flux_Biomass_to_Atmosphere
(058)Flux_Biomass_to_Humus
(064)Init_NPP_0

(057)Flux_Biomass_to_Atmosphere
(058)Flux_Biomass_to_Humus

```
(048) CO2_in_Deep_Ocean_0[upper] = INTEG ( Diffusion_Flux_0[upper] -
        Diffusion_Flux_0[lower], CO2_in_Mixed_Layer_0 * Thickness_0[upper]
        / Mixed_Depth_0)CO2_in_Deep_Ocean_0[layer10] = INTEG (
        Diffusion_Flux_0[layer10], CO2_in_Mixed_Layer_0 *
        Thickness_0[layer10] / Mixed_Depth_0)
```
TonC

Carbon in deep ocean.

(050)CO2_in_Mixed_Layer_0
(052)Diffusion_Flux_0
(065)Mixed_Depth_0

(070)Thickness_0
(051)Concentration_0

```
(049) CO2_in_Humus = INTEG ( Flux_Biomass_to_Humus - Flux_Humus_to_Atmosphere,
        Flux_Biomass_to_Humus * Humus_Res_Time)
```
TonC
Carbon in humus.
(058)Flux_Biomass_to_Humus
(059)Flux_Humus_to_Atmosphere
(061)Humus_Res_Time
(059)Flux_Humus_to_Atmosphere

```
(050) CO2_in_Mixed_Layer_0 = INTEG(Flux_Atm_to_Ocean -
        Diffusion_Flux_0[layer1], Equil_CO2_in_Mixed_Layer)
```
TonC
Carbon in mixed layer.
(052)Diffusion_Flux_0
(054)Equil_CO2_in_Mixed_Layer
(056)Flux_Atm_to_Ocean
(048)CO2_in_Deep_Ocean_0
(052)Diffusion_Flux_0
(056)Flux_Atm_to_Ocean

```
(051) Concentration_0[layers] = CO2_in_Deep_Ocean_0[layers] /
        Thickness_0[layers]
```
TonC / meter
Concentration of carbon in ocean layers.
(048)CO2_in_Deep_Ocean_0
(070)Thickness_0
(052)Diffusion_Flux_0

```
(052) Diffusion_Flux_0[layer1] = (CO2_in_Mixed_Layer_0 / Mixed_Depth_0 -
        Concentration_0[layer1]) * Eddy_Diff_Coeff_0 * 2 / (Mixed_Depth_0
        + Thickness_0[layer1])

      Diffusion_Flux_0[lower] = (Concentration_0[upper] -
        Concentration_0[lower]) * Eddy_Diff_Coeff_0 * 2 /
        (Thickness_0[upper] + Thickness_0[lower])
```
TonC / year
Diffusion flux between ocean layers.
(050)CO2_in_Mixed_Layer_0
(051)Concentration_0
(053)Eddy_Diff_Coeff_0
(065)Mixed_Depth_0
(070)Thickness_0
(048)CO2_in_Deep_Ocean_0
(050)CO2_in_Mixed_Layer_0

```
(053) Eddy_Diff_Coeff_0 = 4000
```
*meter * meter / year*
Eddy diffusion coefficient.
(052)Diffusion_Flux_0

```
(054) Equil_CO2_in_Mixed_Layer = Init_CO2_in_Mixed_Layer_0 *
        (CO2_in_Atmosphere_C / Preind_CO2_in_Atm_0) ^(1 / Buffer_Factor_0)
```
TonC
Equilibrium carbon content of mixed layer.

(046)CO2_in_Atmosphere_C
(045)Buffer_Factor_0
(063)Init_CO2_in_Mixed_Layer_0
(067)Preind_CO2_in_Atm_0
(050)CO2_in_Mixed_Layer_0
(056)Flux_Atm_to_Ocean

```
(055) Flux_Atm_to_Biomass = Init_NPP_0 * (1 + Biostim_Coeff_0 *
        LN(CO2_in_Atmosphere_C / Preind_CO2_in_Atm_0))
```

TonC / year
Carbon flux from atmosphere to biosphere (from primary production)
(046)CO2_in_Atmosphere_C
(043)Biostim_Coeff_0
(064)Init_NPP_0
(067)Preind_CO2_in_Atm_0
(046)CO2_in_Atmosphere_C
(047)CO2_in_Biomass
(041)Atmospheric_Retention_C

```
(056) Flux_Atm_to_Ocean = (Equil_CO2_in_Mixed_Layer - CO2_in_Mixed_Layer_0) /
        Mixing_Time
```

TonC / year
Carbon flux from atmosphere to mixed ocean layer.
(050)CO2_in_Mixed_Layer_0
(054)Equil_CO2_in_Mixed_Layer
(066)Mixing_Time
(046)CO2_in_Atmosphere_C
(050)CO2_in_Mixed_Layer_0
(041)Atmospheric_Retention_C

```
(057) Flux_Biomass_to_Atmosphere = CO2_in_Biomass / Biomass_Res_Time * (1 -
        Humification_Fraction)
```

TonC / year
Carbon flux from biomass to atmosphere.
(047)CO2_in_Biomass
(042)Biomass_Res_Time
(060)Humification_Fraction
(046)CO2_in_Atmosphere_C
(047)CO2_in_Biomass
(041)Atmospheric_Retention_C

```
(058) Flux_Biomass_to_Humus = CO2_in_Biomass / Biomass_Res_Time *
        Humification_Fraction
```

TonC / year
Carbon flux from biomass to humus.
(047)CO2_in_Biomass
(042)Biomass_Res_Time
(060)Humification_Fraction
(047)CO2_in_Biomass
(049)CO2_in_Humus

```
(059) Flux_Humus_to_Atmosphere = CO2_in_Humus / Humus_Res_Time
```

TonC / year
Carbon flux from humus to atmosphere.
(049)CO2_in_Humus
(061)Humus_Res_Time

(046)CO2_in_Atmosphere_C
(049)CO2_in_Humus
(041)Atmospheric_Retention_C

(060) `Humification_Fraction = 0.428`
dmnl
Fraction of carbon outflow from biomass that enters humus stock.
(057)Flux_Biomass_to_Atmosphere
(058)Flux_Biomass_to_Humus

(061) `Humus_Res_Time = 27.8`
year
Average carbon residence time in humus.
(049)CO2_in_Humus
(059)Flux_Humus_to_Atmosphere

(062) `init_co2_in_atm_c = 6.7832e+011`
TonC
Initial carbon in atmosphere.
(046)CO2_in_Atmosphere_C

(063) `Init_CO2_in_Mixed_Layer_0 = 7.678e+011`
TonC
Initial carbon content of mixed ocean layer.
(054)Equil_CO2_in_Mixed_Layer

(064) `Init_NPP_0 = 6e+010`
TonC / year
Initial net primary production.
(047)CO2_in_Biomass
(055)Flux_Atm_to_Biomass

(065) `Mixed_Depth_0 = 75`
meter
Mixed ocean layer depth.
(048)CO2_in_Deep_Ocean_0
(095)CO2_in_Deep_Ocean_1
(052)Diffusion_Flux_0

(066) `Mixing_Time = 9.5`
year
Atmosphere - mixed ocean layer mixing time.
(056)Flux_Atm_to_Ocean

(067) `Preind_CO2_in_Atm_0 = 5.9e+011`
TonC
Preindustrial CO2 in atmosphere.
(054)Equil_CO2_in_Mixed_Layer
(055)Flux_Atm_to_Biomass

(068) `Ref_Buff_CO2 = 7.6e+011`
TonC
CO2 in atmosphere at normal buffer factor.
(045)Buffer_Factor_0

(069) `Ref_Buffer_Factor = 10`
dmnl
Normal buffer factor.
(045)Buffer_Factor_0

(070) `Thickness_0[top5] = 200`

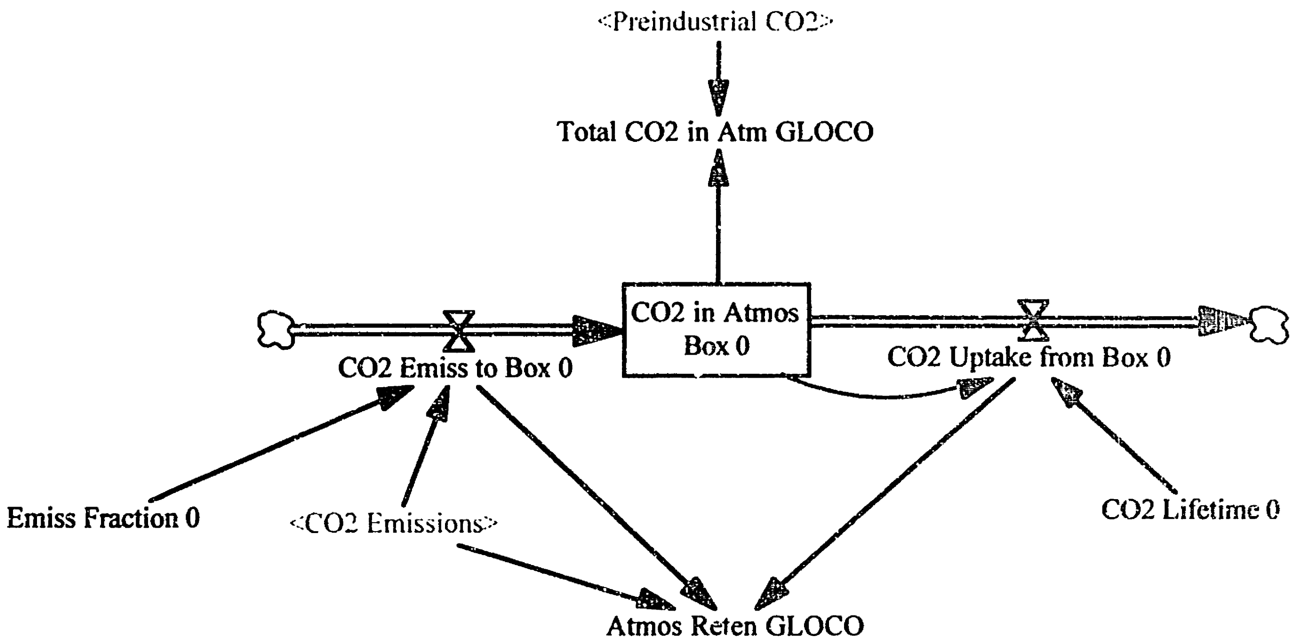
`Thickness_0[bottom5] = 560`
meter
Deep ocean layer thicknesses.

(048)CO2_in_Deep_Ocean_0
(095)CO2_in_Deep_Ocean_1
(051)Concentration_0
(052)Diffusion_Flux_0

.GLOCO

Meta - model fitted to GLOCO. See:

Keller, A. A. and R. A. Goldstein. 1995. Oceanic Transport and Storage of Carbon Emissions. Climatic Change 30: 367 - 395.



(071) `Atmos_Reten_GLOCO = zidz(SUM(CO2_Emiss_to_Box_0[box!]) - SUM(CO2_Uptake_from_Box_0[box!]), CO2_Emissions)`
dmnl
Atmospheric retention of emissions.
(072)CO2_Emiss_to_Box_0
(033)CO2_Emissions
(075)CO2_Uptake_from_Box_0

(072) `CO2_Emiss_to_Box_0[box] = Emiss_Fraction_0[box] * CO2_Emissions`
TonC / year
Emissions, partitioned into atmospheric boxes with different residence times.
(033)CO2_Emissions
(076)Emiss_Fraction_0
(073)CO2_in_Atmos_Box_0
(071)Atmos_Reten_GLOCO

(073) `CO2_in_Atmos_Box_0[box] = INTEG(CO2_Emiss_to_Box_0[box] - CO2_Uptake_from_Box_0[box], (Init_CO2_in_Atm - Preindustrial_CO2) * Emiss_Fraction_0[box])`

TonC
Carbon contents of atmospheric boxes with different residence times. Note that initialization is imperfect.

(072)CO2_Emiss_to_Box_0
(075)CO2_Uptake_from_Box_0
(076)Emiss_Fraction_0
(077)Init_CO2_in_Atm
(078)Preindustrial_CO2

(075)CO2_Uptake_from_Box_0
(079)Total_CO2_in_Atm_GLOCO

(074) `CO2_Lifetime_0[box] = 1e+009, 421.4, 66.25, 7.115, 1.056`
year
Residence times of carbon in box

(075)CO2_Uptake_from_Box_0

(075) `CO2_Uptake_from_Box_0[box] = if_then_else(CO2_in_Atmos_Box_0[box]>1e - 009, CO2_in_Atmos_Box_0[box] / CO2_Lifetime_0[box], 0)`
TonC / year
Carbon uptake from atmospheric partitions. IF THEN ELSE protects against FP error.

(073)CO2_in_Atmos_Box_0
(074)CO2_Lifetime_0

(073)CO2_in_Atmos_Box_0
(071)Atmos_Reten_GLOCO

(076) `Emiss_Fraction_0[box] = 0.1608, 0.2867, 0.2018, 0.2712, 0.0798`
dmnl
Fractional partitioning of emissions to boxes with different residence times.

(073)CO2_in_Atmos_Box_0
(072)CO2_Emiss_to_Box_0

(077) `Init_CO2_in_Atm = 6.77e+011`
TonC
CO2 in Atmosphere in 1965 (Preindustrial level is 5.9e11)

(115)CO2_in_AtmMix
(083)CO2_in_Atmos_Box
(073)CO2_in_Atmos_Box_0
(027)CO2_in_Atmos_DICE
(116)CO2_in_Atmosphere_S

(078) `Preindustrial_CO2 = 5.9e+011`
TonC
Preindustrial atmospheric stock of carbon.

(083)CO2_in_Atmos_Box
(073)CO2_in_Atmos_Box_0
(010)CO2_Rad_Forcing
(029)CO2_Storage
(124)Flux_AtmMix_to_Biosphere
(079)Total_CO2_in_Atm_GLOCO
(087)Total_CO2_in_Atm_ICAM

(079) `Total_CO2_in_Atm_GLOCO = Preindustrial_CO2 + SUM(CO2_in_Atmos_Box_0[box!])`
TonC
Total carbon in atmosphere.

(073)CO2_in_Atmos_Box_0
(078)Preindustrial_CO2

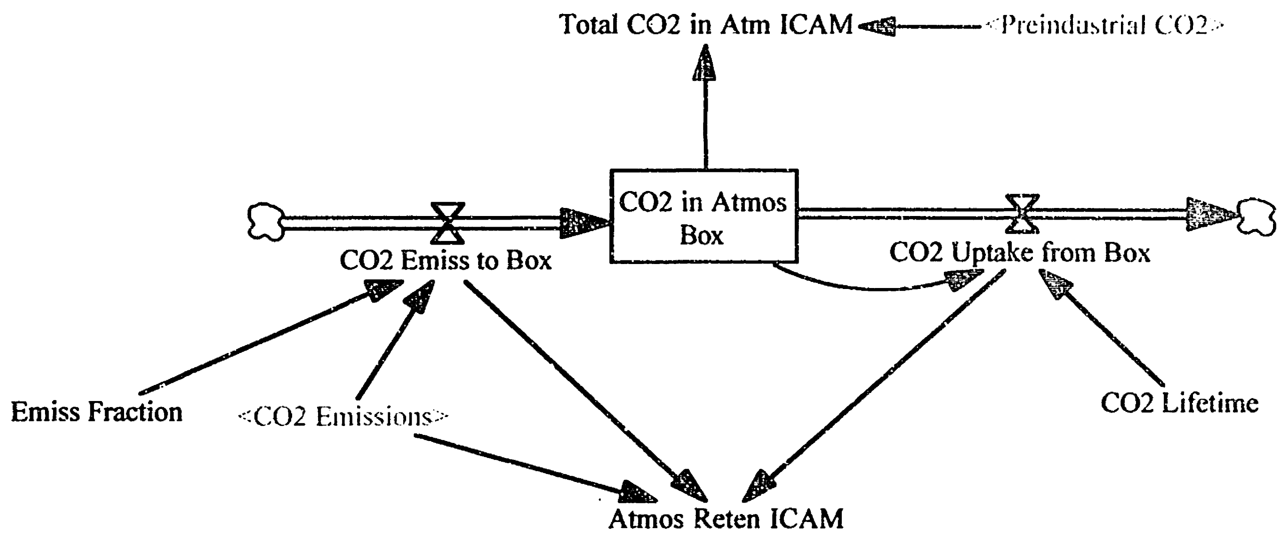
(134)CO2_in_Atm

.ICAM

Meta - model of carbon uptake from ICAM 2.1r; based on Maier - Reimer & Hasselman. See:

Dowlatabadi, H. and M. Ball. 1994. An Overview of the Integrated Climate Assessment Model Version 2. Vancouver, Canada, Western Economic Association.

Maier - Reimer, E. and K. Hasselman. 1987. Transport and Storage of CO2 in the Ocean - An Inorganic Ocean - Circulation Model. Climate Dynamics 2: 63 - 90.




```
(080) Atmos_Reten_ICAM = zidz(SUM(CO2_Emiss_to_Box[box!]) -
        SUM(CO2_Uptake_from_Box[box!]), CO2_Emissions)
```

dmnl

Atmospheric retention of emissions.

(082)CO2_Emiss_to_Box
(033)CO2_Emissions
(085)CO2_Uptake_from_Box

(081) box : (box1 - box5)

Atmospheric boxes.

```
(082) CO2_Emiss_to_Box[box] = Emiss_Fraction[box] * CO2_Emissions
```

TonC / year

Emissions, partitioned into atmospheric boxes with different residence times.

(033)CO2_Emissions
(086)Emiss_Fraction

(083)CO2_in_Atmos_Box
(080)Atmos_Reten_ICAM

```
(083) CO2_in_Atmos_Box[box] = INTEG(CO2_Emiss_to_Box[box] -
        CO2_Uptake_from_Box[box], (Init_CO2_in_Atm - Preindustrial_CO2) *
        Emiss_Fraction[box])
```

TonC

CO2 remaining in atmospheric boxes. Note that initialization is imperfect.

(082)CO2_Emiss_to_Box
(085)CO2_Uptake_from_Box
(086)Emiss_Fraction
(077)Init_CO2_in_Atm

(078)Preindustrial_CO2

(085)CO2_Uptake_from_Box

(087)Total_CO2_in_Atm_ICAM

```
(084) CO2_Lifetime[box] = 1000, 313.8, 79.8, 18.8, 1.2
```

year

Lifetime of carbon in box

(085)CO2_Uptake_from_Box

```
(085) CO2_Uptake_from_Box[box] = if_then_else(CO2_in_Atmos_Box[box]>1e - 009,
          CO2_in_Atmos_Box[box] / CO2_Lifetime[box], 0)
```

TonC / year

Uptake of carbon from atmospheric boxes. IF THEN ELSE protects against FP error

(083)CO2_in_Atmos_Box

(084)CO2_Lifetime

(083)CO2_in_Atmos_Box

(080)Atmos_Reten_ICAM

```
(086) Emiss_Fraction[box] = 0.131, 0.201, 0.323, 0.206, 0.088
```

dmnl

Fraction of emissions to box. Note that these sum only to .949, so there is implicitly a sixth box with zero residence time.

(083)CO2_in_Atmos_Box

(082)CO2_Emiss_to_Box

```
(087) Total_CO2_in_Atm_ICAM = Preindustrial_CO2 + SUM(CO2_in_Atmos_Box[box!])
```

TonC

Total CO2 in atmosphere.

(083)CO2_in_Atmos_Box

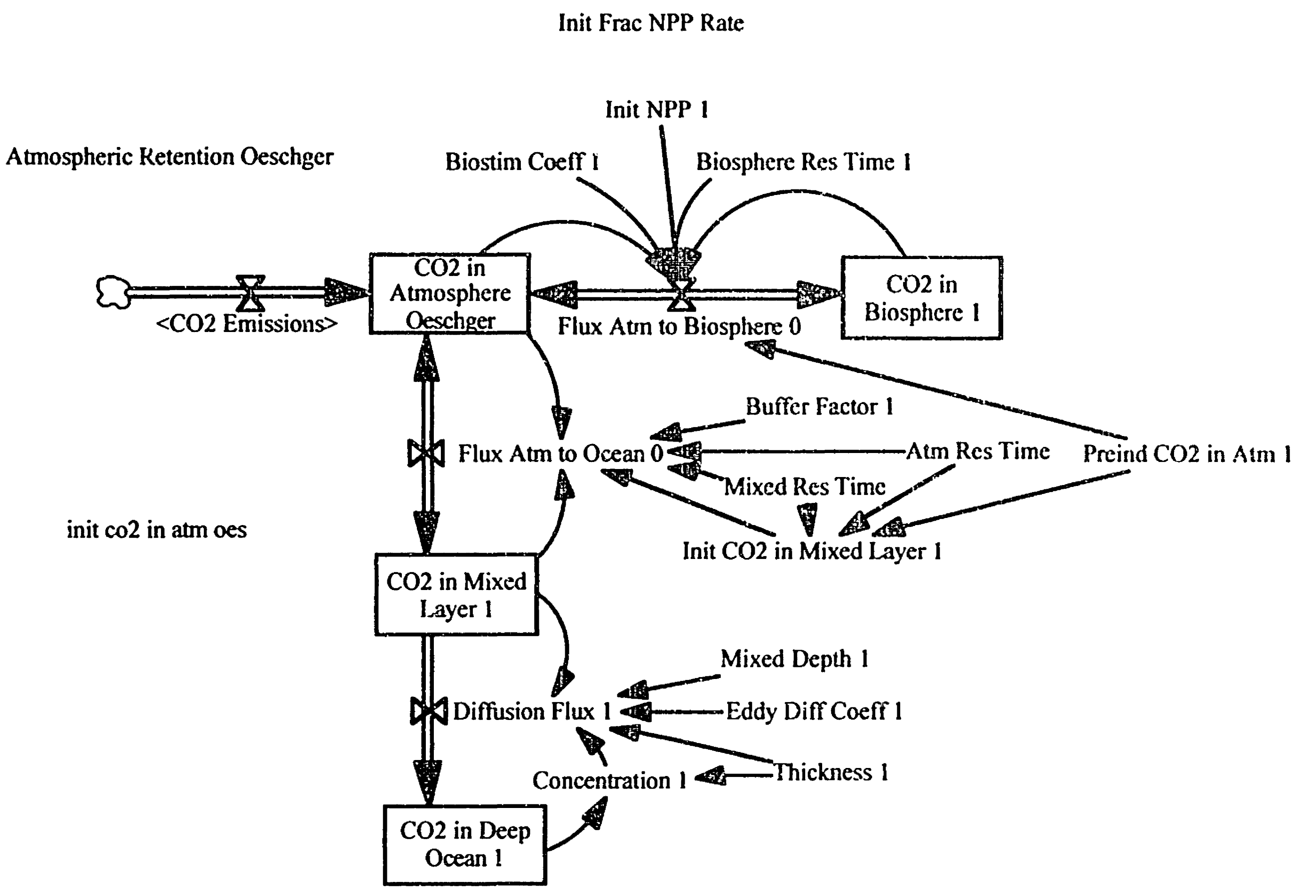
(078)Preindustrial_CO2

(134)CO2_in_Atm

.ModOeschger

Modified replication of the Oeschger model. Major difference is that this version has fewer deep ocean layers (10 instead of 42). See:

Oeschger, H., U. Siegenthaler, et al. 1975. A Box Diffusion Model to Study the Carbon Dioxide Exchange in Nature. Tellus XXVII(2): 167 - 192.




```
(088) Atm_Res_Time = 7.7
```
year

(101)Flux_Atm_to_Ocean_0
(103)Init_CO2_in_Mixed_Layer_1

```
(089) Atmospheric_Retention_Oeschger = zidz(CO2_Emissions -
        Flux_Atm_to_Ocean_0 - Flux_Atm_to_Biosphere_0, CO2_Emissions)
```
dmnl

Atmospheric retention of carbon emissions.

(033)CO2_Emissions
(100)Flux_Atm_to_Biosphere_0
(101)Flux_Atm_to_Ocean_0

```
(090) Biosphere_Res_Time_1 = 60
```
year

Average residence time of carbon in biosphere.

(094)CO2_in_Biosphere_1
(100)Flux_Atm_to_Biosphere_0

```
(091) Biostim_Coeff_1 = 0.2
```
dmnl

Coefficient of response of net primary production to atmospheric CO2 concentration.

(100)Flux_Atm_to_Biosphere_0

```
(092) Buffer_Factor_1 = 10
```
dmnl

Buffer factor.

(101)Flux_Atm_to_Ocean_0

(093) CO2_in_Atmosphere_Oeschger = INTEG(CO2_Emissions - Flux_Atm_to_Ocean_0 - Flux_Atm_to_Biosphere_0, init_co2_in_atm_oes)

TonC

Carbon in atmosphere.

(033)CO2_Emissions
(100)Flux_Atm_to_Biosphere_0
(101)Flux_Atm_to_Ocean_0
(102)init_co2_in_atm_oes

(134)CO2_in_Atm
(100)Flux_Atm_to_Biosphere_0
(101)Flux_Atm_to_Ocean_0

(094) CO2_in_Biosphere_1 = INTEG(Flux_Atm_to_Biosphere_0, Init_NPP_1 * Biosphere_Res_Time_1)

TonC

Carbon in biosphere.

(090)Biosphere_Res_Time_1
(100)Flux_Atm_to_Biosphere_0
(105)Init_NPP_1

(100)Flux_Atm_to_Biosphere_0

(095) CO2_in_Deep_Ocean_1[upper] = INTEG (Diffusion_Flux_1[upper] - Diffusion_Flux_1[lower], CO2_in_Mixed_Layer_1 * Thickness_0[upper] / Mixed_Depth_0)CO2_in_Deep_Ocean_1[layer10] = INTEG (Diffusion_Flux_1[layer10], CO2_in_Mixed_Layer_1 * Thickness_0[layer10] / Mixed_Depth_0)

TonC

Carbon in deep ocean layers.

(096)CO2_in_Mixed_Layer_1
(098)Diffusion_Flux_1
(065)Mixed_Depth_0
(070)Thickness_0

(097)Concentration_1

(096) CO2_in_Mixed_Layer_1 = INTEG (Flux_Atm_to_Ocean_0 - Diffusion_Flux_1[layer1], Init_CO2_in_Mixed_Layer_1)

TonC

Carbon in mixed ocean layer.

(098)Diffusion_Flux_1
(101)Flux_Atm_to_Ocean_0
(103)Init_CO2_in_Mixed_Layer_1

(095)CO2_in_Deep_Ocean_1
(098)Diffusion_Flux_1
(101)Flux_Atm_to_Ocean_0

(097) Concentration_1[layers] = CO2_in_Deep_Ocean_1[layers] / Thickness_1[layers]

TonC / meter

Concentration of carbon in deep ocean layers.

(095)CO2_in_Deep_Ocean_1
(109)Thickness_1

(098)Diffusion_Flux_1

```
(098) Diffusion_Flux_1[layer1] = (CO2_in_Mixed_Layer_1 / Mixed_Depth_1 -
            Concentration_1[layer1]) * Eddy_Diff_Coeff_1 * 2 / (Mixed_Depth_1
            + Thickness_1[layer1])

      Diffusion_Flux_1[lower] = (Concentration_1[upper] -
            Concentration_1[lower]) * Eddy_Diff_Coeff_1 * 2 /
            (Thickness_1[upper] + Thickness_1[lower])
```

TonC / year

Diffusion flux between ocean layers.

(096)CO2_in_Mixed_Layer_1
(097)Concentration_1
(099)Eddy_Diff_Coeff_1
(106)Mixed_Depth_1
(109)Thickness_1

(095)CO2_in_Deep_Ocean_1
(096)CO2_in_Mixed_Layer_1

```
(099) Eddy_Diff_Coeff_1 = 3987
```

*meter * meter / year*

Eddy diffusion coefficient.

(098)Diffusion_Flux_1

```
(100) Flux_Atm_to_Biosphere_0 = Init_NPP_1 * (1 + Biostim_Coeff_1 *
            (CO2_in_Atmosphere_Oeschger - Preind_CO2_in_Atm_1) /
            Preind_CO2_in_Atm_1) - CO2_in_Biosphere_1 / Biosphere_Res_Time_1
```

TonC / year

Carbon flux from atmosphere to biosphere.

(093)CO2_in_Atmosphere_Oeschger
(094)CO2_in_Biosphere_1
(090)Biosphere_Res_Time_1
(091)Biostim_Coeff_1
(105)Init_NPP_1
(108)Preind_CO2_in_Atm_1

(093)CO2_in_Atmosphere_Oeschger
(094)CO2_in_Biosphere_1
(089)Atmospheric_Retention_Oeschger

```
(101) Flux_Atm_to_Ocean_0 = CO2_in_Atmosphere_Oeschger / Atm_Res_Time -
            (Init_CO2_in_Mixed_Layer_1 + Buffer_Factor_1 *
            (CO2_in_Mixed_Layer_1 - Init_CO2_in_Mixed_Layer_1)) /
            Mixed_Res_Time
```

TonC / year

Carbon flux from atmosphere to mixed ocean layer.

(093)CO2_in_Atmosphere_Oeschger
(096)CO2_in_Mixed_Layer_1
(088)Atm_Res_Time
(092)Buffer_Factor_1
(103)Init_CO2_in_Mixed_Layer_1
(107)Mixed_Res_Time

(093)CO2_in_Atmosphere_Oeschger
(096)CO2_in_Mixed_Layer_1
(089)Atmospheric_Retention_Oeschger

```
(102) init_co2_in_atm_oes = 6.7832e+011
```

TonC

Initial carbon in atmosphere.

(093)CO2_in_Atmosphere_Oeschger

(103) `Init_CO2_in_Mixed_Layer_1 = Preind_CO2_in_Atm_1 * Mixed_Res_Time / Atm_Res_Time`
TonC
Initial carbon in mixed ocean layer.
(088)Atm_Res_Time
(107)Mixed_Res_Time
(108)Preind_CO2_in_Atm_1
(096)CO2_in_Mixed_Layer_1
(101)Flux_Atm_to_Ocean_0

(104) `Init_Frac_NPP_Rate = 0.04`
1 / year
Initial net primary production, as a fraction of atmospheric carbon stock.
(105)Init_NPP_1

(105) `Init_NPP_1 = INITIAL ( Init_Frac_NPP_Rate * Preind_CO2_in_Atm_1)`
TonC / year
Initial net primary production.
(104)Init_Frac_NPP_Rate
(108)Preind_CO2_in_Atm_1
(094)CO2_in_Biosphere_1
(100)Flux_Atm_to_Biosphere_0

(106) `Mixed_Depth_1 = 75`
meter
Depth of mixed ocean layer.
(098)Diffusion_Flux_1

(107) `Mixed_Res_Time = 10`
year
Carbon residence time in mixed ocean layer.
(101)Flux_Atm_to_Ocean_0
(103)Init_CO2_in_Mixed_Layer_1

(108) `Preind_CO2_in_Atm_1 = 5.9e+011`
TonC
Preindustrial CO2 in atmosphere.
(100)Flux_Atm_to_Biosphere_0
(103)Init_CO2_in_Mixed_Layer_1
(105)Init_NPP_1

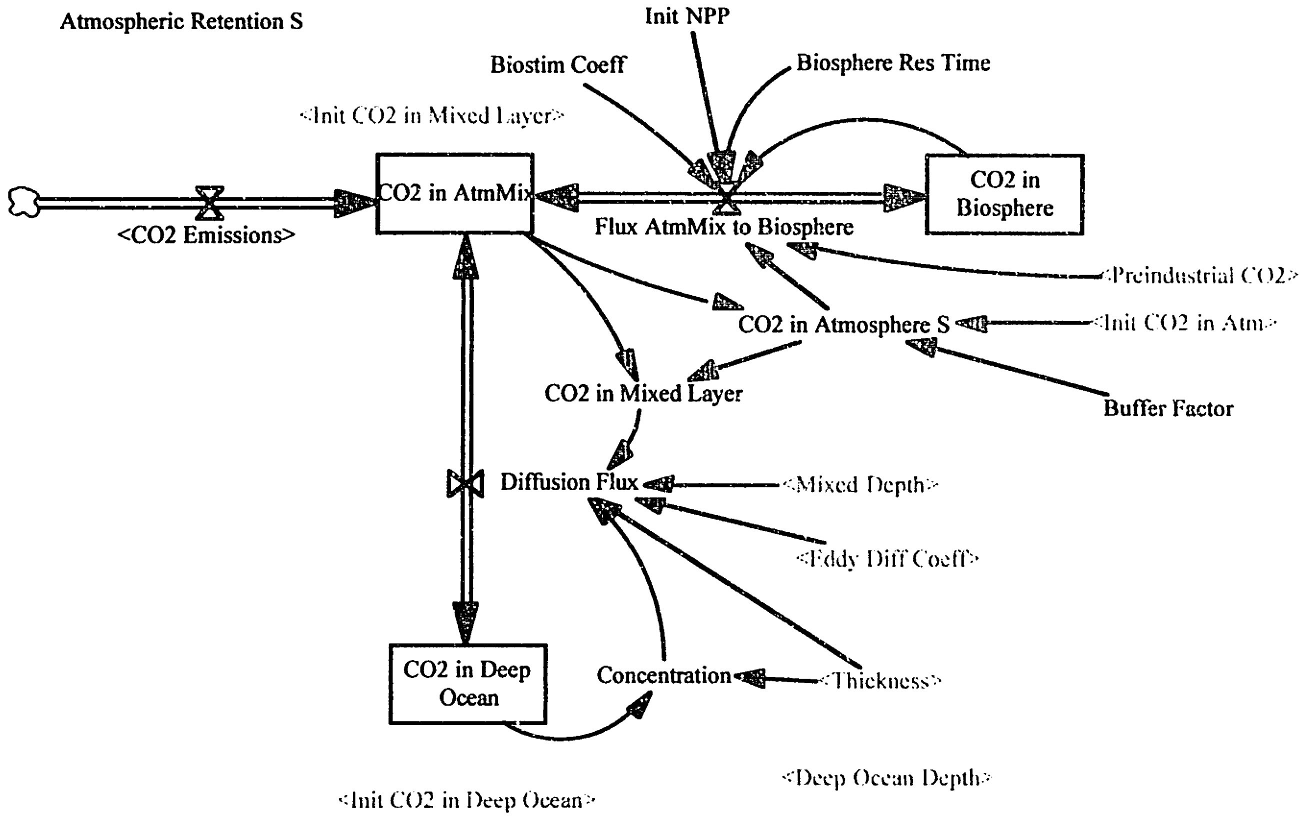
(109) `Thickness_1[top5] = 200`

`Thickness_1[bottom5] = 560`
meter
Thickness of deep ocean layers.
(097)Concentration_1
(098)Diffusion_Flux_1

.NICE

Reduced version of the FREE carbon cycle model, used in the NICE model. Created by linearizing the atmosphere - mixed ocean relationship and solving for equilibrium, and simplifying the biosphere to a single box. This eliminates the troublesome fast atmosphere - mixed ocean dynamics, so that the model may be simulated with a time constant as large as five years. See:

Fiddaman, T. 1996. A System Dynamics Perspective on an Influential Climate / Economy Model. Submitted to System Dynamics Review.



(110) `Atmospheric_Retention_S = zidz(CO2_Emissions - Diffusion_Flux[layer1] - Flux_AtmMix_to_Biosphere, CO2_Emissions)`
dmnl
Average atmospheric retention of CO2
(033)CO2_Emissions
(122)Diffusion_Flux
(124)Flux_AtmMix_to_Biosphere

(111) `Biosphere_Res_Time = 25`
year
Residence time of CO2 in the biosphere. Trees and soils have longer residence times.
(117)CO2_in_Biosphere
(124)Flux_AtmMix_to_Biosphere

(112) `Biostim_Coeff = 0.3`
dmnl
Sensitivity of primary production to changes in atmospheric CO2 concentration.
(124)Flux_AtmMix_to_Biosphere

(113) bottom5 : (layer6 - layer10)
Bottom 5 (thick) ocean layers.

(114) `Buffer_Factor = 10`
dmnl
Revelle or Buffer factor; relates increase in ocean CO2 partial pressure to ocean carbon concentration.
(116)CO2_in_Atmosphere_S

```
(115) CO2_in_AtmMix = INTEG(CO2_Emissions - Diffusion_Flux[layer1] -
        Flux_AtmMix_to_Biosphere, Init_CO2_in_Atm +
        Init_CO2_in_Mixed_Layer)
```
TonC

CO2 in atmosphere and mixed ocean layer.

(033)CO2_Emissions
(122)Diffusion_Flux
(124)Flux_AtmMix_to_Biosphere
(077)Init_CO2_in_Atm
(126)Init_CO2_in_Mixed_Layer
(116)CO2_in_Atmosphere_S
(119)CO2_in_Mixed_Layer

```
(116) CO2_in_Atmosphere_S = (CO2_in_AtmMix - Init_CO2_in_Mixed_Layer * (1 - 1
        / Buffer_Factor)) / (1 + Init_CO2_in_Mixed_Layer / Init_CO2_in_Atm
        / Buffer_Factor)
```
TonC

CO2 in atmosphere, from equilibrium solution to more complex model with explicit atmosphere and mixed layer stocks.

(115)CO2_in_AtmMix
(114)Buffer_Factor
(077)Init_CO2_in_Atm
(126)Init_CO2_in_Mixed_Layer
(134)CO2_in_Atm
(119)CO2_in_Mixed_Layer
(124)Flux_AtmMix_to_Biosphere

```
(117) CO2_in_Biosphere = INTEG(Flux_AtmMix_to_Biosphere, Init_NPP *
        Biosphere_Res_Time)
```
TonC

CO2 in terrestrial biota.

(111)Biosphere_Res_Time
(124)Flux_AtmMix_to_Biosphere
(127)Init_NPP
(124)Flux_AtmMix_to_Biosphere

```
(118) CO2_in_Deep_Ocean[upper] = INTEG ( Diffusion_Flux[upper] -
        Diffusion_Flux[lower], Init_CO2_in_Deep_Ocean * Thickness[upper] /
        Deep_Ocean_Depth)

      CO2_in_Deep_Ocean[layer10] = INTEG(Diffusion_Flux[layer10],
        Init_CO2_in_Deep_Ocean * Thickness[layer10] / Deep_Ocean_Depth)
```
TonC

CO2 in deep ocean, by layer.

(121)Deep_Ocean_Depth
(122)Diffusion_Flux
(125)Init_CO2_in_Deep_Ocean
(131)Thickness
(120)Concentration

```
(119) CO2_in_Mixed_Layer = CO2_in_AtmMix - CO2_in_Atmosphere_S
```
TonC

CO2 in mixed ocean layer, from equilibrium solution to more complex model with explicit atmosphere and mixed layer stocks.

(115)CO2_in_AtmMix
(116)CO2_in_Atmosphere_S

(122)Diffusion_Flux

(120) `Concentration[layers] = CO2_in_Deep_Ocean[layers] / Thickness[layers]`
TonC / meter
CO2 concentration in deep ocean layers.
(118)CO2_in_Deep_Ocean
(131)Thickness
(122)Diffusion_Flux

(121) `Deep_Ocean_Depth = 3800`
meter
Total depth of deep ocean.
(118)CO2_in_Deep_Ocean
(125)Init_CO2_in_Deep_Ocean

(122) `Diffusion_Flux[layer1] = (CO2_in_Mixed_Layer / Mixed_Depth - Concentration[layer1]) * Eddy_Diff_Coeff * 2 / (Mixed_Depth + Thickness[layer1])`

`Diffusion_Flux[lower] = (Concentration[upper] - Concentration[lower]) * Eddy_Diff_Coeff * 2 / (Thickness[upper] + Thickness[lower])`
TonC / year
Diffusion flux of CO2 between ocean layers.
(119)CO2_in_Mixed_Layer
(120)Concentration
(123)Eddy_Diff_Coeff
(130)Mixed_Depth
(131)Thickness
(115)CO2_in_AtmMix
(118)CO2_in_Deep_Ocean
(110)Atmospheric_Retention_S

(123) `Eddy_Diff_Coeff = 4000`
*meter * meter / year*
Ocean diffusion flux coefficient.
(122)Diffusion_Flux

(124) `Flux_AtmMix_to_Biosphere = Init_NPP * (1 + Biostim_Coeff * LN(CO2_in_Atmosphere_S / Preindustrial_CO2)) - CO2_in_Biosphere / Biosphere_Res_Time`
TonC / year
Net flow of carbon from the atmosphere and mixed layer to the biosphere.
(117)CO2_in_Biosphere
(111)Biosphere_Res_Time
(112)Biostim_Coeff
(116)CO2_in_Atmosphere_S
(127)Init_NPP
(078)Preindustrial_CO2
(115)CO2_in_AtmMix
(117)CO2_in_Biosphere
(110)Atmospheric_Retention_S

(125) `Init_CO2_in_Deep_Ocean = Init_CO2_in_Mixed_Layer * Deep_Ocean_Depth / Mixed_Depth`
TonC
Initial CO2 in deep ocean
(121)Deep_Ocean_Depth

(126)Init_CO2_in_Mixed_Layer
(130)Mixed_Depth
(118)CO2_in_Deep_Ocean

(126) `Init_CO2_in_Mixed_Layer = 7.678e+011`
TonC
Initial CO2 in mixed ocean layer

(115)CO2_in_AtmMix
(116)CO2_in_Atmosphere_S
(125)Init_CO2_in_Deep_Ocean

(127) `Init_NPP = 6e+010`
TonC / year
Initial net primary production

(117)CO2_in_Biosphere
(124)Flux_AtmMix_to_Biosphere

(128) layers : (layer1 - layer10)
Deep ocean layers.
(129) lower : (layer2 - layer10) - > upper
Lower 9 deep ocean layers.

(130) `Mixed_Depth = 75`
meter
Depth of mixed ocean layer.

(122)Diffusion_Flux
(125)Init_CO2_in_Deep_Ocean

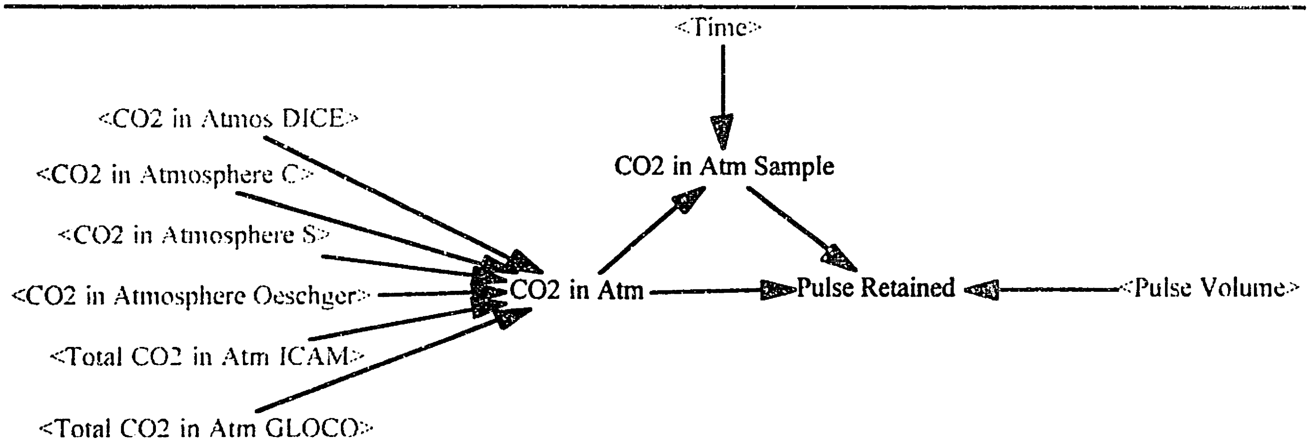
(131) `Thickness[top5] = 200`

`Thickness[bottom5] = 560`
meter
Layers chosen to be relatively thick, as fast dynamics are not of interest.

(118)CO2_in_Deep_Ocean
(120)Concentration
(122)Diffusion_Flux

(132) top5 : (layer1 - layer5)
Top 5 (thin) ocean layers.
(133) upper : (layer1 - layer9) - > lower
Upper 9 deep ocean layers.

.Summary



(134) CO2_in_Atm[DICE] = CO2_in_Atmos_DICE

CO2_in_Atm[FREE] = CO2_in_Atmosphere_C

CO2_in_Atm[ModOes] = CO2_in_Atmosphere_Oeschger

CO2_in_Atm[NICE] = CO2_in_Atmosphere_S

CO2_in_Atm[GLOCO] = Total_CO2_in_Atm_GLOCO

CO2_in_Atm[ICAM] = Total_CO2_in_Atm_ICAM

TonC

(027)CO2_in_Atmos_DICE
(046)CO2_in_Atmosphere_C
(093)CO2_in_Atmosphere_Oeschger
(116)CO2_in_Atmosphere_S
(079)Total_CO2_in_Atm_GLOCO
(087)Total_CO2_in_Atm_ICAM

(135)CO2_in_Atm_Sample
(010)CO2_Rad_Forcing
(137)Pulse_Retained

(135) CO2_in_Atm_Sample[model] = SAMPLE IF TRUE(Time<1965, CO2_in_Atm[model], CO2_in_Atm[model])

TonC

Sampling of atmospheric CO2 in 1965.

(000)Time
(134)CO2_in_Atm

(137)Pulse_Retained

(136) model : DICE, FREE, NICE, ModOes, ICAM, GLOCO

Subscript for different models.

(137) Pulse_Retained[model] = (CO2_in_Atm[model] - CO2_in_Atm_Sample[model]) / Pulse_Volume

dmnl

Fraction of emissions pulse remaining resident in atmosphere.

(134)CO2_in_Atm
(135)CO2_in_Atm_Sample
(039)Pulse_Volume

Control Files

PULSE.CIN

```
{Performs 2xCO2 pulse test}
SAVEPER = 1
Emissions_Switch = 3
Init_CO2_in_Atm = 5.9e+011
init_co2_in_atm_c = 5.9e+011
init_co2_in_atm_oes = 5.9e+011
```

INFINITY.DAT

```
{Emissions from DICE run with continuing technology growth}
{1780-1930 from Goudriaan, J. and P. Ketner. 1984. A Simulation Study for the
      Global Carbon Cycle, Including Man's Impact on the Biosphere. Climatic
      Change 6: 167 - 192. }
CO2 Emiss
1775  0
1780  .01e9
1880  .22e9
1930  1.08e9
1965  4.42111e+009
1975  5.78506e+009
1985  7.2933e+009
1995  8.90189e+009
2005  9.5878e+009
2015  1.10672e+010
2025  1.25816e+010
2035  1.40934e+010
2045  1.55911e+010
2055  1.70904e+010
2065  1.86195e+010
2075  2.01788e+010
2085  2.17613e+010
2095  2.33674e+010
2105  2.50008e+010
2115  2.67602e+010
2125  2.85844e+010
2135  3.04776e+010
2145  3.24457e+010
2155  3.44958e+010
2165  3.66357e+010
2175  3.88731e+010
2185  4.12162e+010
2195  4.36731e+010
2205  4.62522e+010
2215  4.90649e+010
2225  5.20536e+010
2235  5.52187e+010
2245  5.85654e+010
2255  6.21021e+010
2265  6.58384e+010
```

2275	6.97854e+010
2285	7.39548e+010
2295	7.83591e+010
2305	8.30112e+010