Feedback Complexity in Integrated Climate-Economy Models

by

Thomas S. Fiddaman A.B., Engineering Sciences, Dartmouth College, 1990

Submitted to the Alfred P. Sloan School of Management in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Management

at the

Massachusetts Institute of Technology

June 1997

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Sloan School of Management

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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 shortrun 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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	Nazli Choucri Professor of Political Science
	Edward A. Parson Assistant Professor of Public Policy John F. Kennedy School of Government

Acknowledgments

My fortuitous encounter with Dennis Meadows at Dartmouth led to four years of incredibly interesting and fruitful work that prepared me well for this dissertation. Dennis introduced me to global modeling and simulation gaming, which are still central to my work. He was always willing to invest in my development. Early on, Dennis advised me that the purpose of a dissertation is to get a degree, period. Had I heeded his advice, I would probably be a tenured professor by now.

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.

Ted Parson is a walking library of integrated assessment research. He provided invaluable assistance in placing my work in context. More importantly, he has helped me to see my work from the eyes of those not yet inducted into the cult of system dynamics. Nazli Choucri helped me to stay focused on the important aspects of this work by regularly asking me to consider its policy implications, and has helped me to develop a strategy for disseminating my insights.

Elizabeth Krahmer was the first to read many of my chapters. She provided me with a great deal of useful feedback at sometimes astonishing speeds, as well as lots of moral support along the way.

I might not have survived my first year at MIT without the help of Rogelio Oliva, who introduced me to the concept of course bibles, served as the font of all wisdom about the Ph.D. program, and helped me to have faith in the fact that one day I really would get through it all.

Scott Rockart, Anjali Sastry, Hank Taylor, Nelson Repenning, Ed Anderson, Drew Jones, and many other members of the MIT system dynamics community have patiently helped me to refine many parts of this work, and to let off valuable steam on Friday afternoons. Without them it wouldn't be fun to do system dynamics. Jim Hines sustained me through the dry spell between general exams and actually having a thesis topic with some great teaching experience and conversation. He has helped my thinking about life after dissertation greatly.

Fellowship funding from Jim Waters made much of this work possible. From a lively debate we once shared, I gather that he is a climate change skeptic, so I have to applaud his open-mindedness.

Were it not for my Irish Setter, Mobius, I would probably have become a permanent fixture in my home office. His firm conviction that all troubles can be solved by running flat-out around a field every few hours kept me sane and reasonably fit.

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.

Finally, my wife Sarah has made this work possible, worthwhile, and enjoyable. She has been my best friend even at times when I was too tired and cantankerous to deserve any. She always believes in me and when belief alone is insufficient, she fills me up with gourmet food. I'm looking forward to checking my model forecasts against real data with her in 2065.

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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-<u>R</u>ich <u>Energy-E</u>conomy 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 climateeconomy 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 puttyclay 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.

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)	

Table 1: Model Purposes

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.

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

Table 2: Implementation Notes

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.

Model DICE	Type intertemporal optimization	Time discrete	Horizon 1965-2100 [*]	Interval 10 years	Original Language 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

Table 3: Simulation Characteristics

^{*}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:

$$K(t+1) = K(t) - \delta^* K(t) = (1 - \delta)^* K(t)$$
 Eq. 1

$$K(t+n) = (1-\delta)^{n} K(t)$$

$$K = capital$$
 $\delta = depreciation rate$

If $\delta = 10\%$ 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,

Eq. 3

$$K(t+1) = I(t) + (1-\delta)^*K(t)$$

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:

$$K(t+n) = nI(t) + (1-\delta)n K(t)$$
 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:

$$\frac{dK}{dt} = I(t) - \delta^* K(t)$$
 Eq. 5

$$K(t) = \int (I(t) - \delta^* K(t)) dt$$
 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).

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

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Eq. 9

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

$$I(t) = K(t) - K(t-1) + \delta K(t-1)$$

Y = output	L = labor
A = technology	E = energy
$\Omega = climate \ effects$	d = labor share
K = capital	$\gamma = capital \ share$
I = investment	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:

$$K(t) = \frac{\gamma Y(t)}{r + \delta}$$
Eq. 10

$$\frac{dY(t)}{\frac{p}{dt}} = \frac{Y(t) - Y(t)}{\tau}$$
Eq. 11

$$\frac{dK(t)}{\frac{p}{dt}} = \frac{K(t) - K(t)}{\tau}$$
Eq. 12

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

$Y = current \ output$	δ = depreciation rate
Yp = previous output	$\tau = time \ constant$
K = current capital	
Kp = previous capital	

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

Eq. 14

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 = temperature	a = fractional temperature
R = radiative forcing	adjustment rate
	<i>b</i> = <i>radiative forcing coefficient</i>

 $T(t) = \alpha T(t-1) + \beta R(t)$

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:

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





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.





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:

$D^* = f(P)$	Eq. 16
$dD/dt = (D^*-D)/\tau$	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 longand 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.

Model	Equations ¹	State Variables ²	Search	Feedback loops involving			
		variables	opace	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		1108	409	711	25
NICE	300	9 - 21 ⁶	4-22	153	136	108	83
FREE	650	94	1-4	2922	12246	5449	291

Table 4: Complexity Metrics

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.

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 5: Aggregation

Model DICE	Economy capital	Energy –	GHG Cycles atmospheric carbon	Climate surface ocean temperature deep ocean	
Connecticut/ YOHE	capital output	cumulative carbon fuel production	atmospheric carbon	temperature 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	

Table 6: Representative State Variables

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



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:

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

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:

$$X \longrightarrow Y \qquad \qquad Y(t) = f(X(t-1))$$

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:

$$X \longrightarrow Y \qquad \qquad Y(t) = f(X(t)-X(t-1))$$

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.





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.





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.





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).





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.





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).





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.





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).





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).





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.





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 2xCO₂ 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 N₂O 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.





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 (<u>Feedback-Rich Energy Economy model</u>). 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.

Endogenous	Exogenous	Excluded
Economic output	Population	Labor mobility and
Consumption	Factor productivity	participation
Interest rates	Autonomous energy efficiency	Money stocks and monetary effects
Investment	Oil/gas and coal prices (1960- 1990)	Non-energy resources
Embodiment of energy requirements in capital		Regional disaggregation
Energy prices	Nonenergy CO ₂ emissions	Sectoral disaggregation (other than energy)
Energy production	Greenhouse gases other than CO ₂	Fossil-fired electric power generation
Energy technology		
Depletion		Inventories and backlogs
CO ₂ Emissions		
Carbon Cycle		
Atmosphere and ocean temperature		
Climate damages		

Table 7: Model Boundary

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.





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, welldocumented, and widely understood. Using them allows implications of the energyeconomy model to be compared with Nordhaus' results in a common biogeophysical context.

The energy-economy systems in the model draw heavily on Sterman's energyeconomy 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.

$$CDU = \int_{\mathcal{P}} e^{(-\rho \ t)} L(t) U(t) dt$$

$$CDU = cumulative \ discounted \\ utility \\ \rho = rate \ of \ time \ preference$$

$$L = population \\ U = utility \ of \ representative \\ individual$$

$$Eq. 20$$

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).





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).

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

ECI = equivalent consumption index θ = rate of inequality aversion

 $ECI = \left(\frac{c}{c}_{0}\right)^{\Omega} \left(\frac{S}{S}_{0}\right)^{(1-\Omega)}$ Eq. 22 $c = consumption \ per \ capita \\ c_{0} = reference \ consumption \ per \\ capita \\ S = environmental \ services \\ S = S D \\ 0 \ n$ 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.

$$U = \frac{\left(\frac{c}{c}\right)^{(1-\theta)} - 1}{1-\theta}$$
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





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).

2			
Parameter	Alias	Value	Units
Rate of Time Preference	ρ	0	1/year
Rate of Inequality Aversion	θ	2.5	dmnl
Share of Consumption in	Ω	1	dmnl
Utility			

Table	8:	Welfare	Parameters
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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.





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.





(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).

Parameter Va	alue	Units	Notes
Initial Population 3.04	41e9	people	(World Bank 1995)
Initial Population Growth	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)

Table 9: Population Parameters

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 steadystate 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:

$$r = \frac{\left(\frac{\partial}{\partial t}c(t)\right)\theta}{c(t)} + \rho_{c}$$
Eq. 25

c = per capita consumption	θ_c = rate of inequality aversion
r = interest rate	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.

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		20	years	
Time				

Table 10: Interest Rate Parameters

Goods Allocation

The goods allocation sector distributes economic output among energy production requirements, investment requirements, and consumption. The shortterm 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:





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.





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 shortrun 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.

$$Y = Y D_{m} \left(\frac{L}{L}\right)^{\alpha} \left(\frac{KO}{KO}\right)^{(1-\alpha)}$$

 $Y = gross \ output$ $Y_0 = reference \ gross \ output$ $T = factor \ productivity$ L = labor

 $L_0 = initial \ labor$ $KO = operating \ capital$ $KO_0 = reference \ operating \ capital$ $\alpha = value \ share \ of \ labor$

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.





Parameter	Alias	Value	Units	Notes
Value Share of Labor	α	.7	dmnl	Model is denominated in constant 1990 dollars.
Reference Output	Y ₀	6.124e12	\$/year	

Eq. 26

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.





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.





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 =

$$KN\left(\beta_{sr} + \left(1 - \beta_{sr}\right)\left(\frac{EI}{EN}\right)^{\rho} ke, sr\right)\left(\frac{1}{\rho_{ke,sr}}\right)$$

KN = normal short-run capitalenergy aggregate EI = actual aggregate energy input EN = normal aggregate energy input

 $\beta_{sr} = value \ share \ of \ capital \ in \ short-run \ capital-energy \ aggregate \
ho_{ke,sr} = \ short-run \ capital-energy \ substitution \ coefficient$

Eq. 28

Eq. 27

$$\rho = \frac{\sigma - 1}{\sigma}$$

 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.

 $EI = EN\left(\sum_{i} \gamma_{i,sr} \left(\frac{ED_{i}}{ER_{i}}\right)^{e,sr}\right)$ $ED_{i} = energy \ delivery \ rate \qquad \gamma_{i,sr} = value \ share \ of \ energy$

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.

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$$KN = KN_{0} \left(\left(1 - A\beta_{lr}\right) \left(\frac{K}{K_{0}}\right)^{\rho} ke, lr + A\beta_{lr} \left(\frac{EN}{EN_{0}}\right)^{\rho} ke, lr \right)^{\rho} ke, lr \right)$$
Eq. 31

$$KN = normal \ capital-energy$$

 $aggregate$
 $KN_0 = reference \ capital-energy$
 $aggregate$
 $K = capital$
 $K_0 = reference \ capital$
 $EN = normal \ aggregate \ energy$

aggregate energy utonomous icy improvement lue share of $\rho_{ke,lr} = long$ -run capital-energy substitution coefficient $\left(\frac{ER}{i}_{i,0}\right)^{\rho}e,lr$



$$\rho_{e,lr} = long$$
-run energy

substitution coefficient

$$KN = KN \\ 0 \left(\begin{pmatrix} 1 - A \beta \\ lr \end{pmatrix} \begin{pmatrix} \frac{K}{K} \\ 0 \end{pmatrix} + A \beta \\ lr \begin{pmatrix} \frac{LR}{K} \\ 0 \end{pmatrix} \end{pmatrix}$$

$$KN = normal \ capital-energy \\ aggregate \\ KN_0 = reference \ capital-energy \\ aggregate \\ K = capital \\ K_0 = reference \ capital \end{bmatrix}$$

$$EN_0 = reference \ ainput \\ A = embodied \ a \\ energy \ efficient \\ \beta_{lr} = long-run \ va \\ energy \end{bmatrix}$$

input

 $EN = EN_0$

 $ER_i = embodied \ energy$

 $\gamma_{i,lr}$ = value share of energy source

requirement

```
Long Run Production Structure
```

 $ED_i = energy \ delivery \ rate$ $M_{i,sr} = short-run marginal$

product of energy

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.

coefficient

 P_i = perceived energy price η = energy order adjustment

$$EO_{i} = ED_{i} \left(\frac{M}{\frac{i, sr}{P}}\right)^{\eta}$$
$$EO_{i} = energy \text{ order rate}$$

Thomas Fiddaman

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

Table 13: Production Structure Parameters

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.

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

K = capital $\delta = fractional depreciation rate$ I = investment 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.

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

 $DK = desired \ capital$ $\tau_{k} = capital \ correction \ time$ $DK = \frac{K M}{r}$ $DK = \frac{\frac{k}{r}}{r}$ $G = perceived \ fractional \ growth$ $rate \ of \ output$ 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 FREE 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.

$$ER_{i}(t) = \int_{i}^{N} N(t) \left(I(t) + \varepsilon K(t) \right) - (\delta + \varepsilon) ER_{i}(t) dt$$
Eq. 36

$ER_i = energy requirement$	I = investment rate
N_i = planned energy intensity of	$\varepsilon = fractional retrofit rate$
new capital	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.





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.

$$N_{i}(t) = \begin{cases} \frac{ND_{i}(t) - N_{i}(t)}{\frac{1}{\tau} n} dt \\ \int \frac{ND_{i}(t) - N_{i}(t)}{\pi} dt \end{cases}$$
Eq. 37

 $N_i = planned \ energy \ intensity \ of mew \ capital mem capital <math>\tau_n = energy \ intensity \ planning \ delay \ ND_i = desired \ energy \ intensity \ of mew \ capital \$

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.

$$ND_{i} = N \underset{T}{AE DS}_{i}$$
Eq. 38

N_T = total energy intensity of capital

AE = aggregate energy intensity adjustment DS_i = desired share

Eq. 39

$$N_T = \frac{\sum_i ER_i}{K}$$

$ER_i = energy \ requirement$ 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.

 $AE = \begin{pmatrix} M \\ T \\ T \\ T \end{pmatrix}^{\left(\omega \sigma_{ke, lr}\right)} Eq. 40$

$M_T = long-run marginal product$	ω = energy intensity adjustment
of aggregate energy	coefficient
P_T = perceived aggregate energy	$\sigma_{ke,lr}$ = long-run capital-energy
price	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.

$$DS_{i} = \frac{AI_{i}}{\sum_{j} AI_{j}}$$
Eq. 41

$$AI_i = adjusted \ energy \ intensity$$
 $i,j = subscripts \ for \ energy \ sources$

Eq. 42

$$AI_{i} = \frac{ER_{i} \left(\frac{M_{i}, lr}{P_{i}}\right)^{\left(\substack{\omega \ \sigma \\ e, lr\right)}}}{K}$$

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.





Response of embodied energy requirements for oil to a step increase in oil prices for $\omega = 1$. 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 $\omega = 1$, 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. $\omega = .33$, 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.

$$A(t) = \frac{\int AEEI(t) (I(t) + \varepsilon K(t)) - (\delta + \varepsilon) A(t) dt}{K(t)}$$

$$A = average \ embodied \ AEEI \ of \qquad K = capital \\ AEEI = autonomous \ energy \qquad \varepsilon = fractional \ retrofit \ rate \\ efficiency \ improvement \ level \qquad \delta = fractional \ discard \ rate \\ of \ new \ capital$$

$$Eq. 43$$

Eq. 44

$$AEEI(t) = \int \alpha_a \left(AEEI_{\infty} - AEEI(t) \right) dt$$

 $AEEI_{\infty} = asymptotic \ energy$ $efficiency \ improvement \ level$ $\alpha_a = fractional \ autonomous$ $energy \ efficiency \ improvement$ rate





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

Eq. 45

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.

$$EP_{i} = EP_{i,0} \left(\alpha_{i,r} \left(\frac{R}{R}_{i,0} \right)^{i,r} + \left(1 - \alpha_{i,r} \right) EII_{i}^{i,r} \right)^{i,r}$$

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

$$\alpha_{nonren, r} = \left(\frac{\binom{R}{i, 0}}{\tau \underset{r}{EP}_{i, 0}}\right)^{r} \qquad \alpha_{renew, r} = \left(\frac{\binom{R}{i, 0}}{\underset{i, 0}{EP}_{i, 0}}\right)^{r}$$
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.

$$EII_{i} = TE_{i} \left(\frac{KE}{KE}_{i,0}\right)^{\beta} \left(\frac{V}{V}_{i,0}\right)^{\left(1-\beta\right)} Eq. 47$$

$$EII_{i} = TE_{i} \left(\frac{KE}{KE}_{i,0}\right)^{\beta} \left(\frac{V}{V}_{i,0}\right)^{\left(1-\beta\right)}$$

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

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 energyintensive 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.

Parameter	Alias	Value	Units	Notes
Capital Share	Biky			
(nonrenewable)	, 1,Kv	.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_{i0}			
(coal)	1,0	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)

Table 17: Energy Production Parameters

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).

$$\begin{aligned} & \operatorname{KE}_{i}(t) = \begin{cases} \frac{KC(t)}{i} & \operatorname{Eq.} 48 \\ \int_{-\infty}^{i} c & -\delta_{i} & \operatorname{KE}_{i}(t) \, dt \end{cases} \\ & \operatorname{KE}_{i} = energy \ capital \\ & \operatorname{KC}_{i} = energy \ capital \ under \\ & \operatorname{construction} \end{cases} \quad \begin{aligned} & \tau_{c} = capital \ construction \ delay \\ & \delta_{i} = energy \ capital \ lifetime \\ & \delta_{i} = energy \ capital \ lifetime \end{cases} \\ & \operatorname{Eq.} 49 \end{aligned}$$

 $EKO_i = energy$ 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).

$$EKO(t) = MAX \left(0, \delta_{i} KE(t) + \frac{DKC(t) - KC(t)}{i} + \frac{DKE(t) - KE(t)}{kc} + \frac{DKE(t) - KE(t)}{i} + \frac{KE(t) GE(t)}{i} \right) Eq. 50$$

$$DKE_{i} = \frac{KE M EO}{i \ i, k \ i}$$

$$DKE_{i} = \frac{KE M EO}{r \ NEP}_{i}$$

$$M_{i,k} = marginal \ product \ of \ energy$$

$$EO_{i} = energy \ order \ rate$$

$$NEP_{i} = normal \ energy \ production$$

$$rate$$

$$DKC_{i} = KE_{i} \left(\frac{\delta}{i} + GE_{i} \right) \tau_{kc}$$
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.

Parameter	Alias	Value	Units	Notes
Capital Lifetime	$1/\delta_i$			
(coal)	1	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)

Table 18: Energy Capital Parameters

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).

$$TE_{i} = \frac{1}{LL_{i} + \frac{1 - LL_{i}}{ET_{i}^{\nu} AT_{i}^{(1-\nu)} S_{i}}}$$

 $TE_i = energy \ technology \ level$ $LL_i = lower \ limit \ to \ cost$ $reductions \ from \ technology$ $ET_i = endogenous \ technology$ $(learning \ curve)$

 AT_i = autonomous technology S_i = scale economy effect v = 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).

$$ET_{i} = \beta_{t} \ln \left(\frac{C_{i}}{C_{i,0}}\right)$$

$$C_{i,0} = initial \ cumulative \qquad \beta_{t} = learning \ curve \ coefficient$$

$$C_{i} = cumulative \ investment$$

$$C_{i}(t) = \int_{i} I(t) \ dt$$
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.

Eq. 53

Eq. 57

$$AT_{i} = e^{\begin{pmatrix} \alpha & t \\ t \end{pmatrix}}$$
Eq. 56

 α_t = fractional autonomous energy technology growth rate

 $S_{i} = \left(\frac{KE_{i}}{KE_{i,0}}\right)^{s}$

 $KE_i = energy \ capital$ $KE_{i,0} = initial \ energy \ capital$ $\gamma_s = scale \ coefficient$

Figure 62: Energy Technology



	Table	19:	Energy	Technology	Parameters
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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)	LLi	.1	dmnl	
(oil/gas)	Ĩ	.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).

$$P_{i} = PP_{i} + \mu_{i} + D_{i} + T_{i}$$
Eq. 58
$$P_{i} = energy \ price$$

$$PP_{i} = producer \ price$$

$$\mu_{i} = depletion \ rent$$

$$PP_{i}(t) = \int_{j} \frac{IP(t) - PP(t)}{\frac{i}{p}} dt$$
Eq. 59

 $IP_i = indicated producer price$ τ_{v} = 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.

$$IP_{i} = PP_{i} \left(\frac{AC}{PP_{i}}\right)^{a} \left(\frac{MC}{PP_{i}}\right)^{m} \left(\frac{EO}{NEP_{i}}\right)^{d}$$
Eq. 60

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

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.

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	γd	2	dmnl

Table 20: Energy Pricing Parameters

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 CO₂ emissions and the atmospheric concentration of CO₂. 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.

$$T = \varepsilon T + T$$

$$i c e$$

Eq. 61

$$T_{i} = \text{total tax} \qquad T_{c} = \text{carbon tax}$$

$$\varepsilon_{i} = \text{carbon content} \qquad T_{e} = \text{energy tax}$$

$$T_{e}(t) = \int_{J} \frac{DT(t) - T(t)}{t} dt$$

Eq. 62

$$\tau_t = tax$$
 implementation tin

$$T_{c}(t) = \int_{J} \frac{DT_{c}(t) - T_{c}(t)}{\frac{\tau}{t}} dt$$

 DT_e = desired energy tax

ime

Eq. 63

Eq. 64

 DT_c = desired carbon tax

$$DT_{c} = T_{0} + \frac{\frac{T}{E}}{0} + \frac{T}{\frac{2}{C}} + \frac{2}{\frac{2}{a}}$$

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



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 64: Carbon Taxes





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 Parameter	Table .	21:	Tax	Policy	Parameter
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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).

$$\int_{0}^{T} e^{(-rt)} (U(Q,t) - C(R,Q,t)) dt$$
Eq. 65
$$U = utility$$

$$R = resource remaining$$

$$r = interest rate$$

$$C = resource \ extraction \ cost \qquad r = interest \ rate
Q = resource \ consumption \ rate \qquad T = planning \ horizon
$$\frac{\partial}{\partial t} \mathbf{R}(t) = -Q \qquad \left\{ \begin{array}{l} 0 \le \mathbf{R}(T), \mathbf{R}(0) = \mathbf{R} \\ 0 \end{array} \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).

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

$$J = current value Hamiltonian
\mu = shadow price (co-state variable) of resource
\mu = \left(\frac{\partial}{\partial Q} U(Q, t)\right) - \left(\frac{\partial}{\partial Q} C(R, Q, t)\right)$$
Eq. 68

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

CO₂ 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: Emission	s Parameters			
Parameter	Alias	Value	Units	
Carbon Content	ϵ_{i}	0247	TonC/CI	
(oil/gas)		.0247	TonC/GJ	

ъ T 1.1 22

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 CO₂ increases (Wullschleger, Post et al. 1995), according to:

$$NPP = NPP_{0} \left(1 + \beta_{b} \ln \left(\frac{C}{a} \\ \frac{C}{a, 0} \right) \right)$$

NPP = net primary production $NPP_0 = reference net primary$ production $\beta_b = biostimulation coefficient$ $C_a = CO_2$ 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



Eq. 70

It is worth noting that this formulation is not robust to large deviations in the atmospheric concentration of CO₂. As the atmospheric concentration of CO₂ approaches zero, net primary production approaches minus infinity, which is not possible given the finite positive stock of biomass. As the concentration of CO₂ 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).

$$C_{b}(t) = \int_{J} \text{NPP}(t) - \frac{C_{b}(t)}{\frac{\tau}{b}} dt$$
Eq. 71



 τ_h = humus residence time

The interaction between the atmosphere and mixed ocean layer involves a shift in chemical equilibria (Goudriaan and Ketner 1984). CO₂ in the ocean reacts to produce HCO_3^- and CO_3^- . In equilibrium,

$$C_{m} = C_{m,0} \left(\frac{C}{a}_{a,0}\right)^{\left(\frac{1}{\zeta}\right)}$$

$$C_{m} = CO_{2} \text{ in mixed ocean layer} \qquad C_{a} = CO_{2} \text{ in atmosphere}$$

Eq. 73

 $C_m = CO_2$ in mixed ocean layer $C_{m,0} =$ reference CO_2 in mixed ocean layer $C_{a,0} =$ reference CO_2 in atmosphere $\zeta =$ 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 CO₂ 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.

$\begin{pmatrix} C \end{pmatrix}$	Eq. 74
$\zeta = \zeta_0 + \delta_b \ln \left \frac{a}{C} \right $	
(a,0)	

$\zeta = buffer factor$	$C_a = CO_2$ in atmosphere
ζ_0 = reference buffer factor	$C_{a,0} = reference \ CO_2 \ in$
$\delta_b = buffer \ CO_2 \ coefficient$	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:

Eq. 75

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

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

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 CO₂ 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.

	A 1 ·	\$7.1	TT	NT /
Parameter	Allas	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	ζ0	10	dmnl	(Goudriaan and Ketner 1984)
Deep Ocean Layer Thickness	d _n			
(top 5 layers)		200	meters	
(bottom 5 layers)		500	meters	

Table 24: Carbon Cycle Parameters

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.





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 .

Eq. 76

$$T_{equil} = \frac{\kappa \ln \left(\frac{C}{a}\right)}{\lambda \ln(2)}$$

 $T_{equil} = equilibrium temperature$ $C_a = atmospheric CO_2$ concentration $C_{a,o} = preindustrial atmospheric$ CO_2 concentration



Figure 72: Equilibrium Temperature Response



Figure 73 shows the absolute temperature following a pulse doubling of atmospheric CO₂. The response is roughly a first-order smoothing of the pulse response of atmospheric CO₂. 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 CO₂ 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 CO₂ Pulse

Table 25: Climate Parameters

Parameter	Alias	Value	Units	Notes
Climate Sensitivity	$\kappa_{/\lambda}$	2.908	DegreesC	(Nordhaus 1994)
Radiative Forcing Coefficient	к	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.

$$D(\Delta) = 1 - \frac{1}{\theta}$$

$$D = climate \ damage \ effect$$

$$\Delta = deviation \ from \ adapted$$

$$Eq. 77$$

$$Eq. 77$$

$$\theta_1 = climate \ damage \ scale$$

$$\theta_2 = climate \ damage \ nonlinearity$$

temperature Δ_r = reference deviation from adapted temperature

$$\Delta = \begin{vmatrix} T - T \\ a \end{vmatrix}$$

T = temperature of atmosphere and upper ocean Eq. 78

 T_a = adapted temperature

Eq. 79

$$T_{a}(t) = \int_{J} \frac{T(t) - T_{a}(t)}{\tau_{a}} dt$$

 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 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 CO₂ Pulse

Table 26: Impact Parameters

Parameter	Alias	Value	Units	Notes
Climate Damage Scale (tangible)	θ_1	.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).

	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.

Table 27: Contrasting Scenario Assumptions

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.





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 shortrun 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.





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.





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.





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.





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.





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.





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

39%

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.

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

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

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

10%

H. Behavior

Scenario G

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.





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.




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.





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.





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.





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.





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.





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).

Р	Price (\$/GJ)
2000	2050
3.35	14.52
0.00	<u>0.00</u>
3.35	14.52
3.02	6.55
<u>1.70</u>	<u>6.05</u>
4.72	12.60
	P 2000 3.35 <u>0.00</u> 3.35 3.02 <u>1.70</u> 4.72

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

		Price	(\$/GJ)	
	2	.000	2	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)	<u>5.20</u>	<u>3.60</u>	<u>21.98</u>	<u>15.22</u>
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)	<u>.93</u>	<u>.64</u>	<u>3.93</u>	<u>2.72</u>
Total Price	2.01	5.26	4.82	21.44

	Table .	30:	Effect	of	Optimal	Carbon	Tax,	with	and	without	Depletion	Таэ
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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 topdown 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 energyrelated 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.

	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

Table 31: Impact of Technology Specification

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 energyeconomy 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.





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 2xCO₂ 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.

	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	1 5	1 5
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

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

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.

		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
0	Optimal Tax	0.34	0.37	877	2.2

Table 33: Impact of Welfare Criteria

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 $\pm 10\%$. 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 CO₂ 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, $\sum [X_p(t) - X_b(t)]^2$.

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 capitalenergy 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.

		Rank		
	Emissions	Output Tem	perature	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.
		Rank		
	Emissions	Output Tem	perature	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

Table 35: Scenario J Parameter Sensitivity

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 puttyclay structure in Scenario J makes retrofits potentially important.

	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

Table 36: Sensitivity Rank Differences

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.

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			

Table 37: Parameter Distributions

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.

	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

Table 38: Uncertainty of Key Variables

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.





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.





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 riskneutrality. 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 \pm \$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 CO₂ 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.

	0 1 0				
	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	1.2	18.3	6.3	5.2	0.588
(10 ⁹ TonC/year)	(-73%)	(-60%)	(-73%)	(-77%)	(+39%)
Temperature in 2100 (DegreesC)	1.42	5.11	2.89	2.91	0.234
	(-23%)	(-13%)	(-23%)	(-21%)	(-3%)

Table 39: Multivariate Sensitivity of Key Variables with Carbon Tax

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 nearterm 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 noncarbon 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 pathdependent 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.

References

- Argote, L. and D. Epple. 1990. Learning Curves in Manufacturing. *Science* 247(23 February): 920-924.
- Arrow, K. 1962. The Economic Implications of Learning by Doing. *Review of Economic Studies* 29(June): 155-173.
- Arthur, B. 1989. Competing Technologies, Increasing Returns, and Lock-in by Historical Events. *The Economic Journal* 99(March): 116-131.
- Barlas, Y. 1989. Tests of Model Behavior That Can Detect Structural Flaws: Demonstration with Simulation Experiments. Computer-Based Management of Complex Systems: International System Dynamics Conference, .
- Beaver, R. 1993. Structural Comparison of the Models in EMF 12. *Energy Policy* 21(3, March).
- Becker, G. S. and C. B. Mulligan. 1994. On the Endogenous Determination of Time Preference. University of Chicago.
- Björkstrom, A. 1986. One-Dimensional and Two-Dimensional Ocean Models for Predicting the Distribution of CO2 Between the Ocean and the Atmosphere. In *The Changing Carbon Cycle: A Global Analysis*, ed. J. R. Trabalka and D. E. Reichle. New York: Springer-Verlag.
- Bolin, B. 1986. Requirements for a Satisfactory Model of the Global Carbon Cycle and Current Status of Modeling Efforts. In *The Changing Carbon Cycle: A Global Analysis*, ed. J. R. Trabalka and D. E. Reichle. New York: Springer-Verlag.
- Brooke, A., D. Kendrick, et al. 1988. *GAMS: A User's Guide*. Redwood City, CA: The Scientific Press.
- Burniaux, J.-M., J. P. Martin, et al. 1992. The Effect of Existing Distortions in Energy Markets on the Costs of Policies to Reduce CO2 Emissions: Evidence from GREEN. *OECD Economic Studies* 19(Winter): 141-161.
- Burniaux, J.-M., G. Nicoletti, et al. 1992. GREEN: A Global Model for Quantifying the Costs of Policies to Curb CO2 Emissions. *OECD Economic Studies* 19(Winter): 49-92.
- Cantor, R. and J. Hewlett. 1988. The Economics of Nuclear Power: Further Evidence on Learning, Economies of Scale, and Regulatory Effects. *Resources and Energy* 10: 315-335.
- Chao, H.-p. 1995. Managing the Risk of Global Climate Catastrophe: An Uncertainty Analysis. *Risk Analysis* 15(1): 69-78.
- Chapman, D., V. Suri, et al. 1995. Rolling DICE for the Future of the Planet. *Contemporary Economic Policy* XIII(3): 1-9.
- Christiansson, L. 1995. Diffusion and Learning Curves of Renewable Energy Technologies. IIASA, WP-95-126.
- Cline, W. R. 1992. *The Economics of Global Warming*. Washington, DC: Institute for International Economics.
- Congressional Research Service. 1980. *The Energy Factbook*. Washington, DC: Library of Congress.
- Costanza, R. 1996. *Managing the DICE Model*. Institute for Ecological Economics, University of Maryland,

http://csf.colorado.edu/ecolecon/authors/Costanza.Robert/costanza_review_no rdhaus.html.

- de Vries, B. 1995. Evaluation of Some Global Energy Scenarios with the TIMEmodel. RIVM.
- de Vries, B. and M. Janssen. 1996. *Global Energy Futures: An Integrated Perspective with the TIME-model*. National Institute for Public Health and the Environment (RIVM), Netherlands, GLOBO Series No. 17.
- de Vries, B. and R. van den Wijngaart. 1995. *The Targets/IMage 1.0-Energy (TIME) Model.* RIVM, 461502000.
- de Vries, H. J. M. 1989. Effects of Resource Assessments on Optimal Depletion Estimates. *Resources Policy* (September): 253-268.
- DeCanio, S. J. 1993. Barriers Within Firms to Energy-efficient Investments. *Energy Policy* 21(September): 906-915.
- Dowlatabadi, H. 1995. Integrated assessment models of climate change: An incomplete overview. *Energy Policy* 23(4/5): 289-296.
- Dowlatabadi, H. and M. Ball. 1994. An Overview of the Integrated Climate Assessment Model Version 2. Vancouver, Canada, Western Economic Association.
- Dowlatabadi, H. a. M. G. M. 1993. A Model Framework for Integrated Studies of the Climate Problem. *Energy Policy* 21(3, March).
- Energy Information Administration. 1995. *International Energy Annual 1993*. Department of Energy, DOE/EIA-0219(93).
- Energy Information Administration. 1995. *International Energy Outlook 1995*. Department of Energy, DOE/EIA-0383(95).
- England, R. 1994. Three Reasons for Investing Now in Fossil Fuel Conservation: Technological Lock-in, Institutional Inertia, and Oil Wars. *Journal of Economic Issues* XXVIII(3, September): 755-776.
- Fankhauser, S. 1995. Valuing Climate Change. London: Earthscan.
- Fiddaman, T. 1995. Formulation Experiments with a Simple Climate-Economy Model. 1995 System Dynamics Conference, Tokyo, Japan.
- Fiddaman, T. 1996. A System Dynamics Perspective on an Influential Climate/Economy Model. *Submitted to System Dynamics Review*.
- Forrester, J. W. 1961. Industrial Dynamics. Cambridge MA: Productivity Press.
- Forrester, J. W., & Senge, P. M. 1980. Tests for Building Confidence in System Dynamics Models. In System Dynamics, ed. A. A. L. J. e. al. New York: North-Holland. 209-228.
- Friedman, L. S. and K. Hausker. 1988. Residential Energy Consumption: Models of Consumer Behavior and their Implications for Rate Design. *Journal of Consumer Policy* 11: 287-313.
- Fung, I. 1991. Models of Oceanic and Terrestrial Sinks of Anthropogenic CO2: A Review of the Contemporary Carbon Cycle. In *Biogeochemistry of Global Change*, ed. R. S. Oremland. New York: Chapman & Hall.
- Gately, D. 1979. Individual Discount Rates and the Purchase and Utilization of Energy-using Durables: Comment. *Bell Journal of Economics* : 373-374.
- Gates, R. 1983. Investing in Energy Conservation: are Homeowners Passing up High Yields? *Energy Policy* 11(1, March): 63-71.

- Gilli, P. V., N. Nakicenovic, et al. 1996. First- and Second-Law Efficiencies of the Global and Regional Energy Systems. IIASA, RR-96-002.
- Goldemberg, J., T. B. Johansson, et al. 1987. *Energy for a Sustainable World*. World Resources Institute.
- 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.
- Grubb, M. 1993. Policy Modelling for Climate Change: the Missing Models. *Energy Policy* 21(3, March).
- Grubb, M., T. Chapuis, et al. 1995. The economics of changing course: Implications of adaptability and inertia for optimal climate policy. *Energy Policy* 23(4/5): 417-445.
- Grubb, M., M. H. Duong, et al. 1994. Optimizing Climate Change Abatement Responses: On Inertia and Induced Technology Development. In *Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*, ed. N. Nakicenovic, W. D. Nordhaus, R. Richels and F. L. Toth. Laxenburg, Austria: International Institute for Applied Systems Analysis. 513-534.
- Guyol, N. B. 1969. *The World Electric Power Industry*. Berkeley, CA: University of California Press.
- Hall, D. C. 1990. Preliminary Estimates of Cumulative Private and External Costs of Energy. *Contemporary Policy Issues* VIII(3, July).
- Hamilton, M. S. 1980. Estimating Lengths and Orders of Delays in System Dynamics Models. In *Elements of the System Dynamics Method*, ed. J. Randers. Cambridge MA: Productivity Press. 162-182.
- Hassett, K. and G. Metcalf. 1993. Energy Conservation Investment: Do Consumers Discount the Future Correctly? *Energy Policy* 21(6): 710-716.
- Hatlebakk, M. and E. Moxnes. 1992. *Misperceptions and Mismanagement of the Greenhouse Effect? The Simulation Model.* Christian Michelsen Research, Report # CMR-92-A30009, December.
- Hausman, J. A. 1979. Individual Discount Rates and the Purchase and Utilization of Energy-using Durables. *Bell Journal of Economics* 10(1): 33-54.
- High Performance Systems. 1996. *ithink Analyst Technical Documentation*. Hanover, NH.
- Hogan, W. W. and D. W. Jorgenson. 1991. Productivity Trends and the Cost of Reducing CO2 Emissions. *Energy Journal* 12(1): 67-85.
- Hohmeyer, O. 1990. Social Costs of Electricity Generation: Wind and Photovoltaic versus Fossil and Nuclear. *Contemporary Policy Issues* VIII(July): 255-282.
- Homer, J. B. 1983. *Partial-Model Testing As A Validation Tool for System Dynamics*. Intl. System Dynamics Conf., Chestnut Hill, MA.
- Hourcade, J.-C. and T. Chapuis. 1994. No-Regret Potentials and Technical Innovation: A Viability Approach to Integrated Assessment of Climate Policies. In *Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*, ed. N. Nakicenovic, W. D. Nordhaus, R. Richels and F. L. Toth. Laxenburg, Austria: International Institute for Applied Systems Analysis. 535-558.
- Howarth, R. B. and B. Anderson. 1993. Market Barriers to Energy Efficiency. *Energy Economics* 15(4, October).

- Huntington, H. G. 1994. Been Top Down So Long it Looks Like Bottom Up to Me. *Energy Policy* 22(10): 833-839.
- International Energy Agency. 1986. Energy Prices and Taxes: Fourth Quarter 1985. Paris: OECD.
- International Energy Agency. 1989. World Energy Statistics and Balances, 1985-1988. Paris: OECD.
- International Energy Agency. 1990. Energy Statistics and Balances of Non-OECD Countries, 1989-1990. Paris: OECD.
- International Energy Agency. 1992. Electricity Supply in the OECD. Paris: OECD.
- International Energy Agency. 1995. Energy Prices and Taxes: Third Quarter 1995. Paris: OECD.
- IPCC. 1991. *Climate Change: The IPCC Response Strategies*. Washington, DC: Island Press.
- IPCC. 1994. Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios. Cambridge: Cambridge University Press.
- Jaffe, A. B. and R. N. Stavins. 1994. The Energy Paradox and the Diffusion of Conservation Technology. *Resource and Energy Economics* 16(2): 91-122.
- Jaffe, A. B. and R. N. Stavins. 1994. The Energy-efficiency Gap. What Does it Mean? *Energy Policy* 22(10): 804-811.
- Jenkins, G. 1989. Oil Economists' Handbook. New York: Elsevier Applied Science.
- Joskow. 1987. Price Adjustment in Long Term Contracts: the Case of Coal. Dept. of Economics, MIT, WP 444.
- Joskow, P. L. a. D. B. M. 1991. What Does a Negawatt Really Cost?, Discussion Paper, MIT-CEPR 91-016WP.
- Kampmann, C. 1996. Feedback Loop Gains and System Behavior. Technical University of Denmark.
- Keller, A. A. and R. A. Goldstein. 1995. Oceanic Transport and Storage of Carbon Emissions. *Climatic Change* 30: 367-395.
- Kelly, D. L. and C. D. Kolstad. 1996. *Malthus and Climate Change: Betting on a Stable Population*. Department of Economics, UC Santa Barbara.
- Kempton, W. and L. L. Layne. 1994. The Consumer's Energy Analysis Environment. *Energy Policy* 22(10): 857-866.
- Koomey, J. G. and A. H. Sanstad. 1994. Technical Evidence for Assessing the Performance of Markets Affecting Energy Efficiency. *Energy Policy* 22(10): 826-832.
- Lovins, A. and H. L. Lovins. 1991. Least Cost Climatic Stabilization. Annual Review of Energy and the Environment 16.
- Lovins, A. B. 1977. Soft Energy Paths. Cambridge MA: Ballinger.
- Lutzenhiser, L. 1994. Innovation and Organizational Networks. Barriers to Energy Efficiency in the US Housing Industry. *Energy Policy* 22(10): 867-876.
- Manne, A. 1994. The Rate of Time Preference: Implications for the Greenhouse Debate. In *Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*, ed. N. Nakicenovic, W. D. Nordhaus, R. Richels and F. L. Toth. Laxenburg, Austria: International Institute for Applied Systems Analysis. 467-474.

- Manne, A., R. Mendelsohn, et al. 1995. MERGE: A model for evaluating regional and global effects of GHG reduction policies. *Energy Policy* 23(1): 17-34.
- Manne, A. S. and R. G. Richels. 1992. Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits. Cambridge, MA: MIT Press.
- Maxwell, D. T. 1996. Three Packages for Processing Influence Diagrams. Journal of Multi-Criteria Decision Analysis 5.
- Meadows, D., Richardson, J., & Bruckmann, G. 1982. *Groping in the Dark*. New York: Wiley and Sons.
- Messner, S. 1996. Endogenized Technological Learning in an Energy Systems Model. IIASA, WP-95-114.
- Metcalf, G. E. 1994. Economics and Rational Conservation Policy. *Energy Policy* 22(10): 819-825.
- Morecroft, J. D. W. 1982. A Critical Review of Diagramming Tools for Conceptualizing Feedback System Models. *Dynamica* 8(1): 20-29.
- Mueller, M. J. 1994. Behavior of Non-renewable Natural Resource Firms Under Uncertainty. *Energy Economics* 16(1): 9-21.
- National Academy of Sciences, ed. 1991. *Policy Implications of Greenhouse Warming—Synthesis Panel.* Policy Implications of Greenhouse Warming. Washington, DC: National Academy Press.
- Nichols, A. L. 1994. Demand Side Management. Overcoming Market Barriers or Obscuring Real Costs? *Energy Policy* 22(10): 840-847.
- Nordhaus, W. 1992. Lethal Model 2: The Limits to Growth Revisited. *Brookings Papers on Economic Activity* 2: 1-59.
- Nordhaus, W. and G. Yohe. 1983. Future Carbon Dioxide Emissions from Fossil Fuels. In *Changing Climate: Report of the Carbon Dioxide Assessment Committee*, ed. Washington, DC: National Academy Press.
- Nordhaus, W. D. 1992. *The "DICE" Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming.* Cowles Foundation for Research in Economics at Yale University, Discussion Paper No. 1009.
- Nordhaus, W. D. 1992. An Optimal Transition Path for Controlling Greenhouse Gases. *Science* 258(20): 1315-1319.
- Nordhaus, W. D. 1994. Managing the Global Commons. Cambridge, MA: MIT Press.
- Oeschger, H., U. Siegenthaler, et al. 1975. A Box Diffusion Model to Study the Carbon Dioxide Exchange in Nature. *Tellus* XXVII(2): 167-192.
- Parson, E. A. 1995. Integrated assessment and environmental policy making. In pursuit of usefulness. *Energy Policy* 23(4/5): 463-476.
- Parson, E. A. and K. Fisher-Vanden. 1995. *Thematic Guide to Integrated Assessment* of Climate Change. CIESIN (Consortium for International Earth Science Information Network), http://sedac.ciesin.org/mva/iamcc.tg/TGHP.html.
- Porter, R. H. 1992. The Role of Information in U.S. Offshore Oil and Gas Lease Auctions. NBER, WP no. 4185.
- Powell, M. 1981. Nonlinear Optimization. New York: Academic Press.
- Ramsey, F. P. 1928. A Mathematical Theory of Saving. *The Economic Journal* 38(December): 543-559.

Richardson, G. P. 1995. Loop Polarity, Loop Dominance, and the Concept of Dominant Polarity. *System Dynamics Review* 11(1): 67-88.

- Rothenburg, J. 1993. Economic Perspectives on Time Comparisons: An Evaluation of Time Discounting. In *Global Accord: Environmental Challenges and International Responses*, ed. N. Choucri. Cambridge, MA: MIT Press.
- Rotmans, J. 1990. *IMAGE: An Integrated Model to Assess the Greenhouse Effect.* Boston: Kluwer Academic Publishers.
- Ruderman, H., M. D. Levine, et al. 1987. The Behavior of the Market for Energy Efficiency in Residential Appliances Including Heating and Cooling Equipment. *Energy Journal* 8(1): 101-124.
- Sala-i-Martin, X. and R. J. Barro. 1995. *Economic Growth*. New York: McGraw-Hill, Inc.
- Sanstad, A. H. and R. B. Howarth. 1994. 'Normal Markets', Market Imperfections, and Energy Efficiency. *Energy Policy* 22(10): 811-818.
- Schelling, T. C. 1995. Intergenerational Discounting. *Energy Policy* 23(4/5): 395-402.
- Schipper, L. and S. Meyers. 1992. Energy Efficiency and Human Activity: Past Trends, Future Prospects. Cambridge: Cambridge University Press.
- Schlesinger, M. E. and X. Jiang. 1990. Simple Model Representation of Atmosphere-Ocean GCMs and Estimation of the Time Scale of CO2-Induced Climate Change. *Journal of Climate* 3(December): 1297-1315.
- Senge, P. M. 1978. The System Dynamics National Model Investment Function: A Comparison to the Neoclassical Investment Function. Sloan School of Management, MIT.
- Sharp, J. A. and D. H. R. Price. 1990. Experience Curves in the Electricity Supply Industry. *International Journal of Forecasting* 6: 531-540.
- Silverberg, G. and B. Verspagen. 1994. Economic Dynamics and Behavioral Adaptation: An Application to An Evolutionary Endogenous Growth model. IIASA, WP-94-84.
- Simon, H. 1979. Rational Decision Making in Business Organizations. *American Economic Review* 69(4): 493-513.
- Sterman, J. D. 1980. The Use of Aggregate Production Functions in Disequilibrium Models of Energy-Economy Interactions. MIT System Dynamics Group, D-3234.
- Sterman, J. D. 1981. The Energy Transition and the Economy: A System Dynamics Approach. MIT Sloan School of Management.
- Sterman, J. D. 1985. The Growth of Knowledge: Testing a Theory of Scientific Revolutions with a Formal Model. *Technological Forecasting and Social Change* 28(2): 93-122.
- Sterman, J. D., Richardson, G. P., & Davidsen, P. 1988. Modeling the Estimation of Petroleum Resources in the United States. *Technological Forecasting and Social Change* 33(3): 219-249.
- Sterman, J. D. 1988. Modeling the Formation of Expectations: The History of Energy Demand Forecasts. *International Journal of Forecasting* 4: 243-259.
- Stern, P. C. 1986. Blind Spots in Policy Analysis: What Economics Doesn't Say about Energy Use. Journal of Policy Analysis and Management 5(2): 200-227.
- Sutherland, R. J. 1991. Market Barriers to Energy-efficiency Investments. *Energy Journal* 12(3): 15-34.

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- 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.
- Toth, F. L. 1995. Practice and progress in integrated assessments of climate change. *Energy Policy* 23(4/5): 253-268.
- Trabalka, J. 1986. *The Changing Carbon Cycle: a Global Analysis*. New York: Springer-Verlag.
- United Nations. 1991. 1989 Energy Statistics Yearbook. New York: United Nations.
- Ventana Systems. 1994. Vensim Reference Manual. Harvard, MA: Ventana Systems.
- Watanabe, C. 1995. Mitigating Global Warming by Substituting Technology for Energy. *Energy Policy* 23(4/5): 447-461.
- Weyant, J. 1995. EMF-14 Demographic, Economic, and Energy Assumptions., http://soe.stanford.edu/ees/design.html.
- Wilson, D. and J. Swisher. 1993. Exploring the Gap: Top-Down Versus Bottom-Up Analyses of the Cost of Mitigating Global Warming. *Energy Policy* 21(3, March).
- World Bank. 1995. Social Indicators of Development. Washington, D.C., World Bank.
- World Energy Council. 1989. World Energy Horizons: 2000-2020. Houston, TX: Gulf Publishing Co.
- Wullschleger, S. D., W. M. Post, et al. 1995. On the Potential for a CO2 Fertilization Effect in Forests: Estimates of the Biotic Growth Factor Based on 58 Controlled-Exposure Studies. In *Biotic Feedbacks in the Global Climatic System*, ed. G. M. Woodwell and F. T. Mackenzie. New York: Oxford University Press.
- Yang, Z., R. S. Eckaus, et al. 1996. *The MIT Emission Prediction and Policy Analysis* (*EPPA*) *Model.* MIT Joint Program on the Science and Policy of Global Change, 6.

Yohe, G. 1996. Personal Communication.

Yohe, G. and R. Wallace. 1996. Near Term Mitigation Policy for Global Change Under Uncertainty: Minimizing the Expected Cost of Meeting Unknown Concentration Thresholds. *Environmental Modeling and Assessment* 1(1): 47-57.

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).

Sector Index

Welfare	
Population	
Economy	
Energy	
Emissions	
Policies	
Carbon Cycle	
Climate	
Impacts	
Simulation Control	

:MACRO: INIT(input)

: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



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

(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

```
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



(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_Laver (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 <i>year</i> Atmosphere - mixed ocean layer mixing time.	(030)Flux_Atm_to_Ocean
(046)	Preind_CO2_in_Mixed_Layer = 7.678e+ TonC Initial carbon content of mixed ocean layer.	011
		(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	

01) upper : (layer1-layer9) 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.



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.


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(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

Simula	ation Control Paramaters	
(076)	FINAL_TIME = 2300 <i>year</i> The final time for the simulation.	(414)Depletion_Planning_Horizon (418)Final_Depletion_Rent
(077)	INITIAL_TIME = 1960 <i>year</i> The initial time for the simulation.	(000)Time
(078)	SAVEPER = 5 <i>year</i> The frequency with which output is stored.	
(079)	TIME_STEP = 0.125 <i>year</i> The time step for the simulation.	(007)Emissions_Pulse
.Datc	2 Contraction of the second	
(080)	<pre>Average_Energy_Price = (Average_There Gas_Production + Oil_Production Primary_Electricity) / (Coal_Production + Primary_Electricity) 0il_Production + Primary_Electricity)</pre>	mal_Price * (Coal_Production + n) + Elect_Price * roduction + Gas_Production + ricity)

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
        (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).

IPCC other GHG radiative forcing (from DICE) (074)Radiative_Forcing (098) Elect_Price \$/G] 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 G]/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 G]/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 <i>GJ/year</i>	
	Nuclear electricity production data (primary eq ((uivalent units). (118)Primary_Electricity (122)Production_Data
(112)	Oil_EIA <i>GJ/year</i> EIA oil production data / forecast.	(114)0:1C ELA
(113)	Oil_Production GJ/year	114)OliGas_EIA
	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 equi (valent units). (118)Primary_Electricity (122)Production_Data
(116)	Price_Data[Coal] := World_Coal_Price	
	Price_Data[OilGas] := (World_Crude_Pr World_Gas_Price * Gas_Productio Gas_Production)	rice * Oil_Production + on) / (Oil_Production +
	<pre>Price_Data[HN] := Elect_Price</pre>	
	<pre>Price_Data[New] := 10 * Elect_Price</pre>	
	Frice 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	e (338)Effective_Primary_Energy_Price
(117)	Primary_EIA GJ/year	

EIA primary production data / forecast.

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(118)	<pre>Primary_Electricity = Hydro_Electricity + Nuclear_Electricity +</pre>
	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)	<pre>Share_Data[source] := Production_Data[source] / Total_Production_Data dmnl Energy production share data by source.</pre>
(124)	Thermal_Electricity <i>GJ/year</i> 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 <i>GJ/year</i>	
	Traditional energy production data.	
(128)	World_Bank_Population:= World_Population * 1e+006 people Population data (World Bank).	
	(135)World_Population	n
(120)	World Cool Price	
(12))	\$/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	
	World Bank population data	
		(128)World_Bank_Population

.Economy.AEEI



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.



(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

.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

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

(162)Desired_Capital_Order_Rate

(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/uear 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.



.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

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] G[equiv/G] 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 \$/GI 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



D-4681

(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)) \$/GI 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]) \$/G] 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 \$/GI 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) \$/G] 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) \$/G] 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



```
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

(208)Energy_Adj_Coeff (216)Energy_Subst_Elast

(200)Adj_Energy_Intensity

(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

(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]) G]/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 G]/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_Ene
                                                     rgy
                                              (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] \$/uear 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) GI/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 EffReference 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!]) \$/uear Total expected energy expenditures, with normal capacity utilization. (225)Normal_Energy_Expenditure (223)Normal_Aggr_Energy_Price

.Economy.FactorProductivity



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	(242)Init_Frac_Factor_	_Prod_Gr_Rt (237)Factor_Prod_Chg_Rt (238)Factor_Prod_Gr_Rt_Decline_Rt
(242)	<pre>Init_Frac_Factor_Prod_Gr_Rt = 0.015 1/ugar</pre>	
	Initial fractional rate of technology growth.	(241)Fractional_Factor_Prod_Growth_Rate
(243)	<pre>Initial_Factor_Productivity = 1 dmnl</pre>	
	Initial technology level.	(239)Factor_Productivity
.Econ	omy.Indicators	
(244)	onsumption_Growth_Rate = TREND(Consumption, Growth_Trend_Time, Hist_Output_Growth_Rate)	
	Fractional rate of change of consumption. (147)Consumption (245)Growth_Trend_T (254)Hist_Output_Gro	ime owth_Rate
(245)	Growth_Trend_Time = 1	
	Time for measuring consumption and output gro	owth trends. (244)Consumption_Growth_Rate (246)Output_Growth_Rate
(246)	<pre>Output_Growth_Rate = TREND(Gross_Ou</pre>	tput, Growth_Trend_Time,
	Fractional rate of change of gross output. (262)Gross_Output (245)Growth_Trend_T (254)Hist_Output_Gro	ime owth_Rate
(247)	Savings_Rate = Total_Investment / G	ross_Output
	Fraction of output invested. (262)Gross_Output (249)Total_Investment	t
(248)	Total_Capital = Capital + Total_Ene	rgy_Capital
	Total capital in all sectors. (157)Capital (325)Total_Energy_Ca	apital
(249)	Total_Investment = Investment_Rate \$/wear	+ Total_Energy_Investment
	Investment in all sectors. (166)Investment_Rate (328)Total_Energy_Inv	vestment (247)Savings_Rate

.Economy.Interest



(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/uear 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



(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



(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 / EffReference 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



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 0 (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.

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

\$/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

(290)Energy_Capital_under_Constr

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 ur 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] G]/\$/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_Rati 0

(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

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```
(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])
      GI
      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])
      GI
      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
      GI
      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
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(296)LR_Marg_Prod_Effect
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(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 Rati 0 (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] G]/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 G]/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 -

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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 \$/GI 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!]) G]/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			
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			
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			
<pre>Total_Energy_Investment = SUM(Energy_Capital_Completion_Rate[source!]) \$/year</pre>			
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[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

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\$/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]) / (Capital_Cost_Basis_Switch * Energy_Production[source] + (1 - Capital_Cost_Basis_Switch) * Normal_Production[source]) \$/G] 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] \$/GI 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]) \$/G] 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] \$/G] 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 \$/GI 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 \$/G] 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 \$/G] 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]) ^

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(Resource_Coeff[source] - 1) / Initial_Production[source] / (1 -Resource_Share[source]) year/GI 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])) \$/uear 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] \$/GI 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] \$/G] 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] \$/GI 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] \$/GI 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 = nolearning; .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

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

(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

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

(368)Cumulative_Energy_Investment

(370)Energy_Learning_Coeff

(379)Init_Cum_Energy_Investment

(377)Indicated_Energy_Technology

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])) \$/uear 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]) GI/vear 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] GI/uear 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] G]/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 G]/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

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

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(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])
      G]/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 Intensitv (311)Normal Effective Capital Intensity (396)Normal Variable Cost (399) Scheduled_Production[source] = MIN(Max_Production[source], Energy Order Rate[source]) GI/uear 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!]) G]/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.

(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.



\$/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 \$/G] 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) \$/GI 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])) \$/G] 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 \$/G] 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/GIMarginal 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] \$/G]/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 \$/G] Target depletion rent at final time.

(427) Time_to_Correct_Rent = 20

(420)Indicated_Depletion_Rent

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/GI 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 \$/G] 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 = 1 282

	<i>year</i> Time to perceive carbon emissions rate. (442)Perceived Emissions Pate			
	(442)Perceived_Emissions_Kate			
(437)	<pre>Energy_Tax = INTEG (Energy_Tax_Adj_Rate, 0) \$/GJ</pre>			
	Tax on all energy sources.			
	(438)Energy_Tax_Adj_Kate (438)Energy_Tax_Adj_Rate (446)Total_Tax			
(438)	<pre>Energy_Tax_Adj_Rate = STEP((Constant_Energy_Tax-Energy_Tax) / Tax_Adj_Time, Initial_Tax_Time) \$/CI/waar</pre>			
	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)	<pre>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)</pre>			
	\$/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_Kate			
	(443)Reference_Emissions_Rate			
	(431)Carbon_Tax_Adj_Rate			
(440)	<pre>Initial_Tax_Time = 1995 year</pre>			
	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)	<pre>Perceived_Emissions_Rate = SMOOTH(Total_Energy_Carbon_Emissions, Emissions Perception Time)</pre>			
TonC/year				
Perceived rate of carbon emissions from energy production. (436)Emissions_Perception_Time (013)Total_Energy_Carbon_Emissions				

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(430)Carbon_Tax (429)Carbon_Content

(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

(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

D-4681



(455)Pop_Gr_Rt_Decline_Rt (456)Pop_Growth_Rate			
(448)) Forecast_Pop_Growth_Rt_Decline_Rt = 0.02 1/uear		
	Forecast rate of decline of population growth rate. Ca (455)I	librated (roughly) to EMF-14 scenario. Pop_Gr_Rt_Decline_Rt	
(449)	<pre>49) Hist_Pop_Growth_Rt_Decline_Rt = 0.01</pre>		
	Historic rate of decline of population growth rate. Ca (455)I	alibrated to World Bank data. Pop_Gr_Rt_Decline_Rt	
(450)	<pre>Initial_Pop_Growth_Rt = 0.0224 1/year</pre>		
	Initial population growth rate. (456)I	Pop_Growth_Rate	
(451)) Initial_Population = 3.041e+009 people		
	Initial population. (458)I	Population	
(452)	52) Labor_Force = Labor_Force_Fraction * Population		
	Labor force. Assumes invariable labor participation. (458)Population (453)Labor_Force_Fraction (262)Gross_Output (264)Marginal_Prod_of_Labor (265)Reference_Labor		
(453)	53) Labor_Force_Fraction = 0.25 FTE/person Fraction of population participating in labor force.		
	(452)I	Labor_Force	
(454)	54) Net_Pop_Incr = Population * Pop_Growth_Rate person/year Net Population Increase (456)Pop_Growth_Rate (458)Population		
	(458)H	Population	
(455)	<pre>55) 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</pre>		
(456)	<pre>456) Pop_Growth_Rate = INTEG(- Decline_Pop_Gr_Rt, Initial_Pop_Growth_Rt)</pre>		

(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

(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

(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
	intensible (onvironmental) convices have zero importance
	(407)Consumption Equiv Loss
	(46) Equiv Consumption Index
	(400)Equiv_Consumption
	(400)Warginar_Equiv_Consumption
(477)	Total_Utility = Population * Utility <i>utiles/year</i>
	Flow of utility, weighted by population; i.e. total utility of all individuals. (458)Population (478)Utility
	(464)Discounted_Utility
(478)	<pre>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/nercon/ugar</pre>
	Utility of a representative individual Reduces to logarithmic utility function:
	$I_{\rm N}$ N(Consumption per Cap) when the Rate of Inequality Aversion > 1
	(466)Equiv Consumption Index
	(400)Equiv_Consumption_index
	(475)Pof Utility
	(473) Ker_Othity (477)Total Utility
	(4//)10ta1_0tility

.Welfare.Constrained

Calculation of discounted utility, modified for inclusion of a hard constraint on atmospheric CO2.



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 (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>ENSITIVITY|
SIMULATE>PAYOFF|payoff.prm
SIMULATE>OPTPARM|conc_tax.prm
SIMULATE>OPTIMIZE|0
```

CONST_TAX.PRM

SIMULATE>SAVELIST

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</pre>
```

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}

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
```

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
```

Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch = 0

```
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
```

```
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}

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
```

E.CIN

Scenario E

```
\{\mathbf{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
```

Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch = 0

```
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
```

```
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
```

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
```

H.CIN

```
Scenario H
```

```
{H}
{Behavior}
{exogenous drivers}
{production structure}
{behavior}
{energy capacitation}
{energy req. embodiment}
{retrofits}
```

I.CIN

Scenario I

```
{I}
{Carbon Cycle}
{exogenous drivers}
```

```
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
```

```
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
```

{depletion}
{energy technology}
{welfare evaluation}
Rate_of_Time_Pref = 0.03
Rate_of_Inequal_Aversion = 1
{carbon cycle}
Carbon_Cycle_Switch = 0

{production structure}
{behavior}
{energy capacitation}

{welfare evaluation}

{carbon cycle}

Rate_of_Time_Pref = 0.03

Rate_of_Inequal_Aversion = 1

```
{energy req. embodiment}
{retrofits}
{depletion}
{energy technology}
```

J.CIN

```
Scenario J
```

```
{J} {energy req. embodiment}
{Fair Discount} {retrofits}
{exogenous drivers} {depletion}
{production structure} {energy technology}
{behavior} {welfare evaluation}
{energy capacitation} {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 $\{\text{Group } 2 - 2xCO2\}$ 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 D-4681

```
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}	
<pre>Energy_Intensity_Adjustment_Time =</pre>	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
```

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```
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.

```
{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 Delevi 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 Output Perc Time 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[oilgas] 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 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
                                        SR Energy Subst Elast
Return Perc Time
                                        Supply Demand Coeff
Resource Elasticity[coal]
                                        Supply Line Correction Time
Resource Elasticity[hn]
                                        Time to Correct Rent
Resource Elasticity[new]
                                        Trend Time
                                        Value Share of Labor
Resource Elasticity[oilgas]
SR Elasticity
                                        Weight to Average Cost
SR Energy Price Perc Time
                                        Weight to Marg Cost
```

EMISS_PAY.PRM

Objective function for measuring sum-of-squares variation in emissions.

```
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
                                        SIMULATE>READRUNCHG
{Group 1 - varying all variables}
                                        SIMULATE>RUNNAME | stoch_opt_7.vdf
SIMULATE>RUNNAME | stoch_opt_6.vdf
                                        SIMULATE>SETVAL | Constant_Tax= -1000
SIMULATE>SETVAL|Constant_Tax= -1000
                                        SIMULATE>SETVAL | Concentration_Coeff=
SIMULATE>SETVAL Concentration_Coeff=
                                               100
      30
                                        MENU>RUN
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_85.vdf
SIMULATE>SETVAL|Constant_Tax= 300
SIMULATE>SETVAL|Concentration_Coeff= 0
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>RUNNAME|stoch_opt_91.vdf
SIMULATE>SETVAL|Constant_Tax= 1000
SIMULATE>SETVAL|Concentration_Coeff= 1000

```
MENU>RUN
                                         SIMULATE>RUNNAME | stoch_opt_96.vdf
SIMULATE>READRUNCHG
                                         SIMULATE>SETVAL | Constant_Tax= 1000
                                         SIMULATE>SETVAL | Concentration_Coeff=
SIMULATE>RUNNAME | stoch_opt_92.vdf
SIMULATE>SETVAL | Constant_Tax= 1000
                                                30
SIMULATE>SETVAL Concentration_Coeff= -
                                         MENU>RUN
      300
                                         SIMULATE>READRUNCHG
MENU>RUN
                                         SIMULATE>RUNNAME | stoch_opt_97.vdf
SIMULATE>READRUNCHG
                                         SIMULATE>SETVAL Constant_Tax= 1000
SIMULATE>RUNNAME | stoch_opt_93.vdf
                                         SIMULATE>SETVAL | Concentration_Coeff=
SIMULATE>SETVAL | Constant_Tax= 1000
                                                100
SIMULATE>SETVAL Concentration_Coeff= -
                                         MENU>RUN
      100
                                         SIMULATE>READRUNCHG
MENU>RUN
                                         SIMULATE>RUNNAME | stoch_opt_98.vdf
SIMULATE>READRUNCHG
                                         SIMULATE>SETVAL Constant_Tax= 1000
SIMULATE>RUNNAME | stoch_opt_94.vdf
                                         SIMULATE>SETVAL | Concentration_Coeff=
SIMULATE>SETVAL | Constant_Tax= 1000
                                                300
SIMULATE>SETVAL Concentration_Coeff= -
                                         MENU>RUN
      30
                                         SIMULATE>READRUNCHG
MENU>RUN
SIMULATE>READRUNCHG
                                         SIMULATE>RUNNAME | stoch_opt_99.vdf
                                         SIMULATE>SETVAL Constant_Tax= 1000
SIMULATE>RUNNAME|stoch_opt_95.vdf
                                         SIMULATE>SETVAL | Concentration_Coeff=
SIMULATE>SETVAL | Constant_Tax= 1000
                                                1000
SIMULATE>SETVAL Concentration_Coeff= 0 MENU>RUN
MENU>RUN
                                         SIMULATE>READRUNCHG
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
                                         SIMULATE>SETVAL | Concentration_Coeff=
{Group 1 - combinatorial}
                                               30
SIMULATE>RUNNAME stoch_opt_zoom301.vdf
                                         MENU>RUN
SIMULATE>SETVAL | Constant_Tax= -60
                                         SIMULATE>READRUNCHG
SIMULATE>SETVAL|Concentration_Coeff= 0
                                         SIMULATE>RUNNAME | stoch_opt_zoom303.vdf
MENU>RUN
                                         SIMULATE>SETVAL | Constant_Tax= -60
SIMULATE>READRUNCHG
                                         SIMULATE>SETVAL | Concentration_Coeff=
SIMULATE>RUNNAME | stoch_opt_zoom302.vdf
                                               60
SIMULATE>SETVAL | Constant_Tax= -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_zoom313.vdf SIMULATE>SETVAL | Constant_Tax= -30 SIMULATE>SETVAL | Concentration_Coeff= 150 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_zoom317.vdf
SIMULATE>SETVAL|Constant_Tax= 0
SIMULATE>SETVAL|Concentration_Coeff=
 60
MENU>RUN
SIMULATE>READRUNCHG|

SIMULATE>SETVAL | Concentration_Coeff= MENU>RUN SIMULATE>READRUNCHG 150 MENU>RUN SIMULATE>RUNNAME | stoch_opt_zoom320.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL | Constant_Tax= 0 SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>RUNNAME | stoch_opt_zoom328.vdf 150 SIMULATE>SETVAL | Constant_Tax= 30 MENU>RUN SIMULATE>SETVAL | Concentration_Coeff= 180 SIMULATE>READRUNCHG MENU>RUN SIMULATE>RUNNAME | stoch_opt_zoom321.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL | Constant_Tax= 0 SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>RUNNAME | stoch_opt_zoom329.vdf SIMULATE>SETVAL | Constant_Tax= 60 180 SIMULATE>SETVAL | Concentration_Coeff= 0 MENU>RUN SIMULATE>READRUNCHG MENU>RUN SIMULATE>READRUNCHG SIMULATE>RUNNAME | stoch_opt_zoom322.vdf SIMULATE>SETVAL | Constant_Tax= 30 SIMULATE>RUNNAME | stoch_opt_zoom330.vdf SIMULATE>SETVAL|Concentration_Coeff= 0 SIMULATE>SETVAL | Constant_Tax= 60 MENU>RUN SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>READRUNCHG 30 MENU>RUN SIMULATE>RUNNAME stoch_opt_zoom323.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL | Constant_Tax= 30 SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>RUNNAME | stoch_opt_zoom331.vdf 30 SIMULATE>SETVAL Constant_Tax= 60 SIMULATE>SETVAL | Concentration_Coeff= MENU>RUN SIMULATE>READRUNCHG 60 MENU>RUN SIMULATE>RUNNAME | stoch_opt_zoom324.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL | Constant_Tax= 30 SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>RUNNAME | stoch_opt_zoom332.vdf 60 SIMULATE>SETVAL Constant_Tax= 60 SIMULATE>SETVAL | Concentration_Coeff= MENU>RUN SIMULATE>READRUNCHG 90 MENU>RUN SIMULATE>RUNNAME | stoch_opt_zoom325.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL | Constant_Tax= 30 SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>RUNNAME | stoch_opt_zoom333.vdf 90 SIMULATE>SETVAL Constant_Tax= 60 SIMULATE>SETVAL | Concentration_Coeff= MENU>RUN SIMULATE>READRUNCHG 120 MENU>RUN SIMULATE>RUNNAME | stoch_opt_zoom326.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL Constant_Tax= 30 SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>RUNNAME | stoch_opt_zoom334.vdf SIMULATE>SETVAL Constant_Tax= 60 120 MENU>RUN SIMULATE>SETVAL | Concentration_Coeff= SIMULATE>READRUNCHG 150 MENU>RUN SIMULATE>RUNNAME | stoch_opt_zoom327.vdf SIMULATE>READRUNCHG SIMULATE>SETVAL | Constant_Tax= 30 SIMULATE>RUNNAME | stoch_opt_zoom335.vdf
SIMULATE>SETVAL Constant_Tax= 60 MENU>RUN 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

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	Information	1987 6.05e+010
1989)	Administration 1995)	1988 6.23e+010
1960 6.64784	1958 4.43664e+006	1989 6.55e+010
1961 6.95902	1959 1.34129e+007	1990 6.63e+010
1962 6.8534	1960 2.56183e+007	1991 6.72e+010
1963 6 95924	$1961 \ 4 \ 09594_{\odot} + 007$	1992 6 760 + 010
$1064 \in 77416$	1062 6 00226 007	$1002 \times 760 \times 010$
1964 6.//416	1962 6.093360+007	1993 6.760+010
1965 6.96237	1963 1.09025e+008	Total Electricity (Guyol
1966 6.94241	1964 1.59522e+008	1969; Energy
1967 6.50688	1980 6.40598e+009	Information
1968 5.72611	1985 1.33e+010	Administration 1995)
1969 5.45512	1986 1.42e+010	1958 1.79e+010
1970 5.2703	1987 1.55e+010	1959 1.97e+010
1971 5 75105	1988 1 68e+010	1960 2 15e+010
1972 5 26886	$1989 \ 1 \ 73 + 010$	$1961 2 3_{0+}010$
	1909 1.730+010	1901 2.30+010
1973 5.00070	1990 1.778+010	1962 2.490+010
1975 6.14003	1991 1.86e+010	1963 2.7e+010
1976 5.44883	1992 1.88e+010	1964 2.93e+010
1977 6.49034	1993 1.95e+010	1980 6.93e+010
1978 7.17429	Other Electricity (Guyol	1985 8.22e+010
1979 7.87244	1969; Energy	1986 8.44e+010
1980 9.20048	Information	1987 8.83e+010
1981 7.35384	Administration 1995)	1988 9.18e+010
1982 6.44922	1958 1.8121e+007	1989 9.5e+010
1983 5 44273	$1959 \ 2 \ 10413e+007$	1990 9 72e+010
1984 4 3131	$1960 \ 2 \ 35966_{+}007$	$1001 \ 0 \ 010+010$
1985 5 27546	$1961 2.69287_{0+}007$	1992 9 950+010
1006 4 00000	1901 2.092070+007	$1992 9.930 \pm 010$
1900 4.99990	1962 3.001/50+00/	
1987 5.78054	1963 3.368666+007	Nonenergy Carbon
1988 5.65552	1964 3.6738e+007	Emissions(IPCC 1991)
Hydro Electricity (Guyol	1980 1.79712e+008	1985 8e+008
1969; Energy	1985 2.78928e+008	2000 1.2e+009
Information	1986 3.33216e+008	2025 1.6e+009
Administration 1995)	1987 3.43512e+008	2050 1.7e+009
1958 5.74306e+009	1988 3.49128e+008	2075 le+009
1959 5.90702e+009	1989 3.54744e+008	2100 7e+008
1960 6.40238e+009	1990 3.58488e+008	Other GHG Rad Forcing
1961 6 77396e+009	1991 3 66912e+008	(Goudriaan and Ketner
1962 7 12661 + 009	1992 3 $76272_{\pm}008$	1984: Nordhaug 1994)
1962 7.1200101009	1002 2 0005201000	1000 0 16
1963 7.470738+009		
1964 7.723610+009	inermal Electricity	1960 0.37
1980 1.620+010	(Guyol 1969; Energy	1970 0.45
1985 1.85e+010	Information	1980 0.55
1986 1.88e+010	Administration 1995)	1990 0.66
1987 1.89e+010	1958 1.22e+010	2000 0.73
1988 1.96e+010	1959 1.38e+010	2025 0.96
1989 1.95e+010	1960 1.5e+010	2050 1.18
1990 2.02e+010	1961 1.62e+010	2075 1.29
1991 2.05e+010	1962 1.77e+010	2100 1.36
1992 2.04e+010	1963 1.94e+010	World Coal Price
1993 2 12e+010	$1964 \ 2 \ 14e+010$	(Congressional
Nuclear Fleatricity	1980 5 230+010	Research Service 1000.
(Curol 1060, Energy	10055.230 + 010	International Energy
(GUYOT TADA' FUELGY		America 1000
	1900 J./08+UIU	AGENCY 1980;

D-4681

International Energy	1967 0.865822	1982 5.09938
Agency 1995)	1968 0.789375	1983 4.40839
1950 1.83396	1969 0.720679	1984 4.48125
1955 1.41089	1970 0.687051	1985 4.40583
1960 1.27833	1971 0.909092	1986 4.10606
1961 1.30591	1972 1.13335	1987 2.81703
1962 1.2377	1973 2.44126	1988 2.48003
1963 1.32293	1974 4.71159	1989 2.10342
1964 1.34327	1975 4.38317	1990 2.71898
1965 1.25054	1976 4.47406	1991 2.96603
1966 1.14891	1977 4.61001	1992 2.51092
1967 1.12912	1978 4.29258	1993 2.26163
1968 1.15165	1979 5.9554	Coal EIA (Energy
1969 1.23422	1980 8.77039	Information
1970 1 30961	1981 8 69359	Administration 1995)
1971 1 35557	1982 7 45944	2000 1 061e+011
1972 1 31991	1983 6 21932	2005 1 155e+011
1973 1 38164	1984 5 9337	2000 1.246 + 011
1974 2 07008	1985 5 36751	Cas FIA (Fnergy
1975 2 7321	1986 2 53951	Information
1976 2 69816	1987 3 28076	Administration 1995)
1977 2 62197	1988 2 50756	$2000 \ 9 \ 41_{0} + 010$
1978 2 46015	1989 3 06/18	2000 9.41010
1978 2.40015	1909 3.00418	2003 1.033 e+011 2010 1 1270+011
1000 2 92162	1990 3.3470	2010 1.127011
1001 2 00660		Information
1000 0 070	1002 2 27004	Administration 1995)
1902 2.070	Nord Cog Drigo	Administration 1995)
1983 2.31332	(Congregational	2000 1.0510+011
1984 1.99282	(Congressional	2005 1.7930+011
1985 1.93236	Research Service 1980,	
1986 1.80543	International Energy	Traformation
1987 1.58402	Agency 1995)	Information 1005)
1988 1.03258	1960 1.69	Administration 1995)
1989 1.71791	1961 1.67	2000 4.2480+011
1990 1.73208	1962 1.66	2005 4.6280+011
1991 1.62826	1963 1.64	2010 4.97/0+011
1992 1.52/19	1964 1.62	Primary Trabalka
1993 1.35947	1965 1.61	(Trabalka 1986)
World Crude Price	1966 1.62	2000 4.62e+011
(Jenkins 1989; Energy	1967 1.64	2025 6.73e+011
Information	1968 1.66	2050 9.09e+011
Administration 1995)	1969 1.68	2075 1.196e+012
1925 2.09445	1970 1.7	Primary WEC (World Energy
1930 1.55743	1971 1.73	Council 1989)
1938 1.75307	1972 1.76	2000 4.5671e+011
1950 1.55436	1973 1.8	2020 6.1585e+011
1955 1.5757	1974 2.06	CO2 Concentration A (IPCC
1960 1.14513	1975 2.47	1991)
1961 1.06124	1976 2.84	1970 437
1962 1.00394	1977 3.27	1990 679
1963 0.992351	1978 3.38	CO2 Concentration B (IPCC
1964 0.940067	1979 3.99	1991)
1965 0.918364	1980 4.59608	1970 398
1966 0.888632	1981 5.09324	1990 492

CO2 Concentration C (IPCC 1900 0.37 1991) 1970 398 1990 469 CO2 Concentration D (IPCC 1990 1.79 1991) 1970 393 1990 413 CO2 Concentration E (IPCC 2075 6.25 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 2050 1.18 1991) 1985 5.9e+009 20005.5e+009EMF GDP (Weyant 19920256.4e+00919902.195e+01320507.5e+00920002.8553e+01320758.8e+00920255.8077e+01321001.03e+01020501.0244e+014CO2Emissions C (IPCC20751.6638e+01420002.8196e+01421002.8196e+014 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 2100 3.5e+009 2000 6.205e+009 CO2 Emissions D (IPCC 2025 8.414e+009 1991) 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 1985 5.1e+009 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 1985 5.1e+009

1960 0.81 1970 1.03 1980 1.36 2000 2.22 2025 3.4 2050 4.82 2100 7.6 CE IPCC Other Rad Forcing (Nordhaus 1994) 00 0.16 60 0.37 70 0.45 80 0.55 90 0.66)0 0.73 25 0.96 DICE IPCC Other Rad 1900 0.16 1960 0.37 1970 0.45 1980 0.55 1990 0.66 2000 0.73 2025 0.96 2075 1.29 2100 1.36 2100 1.30Inscincy 12007 1.014EMF GDP (Weyant 1995)Energy Council 19891990 2.195e+013Energy Information2000 2.8553e+013Administration 19952025 5.8077e+0131960 5.6692e+0102050 1.0244e+0141961 5.6801e+0102075 1.6638e+0141962 5.691e+0102100 2.8196e+0141963 5.7019e+0102100 2.8196e+0141964 5.7129e+0102100 2.8196e+0141965 5.7239e+0102000 9.8414e+0141965 5.7239e+0102000 9.8414e+0141966 5.7349e+0101995)1967 5.7459e+0101990 5.252e+0091968 5.757e+0102000 6.205e+0091969 5.7681e+0102050 1.0031e+0101971 5.7903e+0102050 1.0031e+0101971 5.7903e+0102050 1.1312e+0101974 5.9802e+0102150 1.1312e+0101975 6.3799e+0102000 1.1312e+0101975 6.3799e+0102000 1.1312e+0101975 6.3799e+0102001 1.991)1977 6.746e+0101985 5.1e+0091978 6.8822e+010 EMF GDP (Weyant 1995) Energy CO2 Emissions A1976 6.5086e+010(IPCC 1991)1977 6.746e+0101985 5.1e+0091978 6.8822e+0102000 6.5e+0091979 7.2131e+0102025 9.9e+0091980 7.3438e+0102050 1.35e+0101981 7.3681e+0102075 1.77e+0101982 7.6628e+0102100 2.17e+0101983 7.6845e+010Energy CO2 Emissions B1984 8.054e+010(IPCC 1991)1985 8.4819e+0101985 5.1e+0091987 8.9057e+010 2100 2.17e+010 (Nordhaus 1994) 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+0 2075 2.9e+009 2100 2.7e+009 Coal Production (Internation (International Energy Agency 1989; World Energy Council 1989; Administration 1995)

1988 9.0991e+010	1963 2.1622e+010	1973 1.2263e+011
1990 9.69e+010	1964 2.3184e+010	1974 1.2283e+011
1992 9.38e+010	1965 2.4859e+010	1975 1.1669e+011
Commercial Energy	1966 2.6655e+010	1976 1.2589e+011
(Jenkins 1989;	1967 2.8581e+010	1977 1.311e+011
International Energy	1968 3.0645e+010	1978 1.3217e+011
Agency 1990)	1969 3.286e+010	1979 1.3784e+011
1870 5.88e+009	1970 3.5234e+010	1980 1.3147e+011
1890 1.4196e+010	1971 3.7779e+010	1981 1.2415e+011
1910 3.2844e+010	1972 3.9623e+010	1982 1.1959e+011
1925 4.2042e+010	1973 4.142e+010	1983 1.1881e+011
$1930 \ 4 \ 5696e+010$	$1974 \ 4 \ 2353e+010$	1984 1 $2177e+011$
$1938 \ 4 \ 977_{e} + 010$	$1975 \ 4 \ 2412e+010$	$1985 \ 1 \ 2071e+011$
1950 7 1946 + 010	$1976 \ 4 \ 426_{P} + 010$	1986 1 26430+011
$1960 \ 1 \ 2597 + 011$	1977 4 6032 + 010	$1987 \ 1 \ 2617_{0+}011$
1961 1 31640+011	1978 4.7578 + 010	$1989 1 28630 \pm 011$
1901 1.31040+011	1970 = 1005 - 100	$1900 1.2003 \pm 011$
1962 1.37500+011	1979 5.10050+010	1909 1.302/0+011
1963 1.43740+011	1980 5.15760+010	1990 1.4280+011
1964 1.5020+011	1981 5.27690+010	1992 1.4380+011
1965 1.56960+011	1982 5.26430+010	Primary Energy
1966 1.6401e+011	1983 5.3122e+010	(Goldemberg, Johansson
1967 1.7139e+011	1984 5.7716e+010	et al. 1987; World
1968 1.7909e+011	1985 5.9892e+010	Energy Council 1989;
1969 1.8715e+011	1986 6.14e+010	Schipper and Meyers
1970 1.9556e+011	1987 6.4814e+010	1992)
1971 2.0435e+011	1988 6.7544e+010	1850 2.1444e+010
1972 2.1501e+011	1990 7.6e+010	1870 2.5229e+010
1973 2.2739e+011	1992 7.84e+010	1890 3.1536e+010
1974 2.2898e+011	Oil Production (Jenkins	1910 5.0458e+010
1975 2.3082e+011	1989; United Nations	1930 7.1587e+010
1976 2.4482e+011	1991; Energy	1950 1.0281e+011
1977 2.538e+011	Information	1960 1.5539e+011
1978 2.6467e+011	Administration 1995)	1966 1.9458e+011
1979 2.7319e+011	1870 3.3432e+007	1967 1.9931e+011
1980 2.7125e+011	1890 4.10823e+008	1968 2.0561e+011
1981 2.6868e+011	1910 1.76226e+009	1969 2.1949e+011
1982 2.6715e+011	1925 5.89281e+009	1970 2.3147e+011
1983 2.7155e+011	1930 7.85767e+009	1971 2.4125e+011
1984 2.8373e+011	1938 1.0966e+010	1972 2.5197e+011
1985 2.9263e+011	1950 2.0835e+010	1973 2.6522e+011
1986 2.9891e+011	1955 3.3113e+010	1974 2.6679e+011
1987 3.1047e+011	$1960 \ 4.529e+010$	1975 2.6711e+011
1988 3 21110+011	$1961 \ 4 \ 9277 + 010$	$1976 \ 2 \ 8162e+011$
$1989 \ 3 \ 272 + 011$	1962 5 3464 + 010	1977 2 9045 + 011
$1990 \ 3 \ 2567 + 011$	1963 5 7435 + 010	1978 2 9991 + 011
Cog Production	$1964 \in 1858_{0} + 010$	1970 2.9991011
(International Energy	1965 6 65210-010	1000 2 00740+011
Acongy 1990: World	1965 0.05210+010	1001 2 0695011
Agency 1989, World	1966 7.20650+010	1901 3.00050+011
Energy Council 1989;	1060 0 4540+010	IJOH J.JOL/CHULL
Energy Information	1000 0.4040010	(Tenhing 1000, Maril)
Administration 1995)	1979 9.14610+UIU	(Jenkins 1989; World
1960 1.75390+010	19/U 1.0005e+011	Energy Council 1989;
1961 1.8806e+010	19/1 1.06e+011	Schipper and Meyers
1962 2.0165e+010	1972 1.1221e+011	1992)

1870 1.9349e+010	1966 0.2646	1984 0.225
1890 1.734e+010	1967 0.2715	1985 0.223
1910 1.7614e+010	1968 0.2868	1986 0.222
1930 2.5891e+010	1969 0.3021	1987 0.225
1950 3.0861e+010	1970 0.3169	1988 0.233
1960 2.94e+010	1971 0.3353	1989 0.24
1973 2.7636e+010	1972 0.3534	1990 0.232
1980 3.2789e+010	1973 0.3717	1991 0.225
1984 3.6565e+010	1974 0.4033	1992 0.217
1990 4.8565e+010	1975 0.4442	1993 0.215
Cons Frac GDP (World Bank	1976 0.473	World GDP (World Bank
1995)	1977 0.5002	1995)
1960 0.636	1978 0.5392	1960 6124
1961 0.638	1979 0.5869	1961 6394
1962 0.637	1980 0.6428	1962 6735
1963 0.634	1981 0.7042	1963 7086
1964 0.629	1982 0.7476	1964 7555
1965 0 624	1983 0 7788	1965 7949
1966 0 617	1984 0 8101	1966 8414
1967 0 619	1985 0 8384	1967 8790
1968 0 616	1986 0 8586	1968 9287
1969 0 612	1987 0 886	1969 9822
1970 0 608	1988 0 9203	1970 10254
1971 0 607	1989 0 96	1971 10636
1972 0 604	1990 1	1972 11174
1973 0 593	1991 1 0346	1972 11910
1974 0 593	1992 1 0597	1974 12090
1975 0 601	1993 1 0805	1975 12548
1976 0 597	Invest Frag CDD (World	1076 12171
1977 0 597	Pank 1995)	1977 127/2
1977 0.597	$1960 \ 0 \ 216$	1070 1/211
1970 0 592	1961 0 208	1970 14911
1979 0.592	1962 0 207	1979 14057
1980 0.595	1962 0.207	1980 15111
1981 0.590	1964 0 22	1981 19352
1982 0.612	1965 0 225	1982 1587/
1983 0.012	1965 0.225	1987 16566
1985 0 615	1967 0 221	1984 10500
1985 0.015	1968 0 223	1985 17625
1980 0.017	1960 0.223	1980 19261
1987 0.013	1970 0 22	1987 18201
	1970 0.23	
	1972 0.235	
	1973 0.249	
	1974 0.252	1992 20341
CDD Doflator (World Dorl	1975 0.235	Manld Dop Crowth Dt
100E)	1077 0 244	WOLIG POP GROWLII KT
1060 0 2257	$\begin{array}{cccc} 1 \\ 1 \\ 0 \\ 7 \\ 0 \end{array} \\ \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 $	(WOLTO BALLK 1995)
1061 0 220	1070 0.247	1062 0 0172
1062 0 2420	1000 0 240	1062 0 021
1962 0.2429	1900 U.241 1001 0 220	1964 0 0207
1964 0 2501	1992 0.222	1964 0.0207
1964 U.25UI	1982 U.222	1965 0.0209
1905 U.∠56	1983 0.214	TAPP 0.050A

1967	0.0205		1984	4747
1968	0.0207		1985	4828
1969	0.021		1986	4910
1970	0.0211		1987	4995
1971	0.0208		1988	5081
1972	0.0202		1989	5168
1973	0.0199		1990	5258
1974	0.0195		1991	5345
1975	0.0189		1992	5433
1976	0.0174		1993	5523
1977	0.0171		1994	5608
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	d Population	(World		
Ba	ank 1995)			
1960	3041			
1961	3082			
1062	3135 2201			
1963	3201			
1965	2225			
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	4440			
1001	4442			
エンロエ	4442 4515			
1982	4442 4515 4591			

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:

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.



(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 uear 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

.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.



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
 (020)CO2_Nit_E__;

(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



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.



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], C02_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

D-4681	Thomas Fiddaman	Feedback Complexity in Integrated Climate-Economy Models
		(046)CO2_in_Atmosphere_C (049)CO2_in_Humus (041)Atmospheric_Retention_C
(060)	Humification_Fraction = 0.428	
	Fraction of carbon outflow from biomass that	t enters humus stock. (057)Flux_Biomass_to_Atmosphere (058)Flux_Biomass_to_Humus
(061)	Humus_Res_Time = 27.8	
	<i>Yeur</i> Average carbon residence time in humus.	(049)CO2_in_Humus (059)Flux_Humus_to_Atmosphere
(062)	<pre>init_co2_in_atm_c = 6.7832e+011 TanC</pre>	
	Initial carbon in atmosphere.	(046)CO2_in_Atmosphere_C
(063)	<pre>Init_CO2_in_Mixed_Layer_0 = 7.678 TonC</pre>	e+011
	Initial carbon content of mixed ocean layer.	(054)Equil_CO2_in_Mixed_Layer
(064)	<pre>Init_NPP_0 = 6e+010 TonC / year Initial net primary production.</pre>	
		(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	
	Atmosphere - mixed ocean layer mixing tim	e. (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 = $7.6e+011$	
	CO2 in atmosphere at normal buffer factor.	(045)Buffer_Factor_0
(069)	Ref_Buffer_Factor = 10 <i>dmnl</i>	
	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.



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]>le -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.



	(078)Preindustrial_CO2 (0 (0	085)CO2_Uptake_from_Box 087)Total_CO2_in_Atm_ICAM
(084) CC ye Li	CO2_Lifetime[box] = 1000, 313.8, 79.8 <i>Jear</i> Lifetime of carbon in box	, 18.8, 1.2
	(0	085)CO2_Uptake_from_Box
(085) CC	CO2_Uptake_from_Box[box] = if_then_els CO2_in_Atmos_Box[box] / CO2_Life TonC / upar	<pre>se(CO2_in_Atmos_Box[box]>1e - 009, etime[box], 0)</pre>
U	Uptake of carbon from atmospheric boxes. IF THE (083)CO2_in_Atmos_Box (084)CO2_Lifetime	EN ELSE protects against FP error
	(0 (0	083)CO2_in_Atmos_Box 080)Atmos_Reten_ICAM
(086) En dr	<pre>Emiss_Fraction[box] = 0.131, 0.201, 0 Imnl</pre>	.323, 0.206, 0.088
Fr	Fraction of emissions to box. Note that these sum with zero residence time.	only to .949, so there is implicitly a sixth box
	(0 (0	083)CO2_in_Atmos_Box 082)CO2_Emiss_to_Box
(087) та Та	Total_CO2_in_Atm_ICAM = Preindustrial_ TonC	_CO2 + SUM(CO2_in_Atmos_Box[box!])
Τc	Fotal CO2 in atmosphere.	
	(083)CO2_in_Atmos_Box	
	(078)Preindustrial_CO2	134)CO2_in_Atm

.ModOeschger

D-4681

Thomas Fiddaman

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.



(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

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(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 uear 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

.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:

(098)Diffusion Flux 1



Fiddaman, T. 1996. A System Dynamics Perspective on an Influential Climate / Economy Model. Submitted to System Dynamics Review.

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

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(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 TonCCO2 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



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```
(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

2255 6.21021e+010 2265 6.58384e+010

```
{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
```

2275	6.97854e+010
2285	7.39548e+010
2295	7.83591e+010
2305	8.30112e+010