A Pragmatic CGE Model for Assessing the Influence of Model Structure and Assumptions in Climate Change Policy Analysis

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By:

Stephen Bernow
Alexandr Rudkevich
and Michael Ruth,
Tellus Institute,
Boston MA, USA
and
Irene Peters,
Swiss Federal Institute for
Environmental Science and Technology,
Duebendorf, Switzerland

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Tellus Institute
11 Arlington Street
Boston MA 02116

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1. Introduction

1.1. Purpose of the Project

This report presents a simple pragmatic CGE model with an emphasis on industrial energy use. The purpose of the model is to serve as a tool for the exploration of model structure and assumptions. The motivation for this work was the fact that economic modeling studies influence the debate on the merits of climate change abatement studies and are consulted by policymakers seeking guidance. These studies assess the effectiveness and merits of policy options based on simulations of energy policies with energy-economic models. We believe that policymakers, analysts, stakeholders and the interested public, should understand the strengths and weaknesses of the models and assumptions employed in such studies, so that they may be used constructively.

No single model can address *all* aspects of reality one may care about. Therefore, in order to appreciate how well a model is suited for analyzing specific policies, it is important to have a sense of, first, which real-world phenomena might be relevant for the effectiveness of these policies, and second, how well these phenomena are represented in the model.

As to the first question—which phenomena are important for the effectiveness of specific policies—one could argue that the use of a model would help provide an answer. However, it is inevitable that many assumptions and preconceived notions will enter the construction of any model. Many policy evaluations are carried out with models that contain a great amount of detail on specific, well-researched phenomena, for which a standard methodological treatment exists, but that are not important to the question to be explored. At the same time, the models often neglect other real-world phenomena, perhaps less well researched, that are highly relevant for the subject of analysis.[1] We believe it is important, for the model user as well as for the modeler, to make an *ex-ante*, and *explicit*, choice of the phenomena he or she wants to see addressed in a model.

A prime example of a phenomenon that has been neglected or poorly represented in energy-economic modeling in particular is technical change. Yet technical change is at the heart of energy-economic interactions, and of the efficacy of energy and climate policies and their evaluation. Technical change includes the interacting processes of: investment in and diffusion of new technologies; innovation, learning and scale economies in their production and use; and the resulting growth in the productivity of the economy. Technical change has often been measured as a residual in neo classical production function; and it has also been modeled as a time trend. Energy-economic models have barely begun to explicitly represent the processes by which technical change unfolds and interacts with economic variables. Some models now include the dependence of technical progress on R&D spending, but few, if any, account for the role of increasing returns to scale and technology learning, or the processes by which technologies diffuse.

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[1] For example, many energy-economic models contain great detail on the life-time savings behavior of consumers—a feature that would be relevant for, say, the evaluation of alternative financing options for a pension system. Yet they neglect the difficulties firms encounter in adjusting their physical capital to factor prices and market expectations. Many models assume perfect capital markets, neglecting the credit restrictions facing energy users, that prevent them from undertaking cost-effective investments.

The aim of our effort here is to develop a tool to help explore the impacts upon modeling results of the choice of model structure and assumptions. Through this effort, we hope to broaden the perspective for interpreting the results of modeling efforts, and to stimulate further research and model innovation. To these ends, for our present purposes, we constructed a very simple economic model, limited our treatment of energy efficiency to the industrial sector only, and carried out some test runs to explore the sensitivity of model outcomes to certain structural assumptions. Much work remains to be done in order to further explicate the key modeling issues and outcomes; the work that we describe here is a first step.

Our model is in the Computable General Equilibrium (CGE) tradition. Economics has seen a number of models for policy analysis, including input-output, macro-econometric, and CGE models, as well as hybrids of these types. CGE models have advanced to become the standard tool of economic policy analysis for a variety of reasons. These models incorporate the body of neoclassical General Equilibrium (GE) theory which has come to dominate the mainstream of the economics discipline. GE models are regarded as theoretically superior to other models, but their use for policy analysis has been limited by their lack of sectoral detail. With the substantial increases in computing power and the invention of solution algorithms for large nonlinear equation systems, numerical GE models with great sector detail became solvable and can accommodate national accounting data in detail. Since their invention some three decades ago, CGE models have become ever more popular.

As other models, CGE models and modeling practices have strengths and weaknesses. We believe that CGE modeling, as currently practiced, suffers from a number of shortcomings when it comes to the evaluation of energy and climate change policies. We also believe that CGE models are interesting and powerful tools, which provide a platform for empirical and analytic improvements. Exploring how CGE models might be improved was one purpose of this project. Compared to existing models in the field, the current version of our model is very simple. Still, we have made efforts to ground the model in real-world data and, where the scope of the project allowed, provide plausible parameter values. Our hope is that we would stimulate others who are using this theoretical and modeling framework to pursue similar issues and modeling explorations.

In the remainder of this chapter, we outline what we did in this project: we indicate the changes in model structure that we undertook, the method we used for exploring their significance, and the limitations of our efforts. In the second chapter we begin with a more detailed discussion of the analytical and empirical context of CGE modeling. We reflect on what we perceive to be the merits and deficiencies of CGE modeling practice for the purpose of climate policy assessment, and where we see possibilities for extending and altering the models to make them more suitable for the exploration of energy technology policies. The second chapter also describes the motivation for our alterations of model structure in greater detail. Chapter 3 provides the detailed model structure and describes data development. Chapter 4 spells out the choice of policies we explored, and presents the results of some model runs. Chapter 5 presents the conclusions and offers an outlook. Appendix A contains information on the variables and equations used in the model.

1.2. What We Did in This Project

Model extensions we have undertaken. In this project, we have stayed close to the CGE framework, but have introduced a few distinct alterations to standard modeling practice. These are intended to serve two purposes: first, to demonstrate the sensitivity of model outcomes to specific structural assumptions; and second, to illustrate how a CGE model could be connected to an external model delivering simple technology information that can readily be incorporated into the CGE. Our structural alterations included:

1. Combining the CGE model with an engineering-econometric industrial energy demand model that shows how sectoral energy efficiencies can change over time and in response to policy. The reason for using engineering information as an alternative to standard neoclassical production functions is that the latter are too much at odds with technological reality in many crucial details. While the engineering model that we have used still does not contain as much technical detail, or dynamics, as one would wish to include in a model for energy policy analysis, it is a first step to open a CGE model to external models and analysis.

2. Treating the energy-efficiency investments as capital augmenting, and thereby enhancing the productive capacity of the economy, rather than as simply reducing energy requirements in production. This constitutes an innovation in modeling in that neoclassical economic assumptions about producer behavior, combined with assumptions about the shape of production functions, rule out that environmental technology investments yield side-benefits other than the specific environmental improvement they were meant to address. But the general productivity improvements of environmental and energy-efficiency investments are a well-known phenomenon.[2]

3. Allowing for government activity to play a productive role in the economy, by explicitly representing the services from public capital in private-sector production functions. The rationale is that public capital—as embodied in transportation and other infrastructure, in education and health institutions, etc.—does enhance private-sector productivity and thus could provide powerful policy levers for shaping energy technologies and energy use patterns. On the other hand, accounting for public capital provides a plausible measure of the cost of government policies. Energy and climate policies that require government revenues might very well reduce the government investments in public capital that would otherwise occur, and hence reduce the benefits flowing from these investments to the private sector.

These model refinements are not entirely new. As to providing engineering information to the CGE, there are plenty of hybrid energy-economic models that employ various levels of technology and sector detail. One of the better known is the Global 2000 model by Alan Manne and Richard Richels (1990, 1992). It combines MARKAL, a detailed optimization model of the energy sector, with a very aggregate economic model, ETA-MACRO, which has similarities to a CGE model (it uses a neoclassical macro-economic production function).

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[2] See, for example, Ashford et al., 1979, Ashford, 1993 and 1994. This is also known as the Porter hypothesis (see, for example, Porter and van der Linde, 1995). See also Krause, 1996 and 1998, and Alliance to Save Energy, 1994.

Yet, to our knowledge, there are few sectorally detailed CGE models that use engineering information in an intact fashion (i.e., not pressing data on production technologies into a conventional neoclassical production function with smooth input substitution, etc.). We have information on two such models under development. One is the SGM (Second Generation Model) conceived by Jae Edmonds and implemented by a group of researchers at Pacific Northwest Laboratories.[3] Another is the AMIGA model (All Modular Industrial Growth Assessment), developed by Donald Hanson at Argonne National Laboratories. The latter incorporates, for example, great technology detail at the end-use level, allowing for vintaging of energy using capital.[4]

The fact that we treated energy-efficiency investments as capital additions is a modeling innovation in a sense; such a treatment would be ruled out by the functional specifications of production and assumptions about producer behavior that govern investment behavior in typical CGE models.

As to including a government good in private production functions, this is a well-known specification. Paul Romer (1986, 1990), Robert Barro (1990), and Holtz-Eakin and Schwartz (1995) have used this device in models of economic growth; other researchers who have done so in research on the role of public infrastructure for economic productivity are D. Alan Aschauer (1989) and Alicia Munnell (1990). However, again we are not aware of an instance where this has been used in a sectorally detailed CGE model for the assessment of climate policies.

We have not tackled the question of how to incorporate increasing returns, the effect of random events, and the resulting path dependence of technological development into a model—these were beyond the scope of this project. However we do hope and intend that the model we developed will serve as a platform for exploring sensitivity to these phenomena.

To repeat, the aim of our work is to develop a tool with which one can test the importance of certain modeling assumptions for outcomes of policy simulation. Ideally, such a model would contain a number of switches that toggle-on / toggle-off certain structural features; the model user could run policy scenarios with individual features switched on and off and compare the results. This could result in a greater number of simulation runs since each "toggle" scenario requires the construction of its own base case.

We have modeled one reference scenario and three "toggle" scenarios, or "sensitivities," in which we selectively eliminate the non-standard model alterations we have introduced. (The reference version of the model is described in Chapter 3, the sensitivities in Chapter 4, Section 4.1.) For each of the four model versions, i.e., the reference scenario and the three sensitivities, we have constructed a base case and two policy cases (also described in Chapter 4, Section 4.1.).

1.3. Limitations of the Effort

The model that we constructed, and the set of sample/sensitivity runs are, by design, partial. They embody a small step towards a wide range of explorations and modeling innovations that are needed in order to better evaluate the economic impacts of energy and climate policies. The limitations of the model are:

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[3] Edmonds et al., 1992.

[4] Hanson, 1998 (forthcoming).

1. Only industrial sector energy efficiency is represented. Similar representation of energy-efficiency in transportation, households, commercial buildings, and the electric sector would round out our treatment of energy efficiency.

2. Fuel switching is not represented. For example, a carbon tax (or cap) is likely to cause the prices of certain fuels to increase more than others, causing the fuel mix in each sector to change. The current model could be changed to reflect this phenomenon, for example through empirically-based elasticities.

3. Scale economies and learning in the cost of energy technologies, are not directly represented in the model. One way of accounting for scale economies and learning would be to tie production costs to cumulative production. For this to yield rich insights, the various technologies (or classes of technologies) in use and available for each sector should be explicitly represented and their stocks tracked.

4. Investment behavior is treated as fixed and exogenous. This treatment could be improved by relating investment to such factors as expected profits and the cost of capital, thus providing the model with more detail regarding decision-making by business. This would extend the range of policies that could be meaningfully addressed with the model. An example is ecological tax reform and the potentially resulting “double dividend.” (Many existing models do indeed relate investment to the cost of capital and, in some cases, expected rates of return, but if this is done with the assumption of rational expectations and unlimited credit supply, it is not satisfactory either.)

2. Our Model Extensions: Context and Rationale

2.1. CGE Models: Strengths, Weaknesses, and Opportunities

In this section, we briefly indicate what distinguishes CGE models from other models of the economy, reflect on their strengths and weaknesses, and suggest where they are deficient, especially with regard to the evaluation of energy policies.[5] Many fundamental criticisms are well-known and established in the economics literature, but continue to be ignored in modeling practice, even though adherence to the problematic features of CGE models has troubling implications for model outcomes and, therefore, for policy evaluation.

What are CGE models? CGE models are *general* models in that they represent the economy in its entirety, albeit at a high level of abstraction and aggregation, as composed of a set of inter-related markets. CGE models are *equilibrium* models because they embody the assumption that each market clears, through the movement of prices that equate supply and demand. CGE models are *computable* in that they use equations specified with parameters that assume real values. (Typically, some parameters are based on econometric estimates reported on the literature, while others are computed when the model is calibrated to a set of benchmark data.)

Micro-foundations. Most CGE models have another feature, which is not reflected in their name. They are "consistent with micro-foundations," i.e., the demand and supply functions contained in the models are consistent with (in other words: can algebraically be derived from) the utility and profit maximization calculus which is the core of the neoclassical economic theory of consumer and producer behavior. This theory rests on a number of assumptions, pertaining to technologies, behavior, and institutional factors.

It is these assumptions that, in our view, are the source of the major weaknesses of CGE models. Rather than provide a complete list of problematic assumptions and their consequences, we will highlight the following: first, the normative implications of micro-foundations which bias model results against government intervention; second, the assumption of convex technologies (non-increasing returns to scale); and third, the aggregation over individual actors. The first is a general point, the second two are particularly relevant for the evaluation of energy policies, not least because they impede an adequate representation of technological change.

Normative implications of CGE models. CGE models are typically constructed in such a way that they produce a unique model solution which is "Pareto-efficient." A Pareto-efficient resource allocation (i.e., the pattern of production, investment, and consumption by the various sectors in the economy) is an allocation that leaves no room for unambiguous improvement. No single party—either producer or consumer—can realize an improvement in its position (measured in utility) without another party incurring some deterioration of its position.

Pareto-efficiency is an appealing criterion for evaluating different states of the world because it seems value-neutral. It does not require that the welfare of one party be weighed against that of

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[5] For a more extended discussion than is given here in Section 2.1, see the EAWAG Working Paper "CGE Models, Optimality and Technical Change" (Irene Peters, forthcoming).

another. This "efficiency" criterion would allow a model society to make unambiguous improvements by moving between many different states of the world; every Pareto-inefficient state can thus be unambiguously improved.

The normative implications of a unique, Pareto-efficient model solution are strong. The existence of such a solution, and its uniqueness, suggests that the free market (in the model: the free play of prices, and the lack of regulation) does best: it brings about "efficiency." Government intervention "distorts" this allocation and thus carries a welfare cost.[6] Any policy is evaluated in light of its impacts on efficiency.[7]

Pareto-efficiency is a rather limited, theoretical criterion which obviously cannot be satisfied in the real world. It is thus disturbing that this concept is often invoked in policy rhetoric. No doubt the market is a powerful mechanism that coordinates myriad actors, and it should be relied upon where appropriate. But it does not by definition produce an optimal allocation, as suggested by neoclassical economic theoretical models and the rhetoric that flows from them.

Technically, the result that the solutions of CGE models constitute unique Pareto-efficient resource allocations hinges on the use of micro-foundations.[8] But micro-foundations come with a set of stringent assumptions attached. Many of these are quite unrealistic: for example, the assumption that production technologies exhibit non-increasing returns to scale (we explain below), that firms are price takers, that economic agents act with perfect rationality, and that consumer utility functions are very similar across individuals.

We believe that relaxing these assumptions, to make them more realistic, need not destroy the CGE framework. On the contrary: it would make this framework a flexible tool that would allow a more plausible representation of economic and technical detail. Relaxing these assumptions and departing from neoclassical micro-foundations implies that model solutions are no longer "efficient." This result would rid CGE models of their normative ballast and allow their use for a less biased exploration of policy outcomes and structural changes in the economy.

Increasing returns to scale and technical progress. CGE models rely on the assumption that technologies do not exhibit increasing returns to scale in production.[9] But the existence and importance of increasing returns appear to be beyond dispute. In economics itself, there exists a large body of theory around this phenomenon, addressing, for example, its implication for market

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[6] Usually, allowance is made for a few instances of incorrect prices, called "externalities," which call for limited government intervention in the form of "correcting" the price through taxes or tradeable permits. The fact that "correct" externality taxes (those that restore Pareto-efficiency) are practically impossible to compute because of the second-best problem shall only be mentioned in passing here; we have no space to delve more deeply into this topic. See, for example Bohm, 1987.

[7] See also Shoven and Whalley, 1992, p.34.

[8] The (assumed) uniqueness of model solutions can also be an outcome of solution practices. Certain solution algorithms simply stop executing when they find a solution, even though there could be a multitude of solutions.

[9] "Increasing returns to scale" is a property of a production relationship: increasing returns are present when an increase in all inputs by the same factor leads to a more than proportional increase in output—or, equivalently, when the expansion of output by a given factor requires a proportionately lower increase in inputs and, hence, lowers unit costs.

forms and policy options to contain market power. Recently, increasing returns have gained renewed attention by economists, for their role in the process of technological change.[10]

There are three related but distinguishable grounds for increasing returns. First, the minimum efficient scale of operations is quite large in some industries, so there are increasing returns until a firm reaches the efficient size. This type of increasing returns can be observed in the production of large-scale and complex items, such as ships or nuclear reactors. Second, many production processes exhibit the phenomenon of “learning by doing”: as an industry produces more and more, it gains experience, and the unit costs of its output steadily decrease. First observed in the manufacture of airplane frames[11], learning by doing is typical for many large-scale, technically complex products. Third, for some technologies there are benefits to making the same choice as others around you, giving rise to system-wide economies of scale, or “network externalities.” The choice of computer operating systems (e.g., Windows vs. Macintosh) is a recent example.

Increasing returns allow positive feedback: an increase in production lowers unit costs or, for system-wide economies of scale, increases demand, and thus makes it more likely that even more will be produced in the future. As a result, the development of technologies is path-dependent; a small initial head start for one firm or technology over another can determine which of several alternatives becomes dominant. Through the operation of positive feedbacks, society can become locked into technically inferior technologies. Historically, government industrial policy, like targeted subsidies and government R&D, have been crucial for the development of specific energy technologies and the transportation infrastructure. Many would argue that there exist technically superior alternatives to these, which cannot compete on the basis of cost because they have not benefited from the learning and refinement like those technologies which are in place today.

This phenomenon is common in the energy sector where all the various forms of increasing returns occur. The minimum efficient scale for energy-efficient transportation and land use planning may be substantial. Rapidly declining unit costs through learning by doing are a much-discussed characteristic of solar power, wind energy, and other renewable technologies. For technologically complex options, such as use of alternatively powered vehicles, system-wide economies of scale (based on, e.g., availability of fuel, spare parts, and repair expertise) will be critical. This has profound implications for energy, and hence for climate change policy.

The assumption of non-increasing returns in CGE models. The above discussion suggests strongly that to be useful for analyzing climate change policy, economic models should make increasing returns central to its treatment of technology. The reality of technical change, in energy and other areas, is fundamentally one of increasing returns and positive feedback, resulting in path dependence and inherent unpredictability of technological development.

Unfortunately, general equilibrium modelers go to great lengths to avoid increasing returns to scale in technologies. One reason may be that the standard neoclassical assumptions about pricing behavior adopted in CGE models cannot be maintained when increasing returns are present, and modelers are reluctant to abandon those assumptions. To ensure that a model solution exists at all,

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[10] See foremost Brian Arthur, 1994. Earlier, other economists have included increasing returns into their models; e.g., Paul Romer (1990) in models of economic growth (while not allowing for increasing returns at the firm level though), and Paul Krugman into models of international trade. These models are essentially static, while Brian Arthur’s are dynamic.

[11] Alchian, 1963.

alternative modes of pricing behavior have to be introduced which would divorce the existence of a model solution from its Pareto-efficiency property.[12]

Another reason that increasing returns have been neglected may be that it is difficult to model this phenomenon. While several authors have dealt with increasing returns in a static context, few have embraced its dynamic nature. To our knowledge, only one author and his collaborators have formalized increasing returns in a truly dynamic context, allowing for the influence of random elements and path dependency.[13] However, this work does not (yet) employ a system-wide framework, representing an entire economy with interdependent sectors.

Aggregation of agents. As explained above, the term “micro-foundations” refers to supply and demand functions that are consistent with the neoclassical economic theory of the behavior of micro-units in the economy—consumers and producers. Even if we held that this theory was an adequate representation of individual firms or consumers, the way in which it is applied in CGE models is troubling. It is standard practice to invoke a “representative consumer,” or a “representative producer” in a sector, using a single utility or production function, assuming that some meaningful aggregation over individual utility or production functions is possible. This is problematic in two respects.

First, in order for an aggregate function to exist at all, it should be derivable from a number of micro-functions. However, the micro-functions that would yield an aggregate function with the desirable neoclassical properties would have to satisfy rather stringent criteria which are hardly met in reality. Summing over ordinary production and utility functions would not result in aggregate functions that obey the neoclassical assumptions. This is ironic, because so many of the results and conclusions of neoclassical economics, particularly its normative implications, rest on these very assumptions about the shape of production and utility functions. This “aggregation problem” is well-known in economics but is ignored when welfare conclusions are drawn from model results.[14]

Second, the interaction of agents is an essential part of socio-economic reality that affects the behavior of individuals, households, and firms. Interaction between agents is a process by which information can be distributed. Thus, it is particularly relevant to those processes that hinge on the diffusion of information—be it financial speculation, the formation of fashions or, particularly important to technical change, the diffusion of new technologies.

But interaction between agents is also one important factor in shaping preferences. Individual preferences change over time—as a result of age, education, social status, and experience, of changing ambient social, economic, and cultural conditions, and of physical infrastructure and the spatial organization of society. This phenomenon (“endogenous preferences” in technical, modeling terms) obviously plays an important role in the unfolding of technical change, as people develop new tastes and new values.

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[12] See, for example, Villar, 1996.

[13] This is Brian Arthur, 1994.

[14] See, for example, Kirman, 1992.

Sociology, economics, finance, and even engineering increasingly borrow novel theoretical and modeling approaches from other sciences that constitute "micro-foundations" in a different, and more plausible sense of the word: accounting for a number of interacting agents. These approaches, which originated in computer science, cognitive science, and biology, include neural networks, cellular automata, and agent-based models (see, for example, Beltratti et al., 1996, Conte et al., 1997, DeCanio and Watkins, forthcoming, and DeCanio and Laitner, 1997).

CGE Models: Strengths and Opportunities. Above, we have discussed serious shortcomings of CGE models and modeling practice. Notwithstanding this critique, we believe that CGE models are a highly useful tool when applied in a pragmatic fashion. In our view, the CGE framework is open enough to allow for the major shortcomings to be alleviated.

CGE models are useful because they depict the economy as a system of interrelated sectors, allowing the analysis of indirect effects. They can handle a great level of sectoral detail, in a fashion that can make use of coherent systems of national accounting data. Their advantage over the earlier Input-Output models, which rely on fixed coefficients, is that this is possible while allowing markets to respond to economic variables, if only in a fashion that aggregates across agents within a market.

We believe that the weaknesses of existing CGE modeling practice lies in the adherence to micro-foundations, the assumption of market clearing, the aggregation over individual agents, and the lack of meaningful dynamics. We argue that these can be amended while leaving the model in working order.

One could replace neoclassical micro-foundations with more pragmatic formulations of supply and demand behavior that conform to empirically observable market behavior. This would already constitute an improvement over current practice, since these new formulations would not purport to represent something which they are not (i.e., the outcome of individual consumers' utility maximization or firms' profit maximization exercises). Of course, the functions that would replace neoclassical microfoundations should be based on an understanding of the forces that influence behavior, as well as technology detail and institutional factors that constrain or enable technology diffusion and innovation—empirics alone does not suffice. But there should be more liberty to try out specific functional forms, and an openness to account for phenomena of the social, not only the economic, world. As to the assumption of market clearing, one could allow non-market clearing in certain sectors.[15]

A next step would be to base micro-behavior explicitly on agent interaction and on evolving institutional, cultural and cognitive structures. The use of social simulation models could be promising in that context. Interaction of agents could be captured in a special module (or external model) that would pass on aggregate patterns (e.g., demand trends or market penetration of technologies) to the CGE model. The behavior of economic agents could be made to depend on variables other than prices. Likewise, the evolution of certain technologies could be passed on to the CGE model, though it may be difficult to fully embrace functions with positive feedback in a CGE model. This is largely uncharted territory, though efforts have begun to base economic models on interactive agents that obey simple behavioral mechanisms (Conte et al., 1997, DeCanio and Watkins, 1997).

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[15] A few authors have practiced this pragmatic type of CGE modeling. See, for example, the volume edited by Lance Taylor et al., 1990.

Thus, it does seem possible to make CGE models better describe real-world phenomena and to rid them of the specific normative ballast that they carry, in the form of the purported "optimality" of outcomes based upon presumed well-defined consumer preferences. But it will also be crucially important to embrace the phenomenon of uncertainty, which is due to the nature of complex systems and the fact of human agency—neither of which are captured within the current economic modeling paradigm. Yet both kinds of uncertainty can be reduced (if not eliminated) by actions that aim to shape the future rather than waiting for its mechanistic unfolding based upon past relationships. This should and can be reflected in analysis, though here lie no doubt the biggest challenges.

2.2. Modeling Improvements in Energy Efficiency

2.2.1. Current Practice

In the following, we describe how energy-efficiency investment and its role in production is treated in mainstream, neoclassical CGE policy assessment models. We will also say a few words on hybrid energy-economic models that use a CGE framework to represent the economy and a technical model to represent the energy sector.

To understand how conventional, neoclassical CGE models treat energy-efficiency investment, it is useful to distinguish between investment in response to energy price increases and investment in response to energy-efficiency regulation. The first is a very common subject of mainstream, neoclassical CGE modeling studies; the second has been analyzed much less often in this framework. In fact, to illustrate our description, we draw on two examples of CGE studies of *environmental* regulation, rather than *energy-efficiency* regulation, since the latter are so rare. The reason is that energy price increases, and policies leading to energy price increases (i.e., taxes), are very straightforward to implement in neoclassical models, because prices are the primary economic variables guiding the behavior of economic agents in these models. It is less obvious how regulation should be implemented in a conventional CGE model because it lacks the relevant "policy-levers." (Hybrid energy-economic models that use a technical energy sector module could accommodate a regulation policy more easily.) The practice that we find problematic, and that we wish to depart from, can equally well be illustrated with the broader example of environmental regulation.

To appreciate the implications of current modeling practice, it is useful to have a notion of a few theoretical concepts. We briefly summarize these, beginning with the distinction between input substitution and technical progress, followed by the distinction between autonomous and induced technical progress and, in modeling, by the distinction between exogenous and endogenous technical progress. We discuss these concepts in the neoclassical framework, but also mention briefly how they are treated in hybrid models.

Substitution between inputs vs. technical progress (neoclassical production function). In the typical CGE model, which draws on the neoclassical economic theory of producer behavior, producers use a number of inputs according to a neoclassical production function, like Labor, Capital, Energy, and Materials. These inputs are usually aggregates of other inputs. (Aggregation is carried out by using an index, often the Divisia index, or by using a production function, where the aggregate is the output and the entities to be aggregated are the inputs. This practice is called "nesting.") For example, in models with an emphasis on energy, the energy input is often an aggregate of electric and non-electric energy, where the latter again is an aggregate of different fuels. Materials are often an aggregate of all intermediate inputs (including or excluding energy, depending on whether the energy input is specified separately). Some models disaggregate labor, for example, into a skilled and an unskilled type. Few models disaggregate capital. When this is done, capital is usually differentiated into broad categories such as structures and equipment, or into different vintages.

In this neoclassical specification of production, improvements in energy efficiency[16] can come about in two ways: first, through a substitution of inputs away from energy and towards other inputs; second, through an improvement in the technology available to the producer (technical progress resulting in higher energy efficiency). Note that in this theoretical setting, producers have perfect information and always use the best (i.e., cost-minimizing) technologies available.

The neoclassical production function is based on the notion that inputs can smoothly be substituted against each other. Furthermore, it is assumed that the marginal productivities of inputs are declining (that is, the more of an input is used, the less this additional amount of input causes output to grow, all other things equal). This construct can be translated geometrically into a family of isoquants. An isoquant is a locus (or set) of points representing input combinations which a producer can employ without waste to produce a given amount of output. Given the conventional assumptions about the shape of the production functions and a vector of input prices, there is a unique cost-minimizing combination of inputs. The choice of input mix to produce an output depends on input prices alone.[17] If the price of an input rises, producers will choose another point on the isoquant by substituting away from this input towards the others.[18] Producers' input demand functions follow from their cost-minimizing behavior and the shape of the production functions.

The neoclassical production function concept distinguishes substitution between inputs, which is the movement *on* an isoquant, from technical progress, which is reflected in a movement *of* the isoquant towards the origin, reflecting the fact that a given amount of output can be produced with smaller amounts of inputs.[19, 20]

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[16] Energy efficiency is the amount of output produced per unit of energy input—this is the same as energy productivity, and the reciprocal of energy intensity

[17] To be exact, in the general case, the choice of input mix depends on input prices and scale of operation, but under the standard assumption of constant returns to scale, the input mix depends solely on relative input prices. (Technically put, a homothetic production function has linear expansion paths, and a Constant Returns to Scale function is a specific instance of a homothetic function.)

[18] This is simply put. If there are more than two inputs in a production function, there is the possibility that some inputs are complements, rather than substitutes. If input A is a complement of input B, then a price increase of A would reduce the use of A and B—but the use of some other input, say C, will have to increase.

[19] For a recent critique of the theoretical concept of a production efficiency frontier, see DeCanio, 1997. He questions the sharp distinction between "substitution" and "technical change," arguing that any substitution requires information, which producers do not have freely at their disposal, even at an industry-wide level.

[20] In this discussion, we implicitly follow the economic jargon that operationalizes technical change as "increase in input efficiencies," or improvement of production processes, neglecting the fact that technical change often comes in the form of new products. This practice might be an acceptable approximation at a

Technical progress can be "neutral" or it can be "biased." It is neutral when all input requirements decrease in equal proportion; it is biased when the requirement for one input decreases in greater proportion than the requirement for others. This intuitively plausible notion of bias in technical progress was first put forward by Sir John Hicks, and has been used later by writers who worked with highly stylized aggregate production functions in economic growth models.[21] Neutral technological progress does not affect the geometry of an isoquant, but manifests itself solely through a movement of the isoquant towards the origin. Biased technological progress could be thought of as a process that changes the geometry of an isoquant, while moving the isoquant towards the origin.

While this distinction between substitution and technical change seems clear conceptually, it is not easy to detect in practice. Even if one subscribed to the notion of a neoclassical production function with smooth substitutability of inputs, real-world phenomena such as changes in capacity utilization (which occur regularly during the business cycle) complicate the measurement of technical change.

Substitution vs. technical change: hybrid models. The same issues arise in models that do not use a neoclassical specification for production and energy use. Improvements in energy efficiency can come about through substitution or technical progress. Technical, engineering-type models often use more explicit technology representations, for example a linear mix of technologies. While they might allow for smooth input substitution over some range, they also contain discontinuous switching between technologies. Substitution thus would not always be smooth in the case of an individual firm. In hybrid models, technological progress is far more likely to appear in a biased form.

Technical change: autonomous or induced? Undoubtedly, there have been technological advancements in the past that have caused input requirements, and energy input requirements in particular, to decrease drastically. Technical change is continuing; and its direction and extent (which input requirements decrease more than others, and by how much) is of crucial importance for the future cost of policies to abate greenhouse gas emissions. The faster the pace of technical progress, and the more it is directed towards saving energy inputs, the smaller will be the future cost of reducing greenhouse gas emissions.

Can we influence technical change? Or does it unfold independent of our activities, out of our control? Economists like to distinguish these two possibilities as "induced" and "autonomous" technical change. Obviously, to the extent that technical progress happens in a socio-economic, cultural, and political context, it will always be induced, in the sense of depending on some variable that is influenced by humans. The distinction then points to the possibility that technical change is the result of some effort, or action, that is intended to bring it about.

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high level of sectoral aggregation. For example, the application of time switches (a new product) for electric lights would reduce the energy intensity of the service "lighting."

[21] For discussions of bias of technical progress, see John Hicks, 1932, and Binswanger and Ruttan, 1978.

The possibility that technical change is induced entered the debate on energy and climate change policies a few years ago.[22] Induced technical change opens up the opportunity that policies can be designed to stimulate technological change into a specific, desired direction, such as increasing energy efficiency. Learning by doing and other positive feedback mechanisms could contribute to the positive impact that policy could have on the direction and speed of technical change. (Some authors though warn that this dependence of technical change on economic activities and policies can be the source of cost and inefficiency; we will briefly return to this below.[23])

Technical progress in policy assessment models: exogenous and endogenous. Policy assessment models that do not account for induced, energy-saving technical change would tend to overestimate the cost of implementing policies such as those designed to decrease greenhouse gas emissions. The question is how exactly this phenomenon should be treated in a model. Ideally, if in the real world technical progress responds to socio-economic variables, this should be represented in a model. Technical change should be made *endogenous*, that is, variables that represent technical change (for example, increases in productivity) should be functionally dependent on other variables in the model. However, since the real-world processes of technical change are so complex, there is the danger that representing these phenomena too simply within a model does more harm than good. An alternative to endogenous modeling of technical change is to experiment with different rates of technical change specified exogenously, exploring the sensitivity of model results to these parameters, and assessing which would be plausible in response to certain policies, either by informed judgement or by analysis with different tools.

Many energy-economic models that are used for the assessment of climate change policies account for energy-relevant technical change. Most treat this change as exogenous, with parameters in the production functions that cause them to shift over time, reflecting growth in energy productivity. The Global 2000 model by Manne and Richels (1990, 1992), a hybrid energy-economic model, uses the now famous Autonomous Energy-Efficiency Index (AEEI) to represent an economy-wide exogenous energy-efficiency increase. Other models, for example the EPPA of Massachusetts Institute of Technology (an offspring of the GREEN model developed at OECD) contain sector-specific exogenous productivity increase parameters.[24]

This formulation—the inclusion of an exogenous shift parameter in a production function—is a specific instance of a practice dating back to Robert Solow (1957) who represented technical progress in an economy-wide production function with an exogenous parameter reflecting growth in total factor productivity. But while Solow introduced this term to account for otherwise unexplainable historical productivity growth, many of the energy-economic models offer the exogenous shift parameters as an option for the model user to carry out sensitivity analyses. We believe this is a good practice, until a satisfying endogenous treatment of technical change has been developed.

There are some important exceptions to the exogenous treatment of technical change in energy-economic CGE models. One is Dale Jorgenson's et al. DGEM (Dynamic General Equilibrium Model), which contains a formulation of technical change as endogenous: sectorally differentiated

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[22] The concept of induced technical change is not new; an early formal treatment is due to Sir John Hicks (1932). For a discussion of the relevance of this phenomenon to climate change policy see, for example, Grubb, 1995, and Peters, 1996.

[23] Goulder and Schneider, 1997.

[24] Jacoby et al., 1996

productivity growth terms are dependent on input prices.[25] However, this functional specification is problematic, since it treats the biases of technical change as constant—whereas it is plausible that these biases—i.e., the direction of technical change, indicating which inputs are saved in greater proportion than the others—should respond to economic and other variables.[26]

Another exception to the practice of modeling technical change exogenously is the model by Lawrence Goulder and Stephen Schneider, who expand a typical neoclassical production function by a shift term that is influenced by the amount of R&D undertaken by the producer.[27] But since these authors still use a general equilibrium framework that is based on the notion of a unique Pareto-optimal resource allocation, this dependence of technical change on R&D introduces the possibility of a distortion from an ideal allocation. It assumes that there is an optimal path along which technical change unfolds, and that the "incorrect" amounts of R&D could make the economy deviate from this optimal path. We find this representation of technical change unsatisfactory because the notion of a unique optimal trajectory for technical change neglects its inherent path dependence. (See our discussion in Chapter 2, Section 1.)

Current practice: two examples of CGE policy analyses of environmental regulation. We briefly illustrate how CGE analyses rule out side benefits with which environmental technology investments are often associated. The first is Dale Jorgenson's and Peter Wilcoxen's analysis (1990a and 1990b), the second is Michael Hazilla's and Ray Kopp's (1990).

Jorgenson and Wilcoxen, 1990a and 1990b. The authors use the DGEM model and estimate it with data from the Bureau of the Census. They model two effects of environmental regulation on producers: (i) an increase in the operating cost of production, due to environmental regulation, and (ii) an increase in the cost of investment, due to environmental technology investment which producers are forced to undertake to comply with the regulation.

As to (i), the authors assume that current production costs include the cost of complying with environmental regulation. They use environmental compliance cost data from the Bureau of Commerce to compute the operating cost caused by pollution control as a share of overall operating cost. Into their specification of production cost, they include a term that is meant to reflect the operating cost due to environmental regulation. The model is then estimated with time series data. The cost of environmental regulation is assessed by using a model simulation in which the terms for pollution abatement operating cost are eliminated.

As to (ii), the authors assume that environmental regulation forces producers to undertake specific investments; and they *assume* that "investment in pollution control equipment provides no benefit to the producer other than satisfying environmental regulations."[28] "Accordingly, we simulate mandated investment as an increase in the price of the investment good."[29] In other words, the investment in pollution control equipment is an investment in capital that does nothing but reduce pollution—i.e., it does not increase productivity. The authors do not explicitly introduce a second type of capital stock for this (pollution abating versus productive) capital; rather, they simply

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[25] See Jorgenson and Fraumeini, 1981, Jorgenson, 1986, and Jorgenson, Slesnick, and Wilcoxen, 1992.

[26] See Peters, 1996, and Pindyck, 1983.

[27] Goulder and Schneider, 1997.

[28] 1990a, p.330, and 1990b, p.737.

[29] 1990b, p.737.

increase the price of the investment good proportionally. Furthermore, as most CGE modelers do, the authors assume that capital is homogeneous across all sectors.

As a result, the model yields the outcome that the productive capital stock will be smaller than it would be absent the regulation. This is because the overall volume of investment is determined by savings which, in turn, are determined by the savings behavior of households. (Households engage in intertemporal utility maximization, including a labor-leisure choice.) When environmental regulation increases the price of the investment good, not only will the *quantity* of economy-wide investment reduce on the account of the higher price (given that expenditure on investment remained the same), but also the economy-wide *expenditure* on investment will decrease, because the environmental regulation decreases the rate of return on investment, which will lead to reduced saving.

Hazilla and Kopp, 1990. The model of these authors is an offspring of the DGEM, and like DGEM, is estimated econometrically. The authors analyze the social cost of the regulations associated with the Clean Air and Clean Water Acts. They use a data set of compliance cost estimates developed by U.S. EPA. in 1984.

The authors derive the cost-minimizing input demand functions absent environmental regulation to which they simply add input requirements meant to account for the requirements to meet environmental regulation. This modeling strategy rules out that there could be any benefits from the adoption of the pollution abatement technology other than abate pollution. As a result, their model shows an increase in cost due to the abatement expenditures. (This cost estimate is lower than the direct engineering cost estimate because it takes into account indirect effects—sectors with higher costs incurring output decreases.)

Furthermore, the adoption of the pollution control technologies has no consequence on the biases and rates of technical change. The model contains endogenous productivity growth increases just like DGEM, but the introduction of regulation does not affect these. Ironically, the authors urge that intertemporal, dynamic effects of regulation be taken into account. Their model does this on the side of households, which are modeled as making intertemporal choices, but there is no dynamic modeling of technologies, no taking account of effects like learning by doing.

Current practice: evaluation and summary. To be fair, the methodology employed by both sets of authors whose work we described above seems suggested by the data they use. The data are engineering cost estimates for pollution control technologies put together by federal agencies. To a large extent, they are cost estimates of specific end-of-pipe abatement technologies prescribed by the law. One could argue these specific prescribed technologies are less likely to bring about productivity benefits than general process innovations geared at pollution reduction are likely to yield. But our examples illustrate the thrust of such analyses. In the neoclassical GE framework, producers are always using a cost-minimizing technology and input mix, and are always on their cost-minimizing trajectories. As a consequence, investment forced upon producers by regulation (as investments they undertake in response to increasing energy prices), would increase cost, since the producers had, by definition, employed the cost-minimizing techniques prior to the policy.

Due to the assumptions of perfect information and rationality, there is no room for positive surprises when environmental technology investment is undertaken. By definition, such investment is always costly. That regulation increases cost is thus not a modeling result, but a modeling assumption. This assumption leaves no room for the empirically observable phenomenon that regulation has brought about productivity improvements.

2.2.2. Our Approach to Modeling Energy-Efficiency Improvement

We use an external industrial energy demand model to represent the investment in energy-efficiency technologies on a sectoral basis, under a business-as-usual regime, and in response to policies. Furthermore, we allow the energy-efficiency investments to expand the sectoral capital stocks in the CGE model. We comment on both modeling choices in turn.

Using an external industrial energy demand model. The LIEF (Long-Term Industrial Energy Forecasting) model is an engineering-econometric energy demand model for industry. Its sectoral disaggregation accounts for the differences in the technological opportunities and constraints faced by different industrial sectors.

At the heart of the LIEF model are Cost-of-Saved-Energy (COSE) curves that indicate the amount of energy savings that can cost-effectively be put in place, given energy prices. As output, the LIEF model yields energy savings and investment costs. We simulate policies using LIEF, and feed the LIEF outputs into our CGE model. Thus, improvements in energy efficiency, based on industry-specific experience, are exogenous to the CGE structure. There, they show up as changes in the intermediate input coefficients that reflect changes in energy intensities and costs of saved energy as exogenously controllable functions of time. (The CGE part of our model uses the simplest possible formulation of a production function, with all intermediate inputs, including energy inputs, being tied to output through a fixed coefficient absorption matrix.)

The LIEF model implicitly represents substitution between inputs—capital for energy—as well as technical progress, to the extent that the upper parts of the COSE curves depict technologies that are not yet fully in use. Recall that technical change comprises innovation and diffusion—i.e., the first application of new technologies in a commercial setting, and the spread of these technologies. To the extent that energy-efficiency improvements in LIEF are the implementation of novel technologies by a growing number of firms, LIEF depicts some degree of technical change. Of course, in a more dynamic treatment of technical change, the shape of the curves would change over time and in response to diffusion and realization of scale economies.

We chose an exogenous approach to representing technological change because endogenous modeling of technology development in a CGE context could be very complicated. Constructing technology variables as truly endogenous while keeping the model computationally tractable might mean throwing the baby out with the bathwater. There is a danger that in order to endogenize technical change, very simple causal relationships would have to be assumed between technology variables and other variables in the model, which would not do justice to the relationships between these variables in the real world. An intelligent exogenous analysis is a more modest and cautious approach and might be more helpful in yielding policy conclusions. Using LIEF to project energy-relevant technological change is a compromise that makes these rates plausible and allows the user to inspect and alter them as he or she sees fit.

Specifically, we see the following advantages from using LIEF. First, we introduce technology based on engineering analysis and experience, which we believe is more realistic than what could be estimated with a production function. Second, by using LIEF's sectoral disaggregation, we hope to be able to assess whether it is important to allow for sectorally differentiated energy-efficiency improvement assumptions, and thus be able to show a more accurate direction of the effect of energy-efficiency policies.

The second modeling choice pertaining to the representation of energy-efficiency investment is that we allow this type of investment to have positive side-effects. We apply it fully to the "ordinary" sectoral capital stocks. Thus, this investment not only increases energy-efficiency, but it expands the productive capacities of the individual sectors. What we intended to capture is the phenomenon that investments in environmental improvement, including energy-efficiency, often turn out to save production costs in unforeseen ways.

Adding the entire amount of energy efficiency investment to capital formation is of course an optimistic assumption; a more conservative treatment would have been to add a fraction of all energy-efficiency investment to the private capital stocks. The size of this fraction could be the subject of further sensitivity analysis.

2.3. Representing Government's Contribution to the Economy

2.3.1. The Standard Treatment of Government in Economic Models

Current CGE modeling practice affords the government an unfavorable role that does not do justice to its place in the real world. There are two aspects to this. One is the assumption embodied in CGE models with neoclassical microfoundations that the undisturbed market brings about an optimal resource allocation, and that government intervention introduces "distortions" that cause a "welfare cost." We have discussed this above. The other aspect is that the positive contribution of government activity to the economy is not shown. We now turn to this aspect.

Although it is not fashionable to say so, much government activity does indeed enhance the working of the economy. The government creates and maintains a physical transportation, sanitation, and communication infrastructure which provides services to private producers. The government also runs and supports institutions of education and health care, which improve the quality of life in general and the productivity of the labor force in particular. The maintenance of law and order helps contain business costs.

In some sense, this observation is trivial. Without the institution of the state, there would be no economy to analyze. Some fraction of income generated by the economy will always have to be used for maintaining basic governmental functions and infrastructure, whose erosion would be detrimental to the economy. This resource requirement could well be treated as a given nonchanging constraint. However, there are large variations in the amount and character of government activity beyond this basic level. How much of the national product should be invested in public activities is a political and social, as well as economic, decision.

Government activities such as the development and maintenance of physical, institutional, and knowledge infrastructures play a positive role in private production—they enhance the productivity of inputs and lower production costs. The quality of public infrastructure is a major factor for business location. This is well known at the state level; regional economic development policy packages designed to attract firms often contain infrastructure provisions.

Few economic models (at least models of the entire economy that are used for policy assessment) recognize this role of government. In most models, the government extracts income from the economy through taxation, but only part of the use of this income is modeled: some tax revenue is returned to the economy, either to households in the form of transfers or to businesses in the form of subsidies. In addition, in models that contain a capital market and government borrowing, some tax revenue may be used to pay off public debt. This money flows into the pockets of bondholders and reduces the interest burden on the economy in future periods, thus benefiting citizens through a lower tax burden in the future. But the use of tax revenue for government purchases is modeled only incompletely. The government purchases goods and services, but the fate of these purchases usually does not enter the analysis. It is as though these purchases flowed into a black hole, not serving any purpose.

In fact, national accounting convention in industrialized countries calls government purchases "government consumption." But whereas private consumption generates utility, which enters into a welfare measure, or which is seen as desirable in and of itself, government purchases are not shown to yield any intrinsic benefits.

In Computable General Equilibrium models, government purchases typically only enter with their cost. Their financing requires higher taxes or an increase in public debt, which dampens economic activity and growth. Thus, reducing government expenditures would in fact show beneficial effects in these models.

In defense of CGE models, it should be said that they were used to address specific questions, above all, the incidence of taxes and tariffs. A typical objective of general equilibrium analysis would be to assess the least harmful way of raising taxes for financing a given amount of government activity, where the optimal amount of that activity would be the subject of other analysis. But of course this other analysis has not found its way into policy consulting to the extent that CGE models have, or it is questionable in itself. Lip service is paid to the fact that the level of government activity (for example, environmental policy) reflects some political consensus on values to which economic analysis does not extend. But numbers on the cost of government policies seem to speak a stronger language. Thus, modeling the productive input of government would help redress the balance. Exactly how much government expense, and what types, contributes to private productivity is a critical question. This is something that, in a model, should be open to sensitivity analysis, based on empirical and theoretical insight and specific hypotheses.

Most energy-environmental CGE models determine the level of government activity as exogenous, at least in spirit. For example, SGM stipulates a government utility function, and then calibrates parameters of that utility function to data on actual government expenses. Other models take government expenditures as exogenous (for example, government expenditures having a constant share in GDP, in real terms, with the share being determined historically).

2.3.2. Our Treatment of the Government Sector

Our CGE model treats government in an untypical fashion. Government not only collects taxes, pays transfers, and swallows part of economic output as "government consumption," but also maintains a public capital stock which yields services that enter into the private production process.

We assume these services are a pure public good with no crowding. In other words, producer *i*'s use of these services does not diminish their availability to producer *j*. This is an extreme assumption; in the real world, most government services are crowdable. Transportation infrastructure is a case in point. However, we chose this extreme assumption for the purpose of demonstrating its effect.

Note that this modeling device does not yield an estimate of the productivity of government spending. We only calibrate our model, but do not estimate it. Whether the public capital stock is excluded or included in private production functions would be reflected in the values that specific model parameters are assigned in the course of calibration. Thus, inclusion of the public capital stock in private production functions would lead to lower productivity for other factors of production; i.e., labor and private capital, all other things equal. In contrast, a model that excludes the public capital stock would imply that labor and capital "picked up" the contribution of the public capital stock. The same would apply to inclusion or exclusion of other factors, such as natural resources (land-use, environmental quality).

While this modeling device does not indicate the absolute productivity of government spending, it will have an impact on model results when there is a change in the relative size of the public capital stock (i.e., its size compared to that of private capital stocks). When the shares, or amounts used, of production factors change relative to each other (and this will happen in all policy scenarios, even in the base case), a model in which public capital stock is included will produce different results than a model in which it is not.

When public goods are absent from a model, and the contribution of such goods is ascribed to private capital, then government intervention would likely have a negative impact on private production—either it would detract from private capital or cause sub-optimal amounts of it to be used. In reality, though, this is not necessarily the case. Government spending may constitute a public good without causing a negative impact on the productivity of other factors. On the contrary, the maintenance and expansion of public capital stock can increase the productivity of other factors of production.[30]

Our modeling of the government sector serves two purposes, other than addressing our unease with the unsatisfactory and limited treatment that government receives in typical policy assessment models. For one, the public capital stock provides the model with an additional policy lever. A plausible policy measure, such as an expansion of the transportation infrastructure, can thus be modeled explicitly. A more detailed representation of the public capital stock, and additional features such as its interaction not only with private production, but also with household behavior, would even better facilitate such a policy analysis. Also, such a policy lever would be even more important in a model that embraced increasing returns, since a small government intervention could set in motion a positive feedback process that favors certain technologies.

The second purpose of introducing a public capital stock in the model is that it affords us a more satisfactory and, we believe, more plausible measure for the cost of government policies than conventional models allow. We do not subscribe to the cost measure that is employed in many

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[30] Here, we emphasize a public capital stock as the government's contribution to the economy, such as built infrastructure. But, as noted earlier, other government expenditures such as extension services, education, public health maintenance, R&D, and assistance to businesses, can likewise improve private-sector productivity. such as infrastructure and buildings that can enhance such productivity.

conventional CGE models. The cost of a policy is often described as a loss in “welfare,” where welfare is based on the indirect utility of a representative consumer.

Indirect utility is a construct that rests on the model of the individual as a utility maximizer; given the theory, it can be imputed from observable demand behavior. But modeling demand behavior does not require a utility maximization framework to be plausible, and the “representative consumer” does not exist because individual utility functions—unless one makes highly restrictive assumptions—cannot be aggregated to yield a representative utility function with the convenient mathematical characteristics that are typically assumed.

Our rationale for using productive government spending as a means to assess the cost of policies was this: government spending can contribute positively to the economy. At the same time, the need to finance a policy can divert public resources from these productive uses of government spending. If the government is engaged in promoting an energy-conservation policy, this engagement might require either additional tax revenues as opposed to the no policy case, or divert a portion of government revenue to finance this policy at the expense of other government activity. Therefore, if we model the cost of energy-efficiency policies as the cost of diverting funds from government purchases, we should account for their productive effect; otherwise, we would have a policy that yields benefits (improving energy efficiency) but that does not cost anything—not a convincing scenario.

We prefer this method of modeling the cost of government policies because it reflects an essential concern of economics: that using resources for one cause takes resources away from another cause. Note though that we follow conventional analysis here by *assuming* (at the aggregate level) a tradeoff between increasing energy efficiency and other productive purposes. Nonetheless, as we argue above, there is reason to believe, and there is ample empirical evidence, that this trade-off need not always exist, owing to information constraints and bounded rationality.

3. The Model Structure in Detail

3.1. Complete Set of Equations

The model parameters, variables, and equations are described in Tables A.1 through A.4, which are located in Appendix I. Table A.1 lists and defines all parameters and functions, both endogenous and exogenous, for the No Conservation run of the model. Table A.2 contains the same information for the Energy Conservation run of the model. Tables A.3 and A4 list all of the equations used for the two runs of the model. The distinction between these model runs is part of the 'sequenced runs approach' of the model, which is described in Section 3.2.2.

3.2. Description of Model Structure

3.2.1. Major Elements: Producers, Households, Government, the Foreign Sector

General and Summary. Our model is a Computable General Equilibrium (CGE) Model with an intermediate product Input-Output core that is updated in each period. The model contains 21 producing sectors, of which five are energy sectors; a household sector, a government sector, and a foreign sector. (Table 3.1 shows the breakdown of producing sectors.) We distinguish between producers and commodities. Figure 3.1 is a schematic representation of the three main elements of the model (producers, households, and government) and the flows between them. These physical, monetary, and production inputs which flow between the aggregate sectors are described in detail in this chapter, as is the role that energy conservation technologies play in the model.

Relations between producers obey an Input-Output technical coefficients matrix, with the coefficients changing over time and in response to policies according to an exogenous analysis of the investment in energy-efficiency technology. The model is calibrated with an empirical data set of 1994, containing the basic I-O matrices and the energy use by sectors; parameters are loosely based on the economic literature or were given placeholder values as a first approximation. Our model depicts the entire U.S. economy over a period of ten years, beginning in 1994.

Compared to existing CGE models, our model's structure is very simple. The supply of labor is given (or fixed in each period), set equal to an exogenous forecast; there is no intertemporal utility or profit maximization. The total amount of investment is determined through savings behavior that is largely exogenous, except for the funds that satisfy the demand for capital caused by the energy-efficiency investment undertaken by producers. The government budget is always balanced; imports and exports are fixed proportions of existing demand and supply. There is no monetary sector.

Unconventional features of our model are: first, the mechanism determining how energy efficiency (and corresponding investments) increase over time, drawing on an external industrial energy demand model (LIEF); second, the treatment of energy-efficiency expenditures as productive investments; and third, the inclusion of a part of public capital stock as a factor in private production.[31] We describe the major elements in turn.

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[31] Once again, we wish to emphasize that other types of government expenditures can have these positive effects.

Figure 3.1. A schematic representation of the main elements of the model and the flows which occur between them

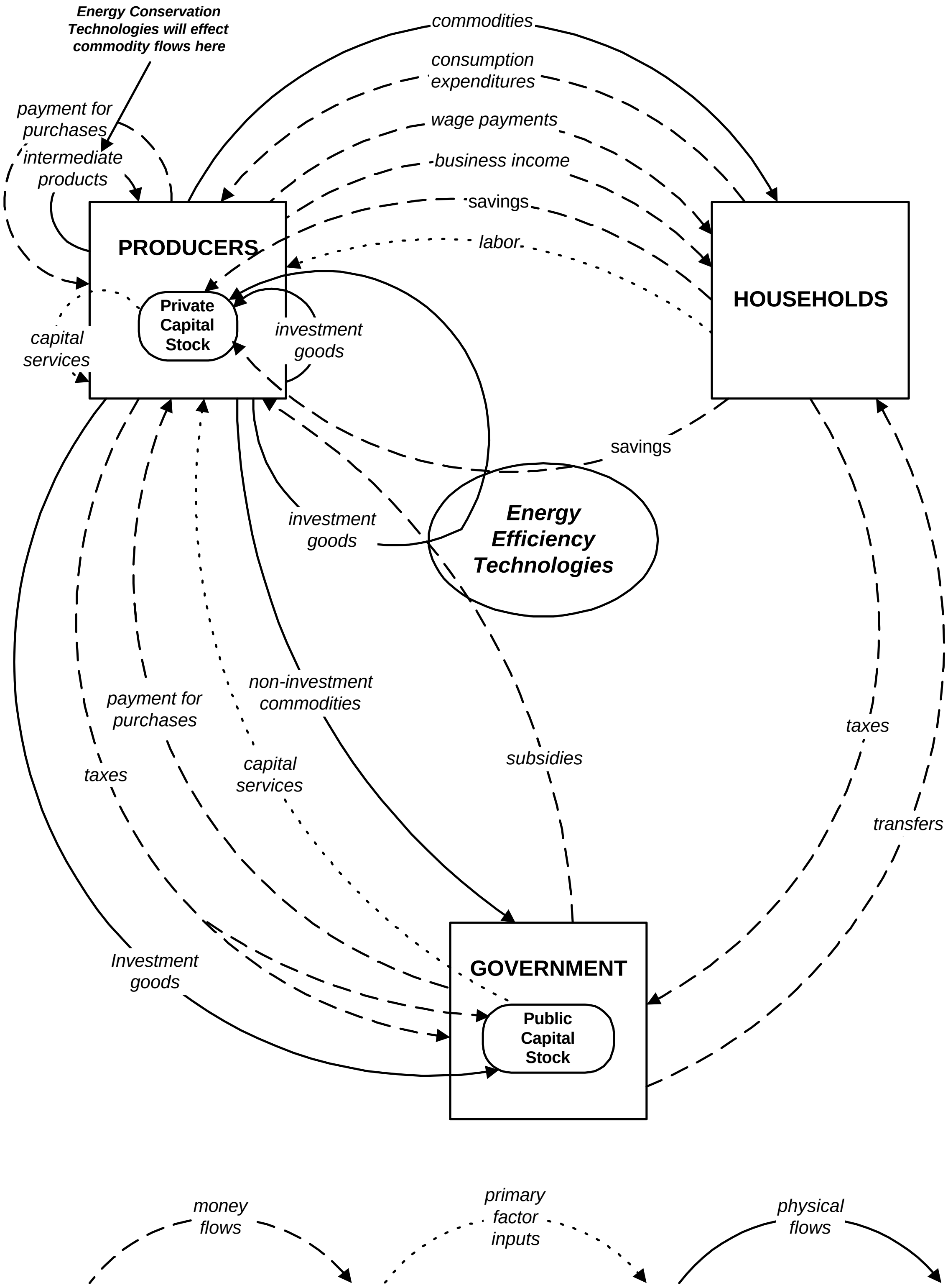

Table 3.1. Sector Breakdown of our Model

Manufacturing Sectors:

- Agriculture
- Coal Production
- Construction
- Paper
- Petroleum Refining
- Stone, Glass, Minerals
- Fabricated Metal Products
- Non-fuel Mining
- Crude Oil and Natural Gas Production
- Food
- Chemicals
- Rubber and Plastics
- Primary Metals
- Other Manufacturing

Non-Manufacturing Sectors:

- Transportation Services
- Natural Gas Services
- Finance, Insurance, Real Estate
- N.E.C. (Not Elsewhere Classified)
- Electricity Generation and Distribution
- Trade
- Services

Of which, Energy Sectors:

- Coal Production
- Petroleum Refining
- Natural Gas Services
- Crude Oil and Natural Gas Production
- Electricity Generation and Distribution

Producers and Investment. The n producing sectors are represented by n representative producers, with producer j's output being X_j ($j = 1, ..., n$). We distinguish between producers j and commodities k ; they both comprise the same list of items, but are not identical. Producers use commodities as inputs, and their outputs are a mix of commodities. Thus, each commodity (whose output is denoted by Q_k) is produced by several producers. (These relations are captured by the Market Shares Matrix $\mathbf{M}$.) Output X_j is the sum of Value Added and intermediate inputs. Value Added is produced according to a Cobb-Douglas function with inputs labor (L_j), private capital (K_j), and public, or government, capital (G). In each period, intermediate inputs constitute fixed proportions of output, captured by the absorption matrix $\mathbf{B(t)}$. (This is the same as a technical coefficient matrix, except that it has the dimension commodities by producers, rather than producers by producers.)

Producers purchase labor from households, and they each maintain their own capital stock K_j from which they derive productive services and in which they invest in each time period. (Note that K_j depreciates according to an annual depreciation rate of m_j ; producers are allowed to use a different depreciation rate ν_j for assessing the depreciation applied when computing their tax liability.) The investment mechanism in our model is extremely simple, except for the investment in energy-efficient technologies, which is modeled as occurring in addition to some "normal" level of investment (see below in the respective section).

The "normal" investment, I, is determined by the supply of loanable funds: households save a constant fraction of their disposable income which, by definition, equals the investment undertaken in the economy (adjusted by savings flowing into and out of the economy; see the section on the foreign sector). Of this total amount of investment, some is used for adjusting inventories or stocks, and some is used for capital formation. An exogenous parameter, r, determines the share of investment used for capital formation, $DK°$, and then this amount is allocated to individual sectors by the exogenous investment share parameters (h_j, $j = 1 \ldots , n$; where $S_j\ h = 1$). Each producer buys from all other producers when making an investment; the composition of an investment good differs across producers, and is captured by the matrix of capital composition coefficients, **S**. The remaining share of investment funds, determined by ($1-r$), is used to accumulate commodities in inventories. A vector of exogenous parameters (j_k ,k = 1…,n; where $S_k\ j_k = 1$) determines the amount of each commodity purchased for inventories. Our motivation for introducing these two separate components of investment expenditures was to maintain a balance of commodity flows while allowing a category of capital investment that would respond to investment policies, and one for inventory investment that would not. Ideally we would like to include a mechanism to treat for inventories—allowing both addition and depletion and accounting for depreciation of inventory stocks. Here we simply used fixed coefficients to describe inventory additions, determined by the base year data.

Finally, producers also pay taxes on their profits to the government; they can receive subsidies and investment tax credits (for detail, see the section on government and taxes).

Households and Labor. Households earn income by providing labor and capital to producers, they consume commodities, they pay taxes to the government and receive transfers from it, they save, and they hold foreign assets.

Households do not engage in intertemporal utility maximization, nor do they make a labor-leisure decision. Rather, the labor supply ($\overline{L}$) is exogenous; it is assumed to be strictly proportional to population size, which grows according to an exogenous projection. Savings behavior is exogenous: households save a constant fraction of their disposable income (disposable means after-tax and after-transfer). Households are not differentiated into workers (primarily earning income from labor) and capitalists (earning income mainly from their assets); the household sector as a whole receives all the income generated in the economy (except for a small portion that flows abroad) and, in addition, income from foreign assets. Taxes are paid on all types of income, but at different rates for the various types (for detail, see the section on government and taxes). The household sector saves different fractions of these income types: q_L of disposable labor income and q_B of disposable capital income and income from foreign assets (these parameters q are called "propensities to save"). These savings fractions are exogenous and fixed, except for the savings induced by energy-efficiency investments (see below the section on how energy-efficiency investment is modeled). The functions describing household demand for commodities, c_k, are derived from the maximization of a CES utility function.[32]

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[32] CES (constant elasticity of substitution) utility and production functions are very popular in empirical economics, and in CGE models in particular. We use this functional form for convenience and interpret it in pragmatic fashion, as providing negative feedback between prices and quantities demanded rather than reflecting the neoclassical theory of consumer behavior.

The foreign sector, or RoW ("Rest of the World"). The foreign sector sells and receives commodities to and from the domestic economy.[33] Exports from the domestic economy to RoW are a fixed proportion of total commodity output, denoted by e_k for each commodity k. Imports from RoW to the domestic economy are fixed proportions of the various demand categories: Q_k^H is the fixed proportion of household demand for commodity k that is imported, Q_k^G is the fixed proportion of government demand for commodity k that is imported. There is a gross absorption matrix $\mathbf{B}$ and an import absorption matrix $\mathbf{B^{imp}}$ which together define a fixed ratio of imported to gross intermediate input demand; the same applies to the demand for investment goods, for which there is a gross capital composition matrix **S,** and a matrix that lists the imported constituents of capital goods, $\mathbf{S^{imp}}$.

The movement of commodities in and out of the domestic economy is mirrored by flows of capital. To maintain the accounting equilibrium of the balance of payments, a trade deficit (surplus) must be offset by an inflow (outflow) of capital. There are two sources of capital outflow and two sources of capital inflow in our model. Capital outflows are, first, exported profits (profits earned by foreign-owned firms); second, savings by domestic households that are invested abroad. The former are a fixed share e_{inc} of overall after-tax profits; the latter are a fixed share l of domestic savings. Capital inflows are, first, earnings from investments made abroad by domestic residents; and second, investments made by foreigners in the domestic economy. The former is determined by f, an exogenous fixed rate of return on foreign assets, and the latter is the residual that equilibrates the trade and capital accounts.

Prices. Prices equilibrate supply and demand in the different markets. We distinguish between the following prices: w is the price for labor, i.e., the equilibrium wage. F_k is the price for the k'Th commodity. P_j is the price of producer j's gross output; P_j^N is the price of one unit of producer j's net output, i.e., his value added. Recall that producers produce several commodities: thus, output is a composite of commodities, and output price a weighted average of the prices F of commodities that constitute the output. The price of agricultural output serves as the numeraire (it is set equal to unity in all years, and all other prices are expressed in relation to it).

3.2.2. Link to an External Industrial Energy Demand Model (LIEF)

Brief description of LIEF. LIEF (Long-range Industrial Energy Intensity Forecasting) is an industrial energy demand model constructed from historical data on energy-efficiency investments by industrial sectors in the U.S. For our work, we have adapted an 18-sector version.[34] This aggregation broadly follows the 2-digit SIC level, but uses a finer disaggregation for energy-intensive sectors while aggregating certain other sectors into 'fast-growing' or 'general manufacturing' sectors.

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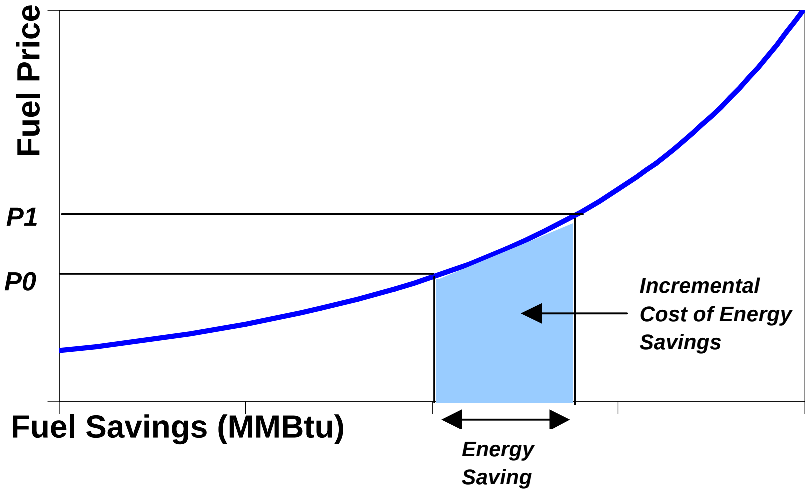
[33] We introduced a foreign sector solely for the purpose of accommodating our economic data. To fit our data set to a closed economy would have required making substantial changes to the input-output matrices in order to keep the economy "balanced." Since we wanted to keep this part of the data as realistic as possible, we created a foreign sector with the simplest possible assumptions and fixed exogenous parameters, whose values were determined through the calibration process. The foreign sector is not a topic of our analysis, nor does its presence affect the essence of our conclusions.

[34] Michael Ruth, 1998.

At the heart of the LIEF model are "Cost-of-Saved-Energy" (COSE) curves, showing the energy savings that can be achieved cost-effectively, given a certain energy price. These curves are derived from the notion that different energy prices imply different *ideal energy intensities* for each sector. The ideal energy intensity is that at which all cost-effective measures to conserve energy have been undertaken. The higher the energy price, the lower the ideal energy intensity, or, in other words, the greater the potential energy-efficiency savings. To reflect the financial constraints and various market and organizational barriers that affect such investments, the historically-based curves embody "hurdle rates" (that operate like discount rates above the normal-cost-of-money). LIEF contains separate COSE curves for electricity and fossil fuels in each sector. Thus, it does not capture fuel switching.[35]

Figure 3.2. shows a schematic COSE curve. The vertical axis indicates the fuel price, the horizontal axis the energy savings, in percent of base year energy savings. The magnitude on the vertical axis is divided by the Capital Recovery Factor (CRF) which reflects the (hurdle) discount rate and the time period for amortization of the investment. The CRF is a scalar, which when multiplied by the upfront expenditure that is required to undertake an investment, yields the amount of yearly amortization that is necessary to pay for the expenditure, for a given interest rate and length of amortization period (usually 10 years). Thus, the higher the CRF, the greater the annual capital cost payments, all other things equal. By representing the vertical axis as the energy price divided by the CRF, these COSE curves allow for direct calculation of the ideal energy intensity at that price, and capital costs associated with that level of energy savings.

Figure 3.2. A schematic COSE curve



LIEF assumes that sectors are, as a rule, not at their ideal level of energy intensity, and that these levels are not achieved instantaneously. Rather, a sector's investments leading to the ideal energy intensity are staggered over a number of time periods. The user specifies the number of years a sector requires to reach its ideal energy intensity, thereby determining the extent to which producers move toward this value during the scenario period. Any base case scenario (such as the one we used from *Annual Energy Outlook 1997*) will include business-as-usual, autonomous

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[35] Allowing for the possibility of fuel switching by, for example, including an elasticity of substitution for fuels, is one of the improvements we intend to make to the model in its next version.

improvements in energy intensity. LIEF begins by determining the industrial investment patterns exhibited in the base case projections and then allows the user to alter assumptions to increase investments under a policy scenario.

LIEF's output is the fuel intensity (i.e., amount of fuel per unit of output), the overall investment cost, and the resulting fuel savings compared to the base year savings for each time period of the analysis, sector, and fuel (fossil or electric).

Link between LIEF and the CGE. We use two outputs from LIEF in the CGE runs: the energy intensities and the cost of investment per unit of output. (We cannot transport the absolute amounts of energy-efficiency investment implied by LIEF to the CGE because there is no guaranty that the two models will use the same absolute magnitudes for sector output.)

The energy intensities predicted by LIEF are used to update the coefficients in the absorption matrix. An increase in the efficiency of electric energy in the primary metals industry would translate into a decrease of the respective coefficient in the absorption matrix, which denotes the use of electricity per unit of primary metals output.

The amount of investment undertaken to achieve this energy efficiency we model explicitly as an *addition* to the investment occurring in the absence of energy efficiency. Recall the method by which we determine the amount of investment *prior* to energy-efficiency investing: household savings constitute loanable funds which, by definition, equal the overall amount of economy-wide investment (adjusted by international capital flows). This investment figure is allocated to the individual sectors by sectoral share parameters h_j, which yields an amount of base investment DK_j° in each sector j. To this we add the amount of energy-efficiency investment implied by LIEF: $s_j X_j$, where s_j is the cost of saved energy per unit of producer j's output.

How is this additional investment financed? We simply assume that additional savings to match the additional investment are forthcoming as needed; the parameter d indicates the size of the adjustment in savings required to implement this assumption. (Some comments on this modeling choice are offered in Section 3.3.2.)

No iteration between LIEF and CGE. We do not iterate between LIEF and the CGE, but take LIEF outcomes as a sufficient proxy for the sectoral energy-efficiency investments per unit of output and the resulting energy intensities. Conceptually, iteration would be required, because the mechanisms embodied in the CGE model cause fuel prices to change: the increased energy efficiencies and, in some policy cases, energy taxes, cause energy demand to reduce, which should result in a decrease in fuel prices. This decrease in fuel prices, returned to LIEF, would generate different (lower) amounts of energy-efficiency investments than those determined in the first simulation of LIEF. A second simulation with these new data would yield different (higher) intensities and different (presumably higher) energy prices again—and so on.

However, we do not pass changes in energy prices back to LIEF. First, we do not anticipate that this correction would result in big changes in the magnitudes that LIEF computes. Second, and more fundamentally, we believe that not relaying changes in energy prices back to LIEF is a more realistic description of producer behavior. Producers are not omniscient and do not foresee the effect that their demand behavior will have on energy prices; it is more likely that they make their investment decisions based on general market trends (to which domestic industrial energy demand contributes only a part) and information about policies that are to be expected.

Sequenced-runs approach. Our method to implement energy-efficiency investments in the CGE model requires two runs of the CGE model in each period: first, a run of the CGE without LIEF, for assessing the period's "normal" investment, to which the energy-efficiency investment is to be added. Second, we run the CGE model again, after the results from LIEF (on sectoral energy investments and efficiencies) have been incorporated. These sequenced runs are necessary not only for the policy cases, but also for the base case because, as explained above, the base case, too, contains energy-efficiency investments.

Thus, our CGE model algorithm is a two-step intertemporal process. For each time period, step 1 computations are implemented under the assumption that there will be no specific energy conservation policy in place and that producers incur no investments in energy conservation. The latter assumption is carried out by setting the absorption matrix in the current period equal to the absorption matrix in the preceding period. The equilibrium found for this time period at step 1 is called "No Policy No Conservation Run, or N-run." It is important to note that the N-run assumes that there is no conservation investment *incremental* to the preceding time period's energy conservation efforts. However, it does assume that during all preceding time periods the policy and energy conservation investments have been taking place. The N-run of the model generates an important benchmark to use at the second step of the algorithm.

At step 2, the model assumes that the absorption matrix in a given time period will be different from the absorption matrix in the preceding period. This difference is caused by incremental energy conservation efforts. Using the benchmarking solution of step 1, the model re-equilibrates to account for: first, the change in the absorption matrix; second, the additional investments made by producers to accommodate incremental energy conservation; and, third, the reallocation of income caused by policies implemented by the government. The equilibrium found in step 2 is called "Energy Conservation and Policy Run, or E-run" of the model. The E-run is the final run of the model for a given time period and sets initial conditions (the level of private and public capital stock) to be used in the N-run in the subsequent time period.

3.2.3. The Government Sector: Revenues, Expenditures, and the Public Capital Stock

General and Summary. Government in our model collects taxes, pays subsidies and grants tax credits to producers; pays transfers to households; and, finally, purchases commodities from the domestic private sector and from abroad. We distinguish between two types of government purchases: those devoted to the maintenance of a public capital stock, which enhances private production, and those serving other purposes which are not part of our model. The government cannot run a deficit and borrow funds; its revenue comes entirely from taxes.

Taxes. There are four types of taxes in our model:
- A tax on labor income.
- A tax on business, or corporate, income. Businesses can deduct the depreciation of their capital stock from the tax base.

- A Social Security tax on wage payments, paid in roughly equal shares by employer and employee. Labor and business income taxes are assessed after the Social Security tax, i.e., they are assessed on a tax base from which Social Security tax payments have already been deducted.
- Indirect business taxes on the final sale of commodities for household consumption.

The symbols for the proportional tax rates are t^L for the labor income tax rate, t^B for the business income tax rate, $t^{SS,L}$ and $t^{SS,B}$ for the Social Security tax rate on gross wage income paid by the employee and employer, respectively, and t_k^{ind} for the indirect business tax rates. The sum of the revenues from these four taxes equals government revenue R.

Government expenditures. The government grants transfers to households and purchases commodities from the private sector and from abroad, for the purpose of maintaining a public capital stock (see next section) and for other purposes. In certain policy scenarios, it also subsidizes business investment in energy efficiency.

Transfers to households, F, are a linear combination of base year transfers and the growth in per-capita income. Purchases for purposes other than the public capital stock, Y, are a linear combination of the base year value of such purchases and GDP growth. The composition of these purchases is fixed and is denoted by the shares V_k. Subsidies to business investment are a policy variable; h_j is the fraction of producer j's energy-efficiency investment paid by the government.[36]

The public capital stock. We assume that part of the government expenditure is devoted to the maintenance of a public capital stock G, which can be interpreted to denote the state-owned portions of the transportation, sanitation, health, education and communication infrastructure of the domestic economy. G yields services to private producers. This is modeled by G entering private producers' production functions, alongside the private capital stock figures K_j. But unlike producers' private capital stock, G is "not crowdable"; that means that the use of G by one producer will not diminish the availability of G for another producer. This assumption will not hold in the real world, at least not in this extreme form; the crowding of the transportation infrastructure is a poignant example. We made this assumption for simplicity; it can easily be altered to allow for some extent of crowdability.

Like a private capital stock, G depreciates, at a rate m_g. Government invests in the capital stock in each time period. In the current formulation of the model, the amount of government investment in the public capital stock is the amount of government revenue left over after paying transfers, subsidies, and commodities for "other" purposes. This formulation also provides a means to assess the cost of government policies: expenses for a certain policy will draw resources away from the public capital stock, which will affect private-sector output. Other formulations are plausible and

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[36] In the equations for producer behavior that contain the term h_j, this term denotes the actually resulting proportion of subsidy payment of the government, not the ex-ante announced subsidy rate. The announced subsidy rate has some leverage: by effectively lowering the price of an investment good, it would cause more of it to be purchased (given that the demand for investment goods depends on price). The same applies to the equations containing terms relating to other price-altering government activities. These are κ for the investment tax credit and ν for the depreciation for tax purposes. See also footnote 39.

desirable, in which investment in the public capital stock could be a policy lever. In that case, a different cost measure should be employed.

Calibration and data requirements. The values we assign to the parameters relating to the government capital stock will crucially affect the results of any model simulation. This sensitivity of results to parameters applies to the model as a whole, not only the government sector. But since the government capital stock is one of the model extensions we suggest, we want to exert particular caution regarding its numerical specification.

Recall that this model extension—i.e., the inclusion of a public capital stock into private production functions—comes to bear when there is a change in the size of production inputs, L_j, K_j, or G. Otherwise, including or excluding the public capital stock G from private production functions would not make a difference; if it were excluded, its contribution to production would be picked up by the other production inputs in the process of calibrating production functions. By virtue of our functional specification, the exponents of production inputs add up to unity. Thus, the exponents of L_j and K_j would simply be greater if G were not part of the production function.

The size and the exponent that we assign to G matters for model outcomes once policies affect the size of any production input. The variable G would include all structures and equipment owned by the government and used to provide transportation, education, health care, conservation, and development. This stock accounted for 29 percent of the total capital stock in the economy in 1987[37].

For the exponent of G in private production functions, we chose the value 0.1 across the board. This is a placeholder value which could be altered based on external information but, as far as we know, it is nevertheless conservative, compared to some estimates reported in the literature (Aschauer, 1990).

Another approach to specifying this part of the model numerically would be as follows: we could treat the productivity of the public capital stock as a variable, rather than assigning it an exogenous value. Then we could compute, for a policy under investigation, the productivity which would make the policy just break even in terms of net impact on GDP.

Recall that we suggest using the public capital stock as a measure for the cost of a policy: to finance a policy measure, the government has to draw away resources from the maintenance of the public capital stock; and the more productive the government capital stock, the higher the cost of a policy. Now, for a given energy-efficiency policy, what value of the productivity of the public capital stock would make the policy have a net benefit or a net cost? Having computed the benchmark productivity which would make the policy just about cost neutral, one could assess whether one holds the true productivity of the public capital stock to be higher or lower than that benchmark. This would be a crude method to assess whether a policy is likely to be worthwhile or not, but it could well be more realistic than cost measures based on elusive utility functions.

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[37] This value for public capital stock is from Aschauer (1990). For the present version of the model, the value of public capital was assumed to be only one-fifth of private capital, making it 17 percent of the total capital stock.

3.3. How Policies Are Implemented: Policy Handles and Effects

3.3.1. Policy Handles and Effects in LIEF

Policies are represented both in LIEF inputs and in CGE model parameters. Government policies cause a number of things to happen in our model. Most significantly, they cause producers to invest more in energy-efficiency equipment, and they alter relative prices. In our model, we implement government policies by first letting them affect LIEF, whose results are then passed on to the CGE model. The CGE model takes LIEF results as inputs, responds to them, and, in addition, contains other mechanisms that represent economic actors' responses to policies.

Policy handles in LIEF are: (i) fuel prices, (ii) Capital Recovery Cost factors, (iii) parameters determining the speed of adoption of new energy-efficient technologies, and (iv) the shape of the COSE curves. Most of the policies we would want to analyze can be translated directly into changes in these policy handles.

For example, a tax on the carbon content of fuels would directly translate into a change in fuel prices, lever (i). (The change in the price of electricity as a result of fossil fuel taxes could be assessed on the generation mix or drawing on an exogenous electric generation model.) A loan subsidy guaranteeing a below-market interest rate could translate into a change in the CRF (all else equal), lever (ii). Efficiency standards or industry covenants could be implemented by modifying the efficiency improvement implementation rate, lever (iii). A percent subsidy of energy-efficiency investment would be implemented by a downward rotation of the COSE curve, reflecting a proportional decrease in the price of equipment. Government R&D, which decreases capital costs per unit of efficiency improvement or which increases the efficiency improvements achieved per unit of capital cost, could be implemented by modifying the shape of the COSE curves by the appropriate degree. Each of these policies could have some administrative costs beyond the costs embodied in the COSE curves.

It is only with policies that affect the speed of diffusion and market penetration of a hitherto unused technology (i.e., lever (iii)), that the model user has to make an assumption about the effect of the policy on the lever. For example, there is no clear and unambiguous translation from policies such as RD&D, technical assistance, and standards, to the lowering of cost and non-cost market barriers needed to cause deeper market penetration and faster implementation. Here, some judgement or external information must be used.

LIEF output passed on to the CGE. As we stated earlier, we pass on the following LIEF results to the CGE model: (i) energy intensity for industrial sectors (i.e., amount of fuel used per unit of sector output); and (ii) gross energy-efficiency investment costs per unit of sector output. LIEF also generates energy savings per sector; but these are not passed on to the CGE, since they are embodied in the new coefficients of the intermediate input (or absorption) matrix.

3.3.2. LIEF Results and Policy Handles in the CGE Model

New energy intensities by sector and fuel passed on from LIEF to the CGE model. These cause the coefficients of the absorption matrix **B** to be updated. Recall that this matrix lists the commodity inputs into each sector's production. Note that through this mechanism we capture energy savings. A reduced input requirement, as reflected by a decrease in an element of the absorption matrix, implies a reduction in production cost.

Energy-efficiency investments. As already explained, energy-efficiency investments are modeled as *additional* to investments occurring otherwise; since additional savings to finance them are forthcoming, they do not crowd out, or substitute for, other investments. Energy-efficiency investments augment the capital stock of private producers. Thus, the more of such investment a sector undertakes, the more its capital stock grows. This mechanism, stand-alone, could eventually lead to perverse results, causing implausibly high growth for some sectors; but due to the fact that we tied the amount of energy-efficiency investment to LIEF, it has a natural upper limit.

What, then, is the cost of energy-efficiency improvements to individual producers in our model? The answer is none—these improvements are financed by reduced household consumption in the present. In our model, producers do not feel a cost impact from ratcheting up their investments. One could say that additional investments are financed out of business income, at least partially—but we do not model the financial behavior of producers explicitly; all income in the economy, be it business or labor income, flows to households, who consume or save it.

The fact that additional investments are financed by reduced consumption is a simplistic assumption. The U.S. currently experiences a low savings rate—why would energy-efficiency policies induce people to save more? A better specification of investment behavior and financing is an important next step in improving the model. We would, for example, let investment behavior be driven by some expectation of profits (and let profit expectations in turn be affected by expectations of energy policies).

Policies affecting the speed of diffusion and market penetration of new technologies. There is no explicit policy lever in the CGE model representing this phenomenon. A faster penetration of new technologies implies more energy-efficiency investment to happen in a given time, and with all the associated consequences.

Carbon taxes that translate into higher fuel prices in LIEF are also an input into the CGE model. Carbon taxes, in addition to inducing industrial sector energy-efficiency investments as modeled by LIEF, also affect the fuel prices faced by non-industrial producers and consumers. Thus, they will increase production costs across the board and affect consumption outlays for these fuels, depending on how much fuel substitution and energy conservation will take place. All producers, industrial as well as non-industrial, pay a carbon tax rate t^C on fossil fuels, according to the carbon content of the fuel, $a_k^C, k \in fossil$. They also pay a tax on electricity according to the mix of fossil fuels used in its generation[38]. Government fuel purchases are exempt from the tax, but of course government outlays are affected through the carbon tax via the change in product prices that the fuel taxes bring about.

In the current model, households are affected by the carbon tax through an increase in the relative price of energy commodities. According to the way their behavior is modeled, they will shift consumption away from energy, substituting other products for it. The model does not provide for households to invest in energy-efficiency; thus, their shift in consumption is like a short-term

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[38] To avoid double counting, the electric sector is exempt from paying a carbon tax on its fossil fuel inputs.

response to energy price increases, which is reversible, but would not be if they had invested in new appliances or a heating system.

Government subsidization of energy-efficiency investments. There are two policy levers by which government can subsidize energy-efficiency investment: a direct subsidy of energy-efficiency investment, and an investment tax credit (ITC) targeted at energy-efficiency investment expenditures. The two are equivalent, except of course for parameter values and the fact that there is a natural ceiling to the investment tax credit—it cannot be so big that the tax credit exceeds the tax liability of an enterprise. Both direct subsidy and ITC lower the cost of energy-efficiency investment. The accelerated depreciation for tax purposes also affects the price of energy-efficiency investment; to that extent, it also is a policy lever for energy-efficiency investment (though a blunter one than the targeted investment tax credit, since it applies to all investment alike).

The term h_j denotes the percent of direct government subsidy and k the percent of the investment that firms are allowed to write off their tax liability. (Note that the associated equations, denoting the size of the investment tax credit and the direct subsidy, respectively, use the ex-post investment that has actually occurred in response to the policies, as it comes from the LIEF model.[39])

Other policy handles: tax policies. Income taxes can be used to reimburse part or all of the revenue from a carbon tax. Parameter δC denotes the fraction of carbon tax revenue refunded to households, and parameter dL serves the purpose of adjusting the labor income tax accordingly.

Expansion of the public capital stock. Increasing the public capital stock is one way to enhance the productivity of the economy. Currently, we have not yet built in a relationship between private-sector energy use and public capital stock, but it is plausible that there is such a connection. For example, an expansion of highway infrastructure could induce additional travel and thereby increase energy demand; on the other hand, an increase in the availability of public transport, or energy-efficient means of commercial transport, is likely to reduce the energy consumption arising from demand for transportation services.

3.4. Data Used for the Model

Although our model is meant to be a tool to explore alternative model features and structures, and not for policy analysis, we feel it is crucial to give it a good empirical grounding. Both parameters and base case data should give a realistic picture of the economy and of industrial energy use.

We used input-output data for the entire economy from a single source (Minnesota IMPLAN Group, Inc or MIG). MIG provides annual input-output tables based on the matrices constructed by the Bureau of Economic Analysis (BEA), complemented by and harmonized with its own additional information. We augmented this structure with data from other sources, including the

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[39] Say that the cost of a machine is $1,000. At that price, a firm might be willing to buy three machines. If the government is subsidizing this machine at the rate of 20 percent, the effective price of a machine will be $800. At that price, the firm might be willing to purchase four machines. Thus, the total amount of investment without the subsidy policy in effect is $3000, with the firm paying the entire amount, and, with the subsidy in effect, it is $4,000, with the firm paying $3,200 and the government paying $800.

BEA and the Energy Information Agency (EIA). This proved to be difficult at times because of the need to keep the model in equilibrium for the base year.

Sectors. We chose to represent 21 producing sectors, one government sector, one household sector, and simple mechanisms to account for capital purchases, inventories, and external trade. The choice of the 21 producers and commodities was based on a number of factors. We wanted to stay close to the LIEF structure so that the energy intensity outputs from that model could be easily applied within our structure. At the same time, we wanted a sectoral aggregation along the lines of 2-digit SIC codes, but without the somewhat arbitrary categories such as 'fast-growing manufacturing' and 'general manufacturing,' which LIEF uses. Since the focus of our model is on energy policies, we wanted to account separately for the important energy categories. We kept the service sector highly aggregated because our model at this point focuses on industrial sector energy use.

Since each of our data sources uses a different sectoral scheme, we needed to map their sectors onto our aggregation scheme. For the most part this was straightforward. Table 3.2 below lists the sectors that we used, as well as the corresponding sectors from each of the data sources that were mapped into our sectors.

Table 3.2. The Model Sectors and Corresponding Codes from Our Data Sources

	IMPLAN Codes	**SIC Codes**	**BEA Codes**
Agriculture	1-27	01-09	1, 2
Non-Fuel Mining	28-36,40-47	10, 14	3, 6
Coal Mining	37	12	4
Petroleum Production	38, 39, 57	13	5
Construction	48-56	15-17	7
Food	58-103	20	19
Other Mfg.	104-160, 174-185, 221-229, 415-432	21-25, 27, 31, 39	8, 9, 18, 20-22, 24, 28
Paper	161-173	26	23
Chemicals	186-209	28	25
Petroleum Refining	210-214	29	26
Rubber and Plastics	215-220	30	27
Stone, Glass, Clay	230-253	32	10
Primary Metals	254-272	33	11
Metals Fab. Ind.	273-414	34-38	12-17
Transportation	433-437	40-45	29-33
Electric Services	443, 511, 514	491	38
Gas Services	444	492	39
Retail Trade	447-455	50-59	41, 42
FIRE	456-462	60-65	43-50
Services	438-442, 445, 446, 463-510, 513, 525-527	46-48, 494-497, 72-87	34-37, 40, 51-61
N.E.C	512, 515-524		

The Social Accounting Matrix (SAM). We used a Social Accounting Matrix (SAM) constructed by MIG. It includes the typical input-output data (i.e., intermediate commodity flows between producers, plus final demand and value added data in some detail); and in addition, transfers between institutions, e.g., taxes and transfers. Recall that our model differentiates between producers and commodities; this choice is also reflected in the structure of the SAM.

The SAM also includes flows in and out of the economy. As mentioned earlier, we did not intend to devote much detail to foreign trade in our model. Foreign trade, however, is an integral part of the structure of production; some industries have large shares of imported inputs. As we judged it wise to leave the input-output structure of the data undisturbed, we needed to account for trade flows, but with a simple method. Thus, we fixed the proportion of imports and exports for both intermediate and final demand. We also fixed the shares of domestic households' savings invested abroad and producer income flowing to foreign owners of domestic businesses.

Investment Data. The SAM data give an account of the commodities purchased for investment in both capital accumulation and inventory addition. For capital accumulation, the data also give the amount that each producing sector spends. The data do not indicate which sectors are purchasing which commodities, so the specific mix of capital goods used by each producer is unknown. To obtain this information, we use data from the BEA's tables on detailed investment by purchasing industry and type of asset. BEA numbers do not match the MIG numbers because they only focus on tangible goods, which in our aggregation scheme fall into four sectors: construction, fabricated metal products, other manufacturing (furniture and fixtures), and chemicals. The data recorded in the BEA tables account for roughly 75 percent of the capital investment recorded in the MIG data. We used the data from BEA to allocate purchases of capital goods from these four commodity categories across producers, and then spread the remainder of investment in the MIG data across the other commodity categories in equal proportions for each producer. This procedure ensured that capital accumulation investments and capital commodity purchases were balanced. As for inventory additions, we calculate from the fraction of total investment spent on inventory goods and the allocation of these expenditures across commodities from the MIG data.

Data on the total capital stock for each producer and the depreciation rate specific to each producer were calculated from the BEA's tables on detailed wealth by owning industry and type of asset. In this case the calculation was much more straightforward since only producer-specific data were needed, aggregated across all commodities that form a producer's capital stock.

Regarding public capital, or infrastructure constructed by the government, we assumed this to be 20 percent of the amount of private capital (making it 16.7 percent of the total capital stock of the economy). The depreciation rate for government capital is taken as an unweighted average of the depreciation rates for all producers.

Government Spending. The SAM data give the total amount of spending by the government. Since we are differentiating between two types of government spending (that on infrastructure, and that on "non-productive" purchases), we need to determine the shares of spending on infrastructure investment and other government activities, respectively. To do this we used data from BEA for 1995, which breaks down total government spending into consumption and investment spending. Investment is further broken down into "structures" and "equipment." The shares of spending on these investment categories were applied to the 1994 MIG data for government spending. Spending on "structures" was assumed to be devoted to our commodity category Construction, and spending on "equipment" to our commodity category Fabricated Metal Products. "Non-productive” government spending was then determined by deducting the infrastructure spending from the total government spending that was reported in the MIG data.

Energy Data. Sector use of energy provides the basic building blocks for LIEF, and is derived from the Census Bureau’s Manufacturing Consumption Survey (MECS) for 1994. The projection of industrial energy demand which LIEF uses to generate the base case for the CGE model is taken from EIA's *Annual Energy Outlook* (AEO 97). Inside the CGE structure, energy is treated as a commodity. It appears only in monetary units, not energy units. We initially tried to map energy use from the AEO into the model, but this would have required assuming different prices across sectors (or even producers). For this reason we decided to leave energy units out of the model. MIG and AEO data are used to construct 'carbon content' values for each of the fuels in terms of carbon per 1994 dollar value of fuel. These are calculated on the basis of fuel spending in IMPLAN and total emissions reported in AEO.

4. Model Runs

4.1. Model Versions—Base Case, and Policy Cases: Implementation

Base Case, Policy Cases, and Model Versions. To recall, we mean to assess the impact that aspects of the model structure have on model results. To that end, we use various versions of the model. The reference version of the model is described in detail in Chapter 3; it embodies the three features described earlier: the use of industrial energy conservation supply curves from LIEF; the treatment of energy efficiency expenditures as investment in productive capital; and the inclusion of public infrastructure capital that yields services to private producers. We explore the importance of these structural features by "switching" them "off" selectively. This yields three alternative model versions, or sensitivities. With each of the four model versions (one reference and three sensitivities), we explore two policies. The individual policies and model versions are described in this section; the combinations of these that we simulated are shown in Table 4.1

Construction of the base case and time period of analysis. We benchmarked LIEF to 1994 data on U.S. energy consumption and projections of consumption to the year 2015, provided by the Energy Information Administration (EIA). We assumed these projections to be the ideal energy intensities in the year 2015.

The LIEF COSE curves were fitted in such a way that, by 2015, the ideal energy intensities in the different sectors (as given by the EIA projections) were reached. Although we have benchmarked LIEF to the year 2015, we could not simulate the CGE model for this entire period because of software limitations—all the software would allow is 10 years. Therefore, we analyzed in effect the years 1994 to 2003, but drew on the independently constructed LIEF base case of 22 years. While both the CGE and LIEF models were benchmarked to 1994 economic and energy statistics (see Section 4 in Chapter 3, describing data sources, structure and manipulation), we did not try to match empirical data from 1994 to the present. For this reason, in the following we refer to our period of analysis as Year 1 through Year 10.

The two policies we explore. Policy I: Energy-efficiency standards. The LIEF model does not provide any direct levers for this policy. We translated this policy into the model by shortening the time period during which firms make energy-efficiency investments to achieve their ideal energy intensity. It is plausible that efficiency standards should force firms to adopt new energy-efficient technologies faster than they would otherwise, but firms surely cannot adjust their capital stock instantaneously, and no law would require them to do so. We simulated this policy by halving the time during which firms make their energy-efficiency investments; what is adopted over the course of 22 years in the base case is adopted over the course of 11 years in the Policy I case.

Presently, we have not explicitly modeled any administrative cost for this policy. Recall that the LIEF Model indicates ideal fuel and electricity intensities for each sector, given fuel and electricity prices, and a capital recovery factor that depends on the discount rate and the capital recovery period. To achieve these ideal intensities, sectors undertake investments in energy-efficient technologies over a number of time periods. This staggering of investments in LIEF conforms to empirical observation. It reflects phenomena like capital turnover periods, institutional inertia, lack of information, organizational and financing constraints—in brief, what is generally subsumed under the concept of "hidden costs," often reflected in discount rates that are adjusted upwards ("hurdle rates") as is done in LIEF. Forcing sectors to shorten their implementation time would imply that a given amount of hidden costs are forced upon them in a shorter time. However, since hidden costs do not explicitly enter as costs into the model, the accelerated implementation only yields benefits, no costs. It moves sectors closer to the ideal state of affairs.

Policy II: A revenue neutral carbon tax of $100 per ton of carbon, in conjunction with an investment tax credit (ITC) on energy-efficiency investments, implemented beginning in the first year of the period of analysis at its full level. Fossil fuels are levied with a tax of $100 per ton of carbon, and electricity is taxed according to its generation mix. The entire carbon tax is returned to the economy—partly in the form of a tax credit for energy-efficiency investments, partly as a reduction in the labor income tax. The implementation of this policy was straightforward, since the model has explicit policy handles for the carbon tax, the ITC, and the labor income tax reduction.

The sensitivities we explore. Sensitivity 1: Make energy-efficiency investment solely "end-of-pipe." This we do by following the reference scenario, except that energy-efficient investments are not added to the sectoral capital stocks. I.e., we run LIEF to obtain new energy intensities and the costs of energy-efficiency investments; we let savings be used to finance this additional investment; we let sectors buy additional capital according to the capital composition matrix; but we do not add these energy-efficiency investments to the private-sectoral capital stocks.

Sensitivity 2: Eliminate government capital stock. We treat all government spending as "government consumption." There is no public capital stock G, and private-sector production functions use only private capital K, Labor L, and intermediate products as described by the absorption matrix **B**. Thus, the economy operates with less capital than it does in the reference version of the model. Note that the calibration of this model version results in changes for some model parameters, including the exponents of the remaining production inputs, thereby giving them more "leverage."

Sensitivity 3: Aggregate treatment of energy efficiency. Rather than applying sector-specific COSE curves from LIEF, we use the same average COSE curve for each sector**.** We constructed the average COSE as a weighted average of the sector-specific curves, with the weights being the shares of the sector outputs in the total output of all sectors.

Table 4.1. Combination of Base and Policy Cases and Model Versions

SCENARIOS	**MODEL VERSIONS**
Base Case **Policy I** *Efficiency Standards for Industrial Equipment* **Policy II** *Carbon Tax with Investment Tax Credit*	**Reference Version of the Model:** *As described in Chapter 3* **Sensitivity 1:** *Energy-efficiency investments only "end-of-pipe"* **Sensitivity 2:** *No government capital stock yielding productive services* **Sensitivity 3:** *Average COSE curve instead of sector-specific ones*

4.2. The Reference Model Version: Base Case and Policy Cases

The base case: economywide and sector growth. The base case is characterized by modest growth. GDP grows from $ 7.10 trillion in 1994 to 7.97 trillion in 2003; this corresponds to an annual growth rate of 1.30 percent.

Table 4.2. shows the size and the shares of the different sector outputs in the economy in the base year and the annual sector growth. The Services and F.I.R.E. (Finance, Insurance, and Real Estate) Sectors contribute the biggest shares by far to overall output, followed by some Manufacturing sectors and Construction. The energy sectors are among the smallest. The energy sectors are also the ones with the smallest growth in the base case. Average annual growth rates range from a little below 1 percent to 2.7 percent. The sectors with the highest growth are F.I.R.E., Construction, Chemicals, and Food. (Note that we did not calibrate our model to match exogenous growth rates; we simply calibrated the model with data from the base year. Growth patterns are a consequence of the model structure and the parameters we used.)

Table 4.2. Sector Outputs, Shares, and Annual Growth Rates in the Base Case (Reference Model Version)

SECTOR	OUTPUT in YEAR 1	SHARE of OUTPUT	GROWTH P.A.
Services	2,756,415	22.5%	2.0%
F.I.R.E.	1,941,034	15.8%	2.7%
Trade	1,556,159	12.7%	2.2%
Fabricated Metals	1,355,169	11.0%	2.1%
N.E.C.	816,487	6.7%	0.8%
Construction	791,113	6.4%	2.6%
Other Manufacturing	575,122	4.7%	2.1%
Food	432,461	3.5%	2.4%
Transportation	388,328	3.2%	1.9%
Chemicals	333,364	2.7%	2.4%
Agriculture	257,808	2.1%	2.2%
Electric Services	191,912	1.6%	1.9%
Primary Metals	160,728	1.3%	2.1%
Paper	143,218	1.2%	2.1%
Petroleum Refining	143,067	1.2%	1.0%
Rubber & Plastics	134,430	1.1%	2.2%
Petroleum Production	99,686	0.8%	1.2%
Stone, Clay, & Glass	71,636	0.6%	2.3%
Gas Services	70,740	0.6%	1.6%
Coal Production	27,603	0.2%	1.8%
Non-fuel Mining	27,211	0.2%	2.2%
All Sectors	**12,273,691**	**100.0%**	**2.1%**

The base case: other economic variables. The income distribution in Year 1 is as follows (all after taxes and transfers): labor income 56 percent, business income 22 percent, government revenue (after transfers have been paid) 21 percent. The remainder is income earned by the Rest of the World.

Gross Final Demand (of domestically-produced commodities) is comprised as follows: household consumption 60 percent, government spending 18 percent, investment 13 percent, and gross exports 9 percent. This breakdown of Final Demand remains virtually unchanged in the policy cases.

Government spending grows a little more than GDP, on average by 1.38 percent p.a.. In year 1 of the base case, 8 percent of government spending is devoted to the public capital stock, 36 percent to household transfers, and 56 percent to other, “non-productive,” government purchases. In year 10 of the policy, the share of spending on the public capital stock has grown to 12 percent, and the shares of the other two spending categories have decreased slightly. This development results from the parameters which we assumed for the function that determines the various government spending categories.

The base case: carbon emissions. Carbon emissions grow by 1.33 percent per annum in the base case, from 1.434 million tons in 1994 to 1.614 million tons in 2003. In year 1, these originate with 33 percent from the production of goods for intermediate demand (excluding electricity, which accounts for 28 percent of emissions), and with 39 percent from final demand activities.

The policy cases. The policies mainly affect overall growth, the pattern of sectoral growth, and carbon emissions. They do not have a significant impact on the distribution of income or the institutional composition of final demand. That is, the share of overall household consumption, government demand, and investment demand remain almost constant; but the composition of household demand for individual goods and services changes under the various policies.

Policy impacts on aggregate variables. Table 4.3. shows the impact of policies on three aggregate variables: GDP growth, economy-wide carbon emissions, and carbon emissions from the industrial sectors which we have analyzed with the LIEF model. Figure 4.1. shows the impacts on individual sector outputs.

Table 4.3. Impact of Policies on Aggregate Variables
(Reference Model Version)

	Change in Year 10 of Policy (% of Base Case of Reference Model)	
	Policy I (Standards)	Policy II (Carbon Tax w/ ITC)
GDP	0.36%	0.30%
Carbon, economy-wide	-0.78%	-5.24%
Carbon from industrial sectors	-4.99%	-6.37%

We notice that both policies increase GDP, compared to the base case, and Policy I slightly more so than Policy II. Both policies reduce carbon, Policy II much more so than Policy I. This overall difference is a result of many interacting factors and, in part, reflects the partial nature of the model. Policy I directly decreases industrial energy consumption and carbon emissions (via acceleration of LIEF-based investments). Its effect on energy use and carbon emissions in the rest of the economy (residential and commercial sectors, transportation) is indirect; lower industrial energy demand causes energy prices to decrease which, in turn, causes demands to increase. Policy II also directly decreases industrial energy consumption and carbon emissions (via greater adoption of LIEF-based efficiency owing to higher energy prices and the ITC). But it also directly decreases energy demands in other sectors owing to the elasticity of demand to price increases from the tax.[40] Residential, commercial and transportation energy-efficiency investments are not modeled, nor is fuel switching.

Both policies increase GDP because of our specification of energy-efficient investment—this augments the private-sector capital stock, which increases productive capacity of the economy. Both policies induce more energy-efficient investment than would occur in the Base Case— Policy I through a compression of the implementation time for new investments to achieve ideal energy intensity, Policy II through higher fuel prices.

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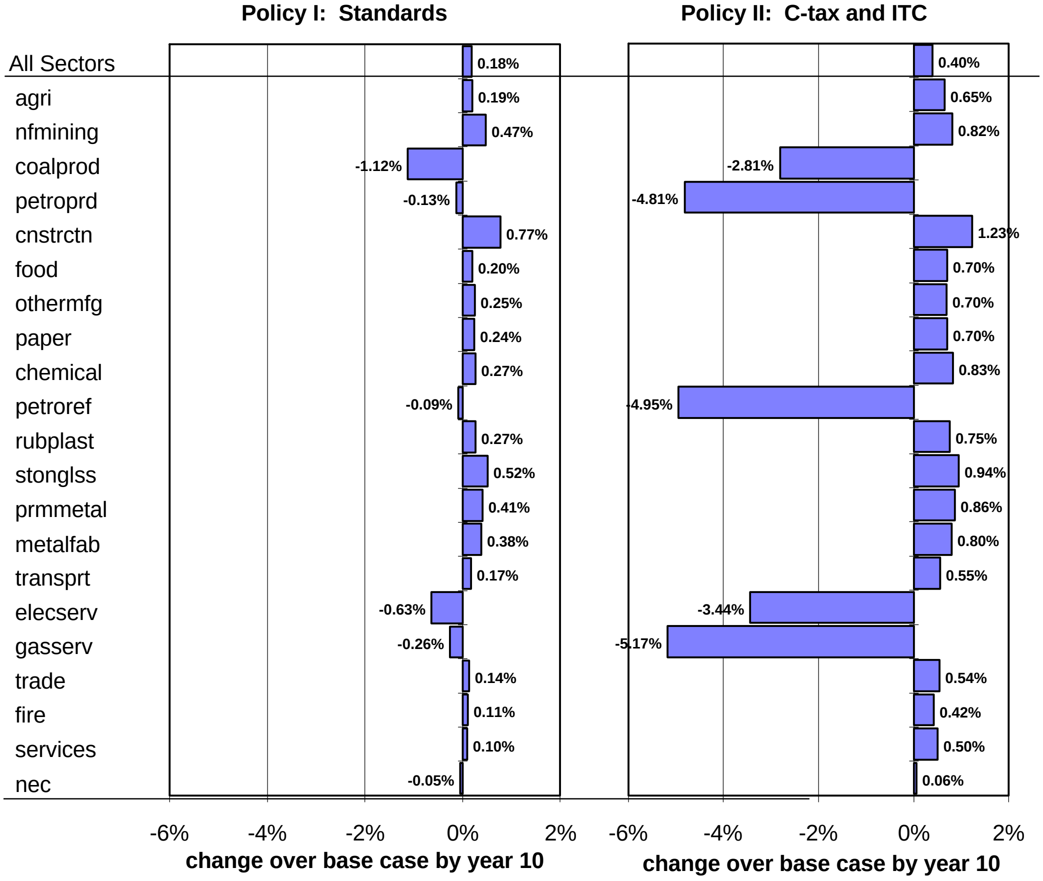
[40] We used a single price elasticity of demand for the household and government sectors. A more detailed treatment would distinguish between short-term and long-term price elasticity of demand; with the long-term elasticity being higher since it allows the adoption of new energy-using appliances and technologies.

Policy impacts on sector outputs. Figure 4.1. shows gross sector outputs. Under both policies, only the five energy sectors experience a drop in output; all other sectors grow. But Policy II, the carbon tax with ITC and labor tax reimbursements, causes the energy sector outputs to drop far more than Policy I. Under Policy I, energy sector outputs decrease by at most 1.12 percent (coal production), whereas under Policy II, they increase by up to 5.17 percent (Gas Services). At the same time, Policy II causes stronger growth in the non-energy sectors than Policy I, but not in the same proportions. However, since growth occurs in those sectors which account for a lot of output, Policy II causes more total gross output growth than Policy I. It is only GDP that is not as big in Policy II as in Policy I—not all sectors that contribute largely to gross output also contribute in the same proportion to GDP.

Figure 4.1. Sector Growth in the Policy Cases
(Reference Model Version)



4.3. The Sensitivities Compared to the Reference Model Version

Table 4.4 shows the impact that the policies have on aggregate variables in all four model versions. (It is an extension of Table 4.3 which showed this just for the reference model version.)

Table 4.4. Impact of Alternative Model Features on Aggregate Results: GDP, Total Carbon Emissions, and Industrial Carbon Emissions

	Change in Year 10 of Policy (% of Base Case of respective model)	
	Policy I (Standards)	Policy II (Carbon Tax w/ ITC)
GDP		
Reference	**0.36%**	**0.30%**
Sensitivity 1	0.05%	-0.03%
Sensitivity 2	0.31%	0.11%
Sensitivity 3	0.27%	0.23%
Carbon, economy-wide		
Reference	**-0.78%**	**-5.24%**
Sensitivity 1	-1.11%	-5.71%
Sensitivity 2	-0.78%	-5.22%
Sensitivity 3	-0.70%	-5.61%
Carbon, industrial emissions		
Reference	**-4.99%**	**-6.37%**
Sensitivity 1	-5.41%	-6.97%
Sensitivity 2	-5.06%	-6.43%
Sensitivity 3	-4.46%	-7.36%

Sensitivity 1: energy-efficiency investment is end-of-pipe
Sensitivity 2: government spending is entirely consumption
Sensitivity 3: use of average instead of producer-specific COSE curve

One of the more striking results of the sensitivity analyses is the impact on GDP of reverting to "end-of-pipe" treatment of energy-efficiency investments (sensitivity 1). For both policies, this effectively eliminates all of the policy-induced GDP increase, from about 0.30 percent to about zero in 2010. Elimination of the other two new model features (sensitivity 2 and 3) also lowers the GDP increase, but not as dramatically. While we have not modeled removal of all three model features together, the results indicate that without these features GDP could decrease rather than increase as a result of the energy policies evaluated.

A more detailed treatment of investment, for example as responsive to the cost of capital, could further augment the difference between this model approach and more conventional approaches, especially in the case of modeling ecological tax reform.

While the various sensitivities to model structure show pronounced GDP effects, the results are broadly similar for carbon emissions. The first order impacts on carbon emissions—changes in energy intensities via the policies modeled in LIEF—are much larger than those caused by changes in output owing to the sensitivity assumptions.

5. Conclusions and Outlook

The model that we constructed is a small first step in a program to explore the importance of model structure to model outcomes, in the context of economic analysis of energy and climate policies. The structure of most energy-economic models neglects certain real-world phenomena which are important to society's ability to meet the challenges posed by the threat of global climate change. By their built-in optimality, these models suggest that ambitious action to reduce fossil fuel use bears great economic cost. We explored a few key technology and economic assumptions that are relevant in modeling the economic costs and benefits of energy policies.

We have launched this program within a CGE framework, taking a pragmatic approach that employs some of its attractive features without being wedded to the constraints embodied in its micro-foundations.

The overall aim of this effort is to develop, and progressively improve, a tool to explore the impacts upon modeling results of the choice of model structure and assumptions, particularly with regard to energy technology. One outcome of these efforts can be to broaden the perspective from which insight on the results of energy/climate policy modeling efforts can be gained, and interpretation deepened; we believe that we have already achieved this in small measure. Another can be to stimulate research and model innovation; we hope that this will ensue through dissemination and discussion.

A much wider range of explorations and modeling innovations are needed in order to better evaluate the importance of model structure and assumptions for estimating the economic impacts of energy and climate policies. Given our modest start, there is much of interest to be done.

Only industrial sector energy efficiency is represented in the current model. Similar representation of energy-efficiency in transportation, households, commercial buildings, and technology choices in the electric sector would round out our treatment of energy efficiency. This would permit more comprehensive and integrated explorations of the relationships between model structure and policy outcomes. A representation of the energy using capital stock in these sectors would allow the explicit distinction between short-term and long-term price responses.

Fuel switching is not represented. For example, a carbon tax (or cap) is likely to cause the prices of some fuels to increase more than others, thereby causing the fuel mix in each sector to change. The current model could be changed to reflect this phenomenon through empirically-based fuel choice elasticities. This would have impacts on both the energy systems and economic activities represented in the model.

Scale economies and learning in the cost of energy technologies, are not directly represented in the current model. One way of accounting for scale economies and learning would be to tie production costs to cumulative production. For this to yield rich insights, the various technologies (or classes of technologies) in use and available for each sector should be explicitly represented, and their stocks be tracked. More broadly, it would be desirable to represent the various factors affecting technological change—invention, innovation and diffusion—and the interaction between these phenomena. Institutional, physical and cultural conditions as well as economic and policy factors can affect the pace and character of technological change. Many of these processes are path-dependent. Depending upon the policy conditions, some technologies which could become problematic in the long run could become "locked-in" based on a combination of economic, institutional, and physical factors, while others whose long-term promise would be realized if learning could continue and scale economies realized could become locked out. Understanding and modeling these phenomena can be critical to developing timely and effective policies.

Investment behavior is treated as fixed and exogenous in the current model. This could be improved by relating investment to such factors as expected profits and the cost of capital, thus providing the model with more detail regarding decision-making by business. This would extend the range of policies that could be meaningfully addressed with the model. An example is ecological tax reform and the potentially resulting "double dividend."

Further research would be valuable on such factors as: institutional constraints and enablers of energy technology diffusion; disaggregation of household demand and investment; the roles of public and private R&D on technological innovation; the impact on productivity of government infrastructure; the impacts on productivity of other government services; and the relationship between infrastructure and energy demand. These efforts could entail empirical research as well as heuristic modeling exercises and sensitivity analysis.

Finally, both with the current model and various stages of its improvement, further sensitivities could be explored, with respect to the types and strengths of policies, and the magnitude of key parameters in the model.

The economic impacts of energy and climate policies will affect society's willingness to devote resources to avert dangerous climate change. As energy-economic models have become important tools in the climate policy discourse, it is essential that they are realistic and appropriate to this challenge. Both climate change and the degree of technological and related changes that may be required to avert it, entail non-linear, path-dependent, and non-marginal processes. Energy-economic models designed to evaluate climate policy should begin to take these processes into account in order that effective inventions can be identified and pursued.

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Appendix A: Model Parameters, Functions, and Equations