Annu. Rev. Environ. Resour. 2004. 29:345–81
doi: 10.1146/annurev.energy.29.062403.102042
First published online as a Review in Advance on July 30, 2004

ADVANCES IN ENERGY FORECASTING MODELS BASED ON ENGINEERING ECONOMICS*

Ernst Worrell,[1] Stephan Ramesohl,[2] and Gale Boyd[3]
[1]Energy Analysis Department, Lawrence Berkeley National Laboratory, Berkeley, California 94720; email: eworrell@lbl.gov
[2]Energy Division, Wuppertal Institute for Climate, Environment, Energy, 42103 Wuppertal, Germany; email: stephan.ramesohl@wupperinst.org
[3]Decision and Information Sciences Division, Argonne National Laboratory, Argonne, Illinois 60439; email: gboyd@anl.gov

Key Words energy modeling, industry, policy, technology

■ **Abstract** New energy efficiency policies have been introduced around the world. Historically, most energy models were reasonably equipped to assess the impact of classical policies, such as a subsidy or change in taxation. However, these tools are often insufficient to assess the impact of alternative policy instruments. We evaluate the so-called engineering economic models used to assess future industrial energy use. Engineering economic models include the level of detail commonly needed to model the new types of policies considered. We explore approaches to improve the realism and policy relevance of engineering economic modeling frameworks. We also explore solutions to strengthen the policy usefulness of engineering economic analysis that can be built from a framework of multidisciplinary cooperation. The review discusses the main modeling approaches currently used and evaluates the weaknesses in current models. We focus on the needs to further improve the models. We identify research priorities for the modeling framework, technology representation in models, policy evaluation, and modeling of decision-making behavior.

CONTENTS

INTRODUCTION 346
POLICY CONTEXT AND IMPLICATIONS FOR ENGINEERING ECONOMIC ANALYSIS 347
Options to Influence Energy Efficiency in Industry 347
Policy Context and Recent Developments 348
Implications for Policy Analysis and Modeling 348
CONVENTIONAL ENGINEERING MODELING 351

Use of Models in Policy Development 351
Modeling Approaches 352
Approaches to Address Barriers for Implementation 355
Approaches to Model Policies 356
CHALLENGES AND REQUIREMENTS 356
Challenges 356
Directions/Issues in Modeling 361
PATHWAYS 365
Better Use of Models in Policy Analysis 368
Improving Models 369
CONCLUSIONS AND RECOMMENDATIONS 374
Research Priorities 374
Short Term Collaborative Projects 375

INTRODUCTION

In recent years, the importance of energy policy has been demonstrated around the world. Deregulation, energy security, climate change, and other environmental challenges all impact energy policy. Energy efficiency will play an important role in future energy policy. New energy efficiency policies have been developed and applied in many countries, varying from standards to voluntary or negotiated agreements to eco-taxation programs with different forms of revenue recycling that slowly shift taxation from labor to resource use.

Energy models are used in policy making to assess future energy demand, the impacts on the economy and environment, as well as the economic, environmental, and social impacts of technology and policy choices. Craig et al. (1) demonstrated the difficulties with forecasting by comparing historical forecasts for energy demand in the year 2000 against the actual trend. Although Craig et al. (1) evaluated the modeling results, this review focuses on the inner working of one group of models, the so-called bottom-up engineering economic models. We evaluate the models against the changing demands put on those models by the policy-making community.

Modelers and decision makers have distinct responsibilities in energy policy development. Policy makers rely on energy models to evaluate, *ex ante*, the potential effects of certain developments and policy choices on issues, such as energy use and economic welfare. Two main types of models have been used in energy analysis, the so-called top-down and bottom-up models. Although the line between model types has blurred, both approaches have advantages and disadvantages (2), and the applicability varies with the problem addressed. All models are an abstraction of the real world and, so by definition, have shortcomings. One of the shortcomings of many energy models is the lack of the capacity to assess the effect of nonmonetary policy instruments. Historically most tools were focused on assessing the impact of price changes and monetary policy instruments, but these tools are less well suited to assess the impact of nonmonetary policies, such as a voluntary program or that of a market transformation initiative. A critical evaluation of the models used to investigate future energy use is needed (3, 4).

We explore pathways for pursuing complementary approaches to engineering economic analysis that could help improve engineering economic modeling from a multidisciplinary background. We address three questions.

1. What are the (new) requirements for engineering economic analysis posed by nonprice energy and alternative regulation climate change policies?
2. What are the strengths and limitations of conventional engineering economic approaches in addressing nonprice and alternative regulation policy measures?
3. What are promising areas for the focus of research and model development that will help accelerate improvements in the realism and policy relevance of engineering economic analysis?

We describe the so-called engineering economic (or bottom-up) models because they include an amount of detail that appears appropriate to model nonmonetary policy scenarios that address energy end use. We further review models with comparatively high levels of detail for the industrial sector, owing to its wide variety in economic, technical, and policy characteristics. We also focus on models that have a time horizon of approximately 20 years, so many of the global, integrated assessment models used for climate change analysis are outside of the scope of this review.

POLICY CONTEXT AND IMPLICATIONS FOR ENGINEERING ECONOMIC ANALYSIS

During the past decades, the energy policy focus has ranged from concerns on supply security in the 1970s, to air pollution prevention in the 1980s, and to the challenge of global climate change mitigation during the 1990s. All aspects illustrate the vital importance of a clean, efficient, secure, and competitive energy supply to industry for society's welfare.

Options to Influence Energy Efficiency in Industry

In 1995, industry consumed 41% of global primary energy consumption, making it the largest single energy-consuming sector (5). The practical design and implementation of energy policies to improve energy efficiency in industry represents a demanding task. Measures have to account for the complex technical, economical, behavioral, and organizational structures that distinguish industry from other end-use sectors. Being a necessary input to transform and process materials into products, energy is a key element of the industrial metabolism. There are countless industrial energy technologies. As a result, the pattern of energy use can differ significantly among sectors and companies. Taking this complexity into account, there are various options to influence energy use in industry.

Although many of these options are addressed directly through energy policies, other influences are related to nonenergy policies, e.g., policies for waste management and pollution prevention affect energy use. Policy activities in different fields not only open the possibility for synergies but may also lead to conflicting demands.

Policy Context and Recent Developments

A diversification of policies influencing industrial energy is observed, challenging the standard modeling approaches. During the 1990s, a series of new policy instruments were developed that represent a changed philosophy toward policy intervention.

- There has been a growing acknowledgment of the complexity of cause-impact relationships that impede efficient policy design, especially given a situation of asymmetric information. Triggered by new public-private partnerships, different voluntary approaches emerged (6–12). Voluntary agreements have been broadly defined as "agreements between government and industry to facilitate voluntary actions with desirable social outcomes, which are encouraged by the government, to be undertaken by the participants, based on the participants' self-interest" (13, 14). These schemes are characterized by a strong involvement of industry in policy implementation and responsibility, resulting in a high degree of freedom for the companies in their response to the policy impulse.
- Secondly, there is a growing understanding of the socioeconomic dimension of industrial energy efficiency. As with any other aspect of production, energy use in industry is a result of company decision making and corporate behavior (15, 16). Energy related decisions in industry are embedded in an organizational process involving many actors. Growing empirical evidence indicates that several barriers hinder this process (5). Instruments and initiatives have been introduced to reduce these barriers.
- Often policy instruments are not applied in isolation but combined within a mix, aiming to benefit from synergies while compensating for weaknesses of individual policy instruments (17).

Implications for Policy Analysis and Modeling

Price clearly matters. It has a pronounced influence on decisions affecting energy use. However, it is not all that matters. The increasing variety (see Table 1) in policy and industry interactions and new policy approaches stresses the need for a comprehensive assessment of policy impacts and program effects, effectiveness, and efficiency. The variety also means that the standard neoclassic economic framework is insufficient for energy models aiming to explore the different dimensions of potential policy impacts. The methodological framework for policy analysis and modeling must be adapted. The three identified impact areas are

TABLE 1 The portfolio of energy policy instruments in industry

	Impacts			
Instrument type	**Availability of energy-efficient technologies**	**Incentives for decision making**	**Increased capability of companies**	**Examples**
Regulation standards	Controls the set of technology choices	Induces high costs for the use of outdated equipment		Motor efficiency standards in the United States and European Union (E.U.)
Subsidies, direct public spending, R&D[a] support	R&D support enhances technical progress and innovation	Investment grants increase the economic attractiveness of options		Found in many OECD countries[b]
Pricing	Indirect incentive for R&D	Affects price relations in favor of energy efficiency measures	Contributes to higher awareness	Carbon taxes, fuel (excise) taxes, technology adoption tax credits, depletion allowances
Emission trading	Indirect incentive for R&D	Creates a price and market for energy efficiency/emission reduction	Contributes to higher awareness	United Kingdom, Canada
Negotiated agreements		Can create an environment for energy efficiency and innovation	Increases energy awareness, communication & dissemination	Dutch Long-term Agreement, Danish CO_2 agreement, German Voluntary Agreement scheme

(*Continued*)

TABLE 1 (*Continued*)

	Impacts			
Instrument type	**Availability of energy-efficient technologies**	**Incentives for decision making**	**Increased capability of companies**	**Examples**
Public voluntary programs	Stimulates R&D		Provides information, know-how, and management support	U.S. Green lights and Energy Star, Industries of the Future U.S. Motor Challenge Voluntary Challenge & Registry (Canada)
Management tools		Lowers (in long term) transaction costs for efficiency action	Increased information Strengthened staff capacities Induced learning effects	Eco-Management and Audit Scheme ISO 14001 Eco-Energy Sweden
Labeling		Better communication of cost parameters	Increases information Higher market transparency	E.U. labels U.S. Energy Star® labels
Technology procurement	Stimulates R&D and innovation		Dissemination of information and know-how Qualification and training	Sweden E.U. energy^{+} initiative
Best practice dissemination			Increases awareness and information	United Kingdom E.U. initiative
Education, qualification, training			Provision of information and know-how	Austrian Ecoprofit U.S. Industrial Assessment Center Program
Agency networks			Networking of actors	Allied Partners, Energy Star®

[a]R&D, research and development.

[b]Organisation for Economic Co-operation and Development.

- Enhanced availability of energy-efficient technologies and measures to improve efficiency [e.g., public support for research and design (R&D)];
- Incentives to influence efficiency-related decision making (e.g., energy price signals); and
- Improved capability of companies to respond to technical opportunities and economic incentives (e.g., education programs).

From the perspective of policy analysis, the first area can be interpreted as the set of technology opportunities provided in engineering economic models, whereas the second area corresponds to the economic decision criteria used in the decision making process. The third dimension is often described by an exogenously fixed penetration rate that incorporates the response function of the target group. These behavioral patterns are increasingly addressed as a policy variable. Important implications for policy analysis include the following:

- Many of the new instruments do not result in a direct effect on energy consumption but contribute to an indirect impact that materializes gradually over time.
- Implementation processes within organizations take time and cause a delay that adds to technical restrictions resulting from stock turnover and investment cycles.
- Policy measures can contribute to accelerated diffusion of energy-efficient technologies. Such a market take-off can follow a nonlinear trajectory that is partially technology specific but can be influenced by the policy environment.
- The combination of policy instruments within a portfolio opens the possibility to increase the effectiveness and efficiency by exploiting synergies.

CONVENTIONAL ENGINEERING MODELING

Policy makers today are facing new challenges in the design of energy policies. More and more, forecasting models are used to evaluate the potential impact of policies. However, the traditional modeling approaches may not suffice within the changing policy environment. This section discusses the approaches commonly used in the models.

Use of Models in Policy Development

Energy models are used in policy making to assess *ex ante* the economic, environmental, and social impacts of technology and policy choices. Energy models are not the sole tool used by policy makers but are used more and more to support decision making processes. The main goals of using modeling tools in energy policy include the following (18):

- Define target levels of greenhouse gas (GHG) emission reductions;

- Find the least social cost response to GHG reduction targets;
- Identify the best technology opportunities for action;
- Assess the effects and costs of proposed public policies and programs (standards, taxes and subsidies, voluntary programs);
- Assess the distribution of costs and benefits of policy choices; and
- Assess the ancillary benefits of improving energy efficiency, such as reduced air pollution and productivity benefits.

Other goals are to

- Estimate (or at least define more clearly) sectoral and subsectoral (industry) costs, including assessments of consumers' surplus, i.e., the benefits that accrue to consumers who are willing to pay more than the market prices;
- Assess the interactive effects of various policies, one on another; and
- Assess the impacts of policies focused on one sector that spread to other sectors (e.g., impact of a policy affecting motor stock on the electricity supply sector).

The role of energy modeling in decision making and policy design has increased in recent years, especially in the debate on climate change and GHG emission mitigation. Simplistic models with limited technology representation are replaced with more complex models with more comprehensive representation of technology and economic feedbacks. Previously, engineering economic models focused on estimating the technical potential for cost-effective energy savings, whereas current models are challenged to better estimate what is achievable given behavioral and policy constraints. Policy modeling has focused on price-based and regulatory policies and is challenged to include nonprice policy instruments (18). The models need to build on interdisciplinary empirical analysis. The increased role of climate change in the energy debate also leads to the need to model a longer time horizon. This is exemplified through attempts to include technological change in models and the extension of scenario periods up to the year 2050. At the same time, policy makers need improved information at low aggregation levels to assess the distribution of costs and benefits across society.

Modeling Approaches

The so-called engineering economic (or bottom-up) approach is rooted in engineering principles that account for physical flows of energy capital equipment. This is coupled with economic information to account for energy expenses and investment that is processed through decision-making rules. The form of the decision making and the way to represent the activities vary among the various modeling approaches. Differences can be found with regard to the degree of activity representation, technology representation, and technology choice (stylistic or explicit), the goal (simulation or optimization), and degree of macroeconomic integration.

TABLE 2 Characterization of selected energy engineering models. The wide variety of models makes it impossible to include them all

Model	Country of origin	Technology representation	Goal of model	Macroeconomic integration
AMIGA[a]	United States	Explicit/stylistic	Equilibrium	Yes
CIMS	Canada	Explicit	Simulation	Yes
EERA	New Zealand	—	Simulation	No
EFOM	European Union	Explicit	Optimization	No
ENUSIM	United Kingdom	Explicit	Simulation	No
ENPEP	United States	Explicit/stylistic	Simulation	No
EPPA	United States	Stylistic	Equilibrium	Yes
ICARUS	Netherlands	Explicit	Simulation	No
IKARUS	Germany	Explicit	Optimization	Yes
ISTUM (ITEMS)	Canada/United States	Explicit	Simulation	No
LEAP	United States	Explicit/stylistic	Simulation	No
LIEF	United States	Stylistic	Simulation	No
MARKAL	OECD/IEA	Explicit	Optimization	No
MARKAL-MACRO	OECD/IEA	Explicit/stylistic	Optimization	Yes
NEMS	United States	Explicit/stylistic	Simulation	Yes

[a]Abbreviations used are AMIGA, All Modular Industry Growth Assessment; CIMS, Canadian Integrated Modeling System; EERA, Energy Efficiency Resource Assessment; EFOM, Energy Flow Optimisation Model; ENUSIM, Energy Simulation Model; ENPEP, Energy and Power Evaluation Program; EPPA, Emissions Prediction and Policy Analysis; ICARUS, Information System on Conservation and Application of Resources Using a Sector approach; IKARUS, Instrumente für Klimagas-Reduktionsstrategien; ISTUM, Industrial Sector Technology Use Model; LEAP, Long-range Energy Alternatives Planning System; LIEF, Long-term Industrial Energy Forecasting; MARKAL, Market Allocation; OECD, Organisation for Economic Co-operation and Development; IEA, International Energy Agency; and NEMS, National Energy Modeling System.

Explicit technology representation describes the actual characteristics of individual technologies. Stylistic technology representation captures the characteristics of a group of technologies through a mathematical function. The mathematical function may be derived from actual technologies represented by, for example, a supply curve. Table 2 provides a rough characterization of selected models.

One key distinction is the activity representation. To account for the differences across industries in the uses of energy and within industries for the structure of production, a simplification is employed to reduce complexity. For example, the Information System on Conservation and Application of Resources Using a Sector approach (ICARUS) model contains a lot of sector and technology detail, but it is basically a static model with exogenously assumed penetration rates. The level of activity representation varies in models, such as Energy and Power Evaluation Program (ENPEP) and Market Allocation (MARKAL), depending on the country and analysis group that are running the model. For example, the Los Alamos-U.S.

MARKAL model has 10 industrial subsectors and over 2400 technologies, although most of these technologies are not industrial. The National Energy Modeling System (NEMS) and Canadian Integrated Modelling System (CIMS) models include 12 subsectors. The Long-term Industrial Energy Forecasting model (LIEF) includes 18 manufacturing sectors. Generally, most models contain sufficient detail in the energy intensive industries and less detail for the light industries. Often, light industries are lumped together, and the technological detail is limited.

The second differentiating factor is that technology representation and technology choice are handled differently in engineering economic models. In the engineering economic framework, the model must allow for some mechanism through which choices about energy use are made. In the most generic form, the model accounts for economic conditions, such as energy prices, discount rates, and technological information, driving choices on energy-using equipment. The degree to which the technology information is explicitly modeled differs and can be a defining trait of the approach. Many models use explicitly modeled technologies (e.g., All Modular Industry Growth Assessment (AMIGA), Instrumente für Klimagas-Reduktionsstrategien (IKARUS), Industrial Sector Technology Use Model (ISTUM), and CIMS). Other models do not explicitly describe technologies but have a parametric description. For example, the LIEF model uses a set of conservation supply curves. Conservation supply curves (19) depict the relationship between cost-effective savings and energy prices for each industry. These curves are parameterized by the percent of energy use that could be reduced cost effectively in the base year and an elasticity parameter, showing how industry energy use changes in response to changes in energy prices. The values of these parameters are estimated from historical observations. For most sectors, NEMS models include explicit technologies, but for the industrial sector, NEMS has a stylistic representation of technologies, so cost-benefit analyses have to be done exogenous to the model.

Regardless of how technology is represented in the model, there are three factors that influence technology choice in the models. They include the following:

1. The state and availability of the current and emerging technology;
2. Economic costs, i.e., energy prices and equipment costs feed into technology choices as the model looks at life-cycle costs for various equipment choices; and
3. Operational decision rules, which are expressed as a rate at which an ideal energy intensity is approached, embedded in discount rates, or is reflected in the way cost calculations are done.

If these are the only "handles" available, energy technology choices can only be explicitly modeled as functions of energy prices, operating and maintenance costs, and capital costs. Although these directly affect energy technology choice, in reality, there are many other factors that influence the investment decision. Moreover, many of the socioeconomic decision variables addressed by nonmonetary policy instruments are not explicitly incorporated into decision rules but included in an aggregated representation of a penetration rate. The penetration rates are most often modeled exogenous to the model. Various approaches to modeling market variations and other intangibles are emerging, e.g., CIMS introduces monetized conditions to reflect these factors.

Third, models differ in their general modeling philosophy with regard to their ultimate goal and scope. *Optimization models* are used to find the optimal set of technology choices to achieve a specified target at the lowest costs. A well-known optimization model is MARKAL, although other linear-programming models are used as well. Sector and technology representation varies widely in the different MARKAL models used around the world. The MARKAL community (20) has started to include technical learning (for energy conversion technologies) in their models, as well as material flows (21), multiple greenhouse gases, and macroeconomic links. *Simulation models* provide a quantitative illustration of exogenously defined scenario strategies. Because of the technical and structural information incorporated, they allow evaluation of impacts and interrelations of different policies in a systematic manner. Cost information plays a central role, but strategies can follow other priorities (such as supply security). *Integrated models* (e.g., AMIGA, NEMS, MARKAL-MACRO, and CIMS) include the interaction between changes in energy use and the economy instead of using a preset economic development scenario. The modeling approach for the energy sector may be a simulation or optimization, i.e., either type of model above may be integrated into an overall economic model. The macroeconomic system is often designed on the basis of a general equilibrium model. The link to the economy helps to estimate the full costs and benefits of different scenarios.

Approaches to Address Barriers for Implementation

The implementation and transfer of energy-efficient technologies and practices is often hampered by barriers that slow their market penetration (5) or by the lack of sufficient incentives. Among the multitude of hindering factors, many barriers offer the opportunity to improve energy efficiency by removing or modifying these obstacles to the spread of technology, such as lack of information.

Barriers for energy efficiency improvement are generally not captured in the models. The movement toward considering these aspects contributes to the discussion of creating appropriate energy scenario definitions, but at the present time, there is little understanding of how to translate these factors quantitatively into the analytical framework. In some models (e.g., LIEF), it is argued that these factors are implicitly considered because they exist in the historical data or in an assumed high discount rate. This approach, however, is part of the problem itself. Decision parameters that used to be fixed through aggregated factors, such as hurdle rates or elasticities, are now target variables of policies. The scope for decision making and patterns of adoption behavior change over time, and historical data may be of limited value for an assessment of future developments—especially under changing policy conditions. The decision-making process around investment is not yet well understood, and further research to understand the mechanism and represent it in a modeling framework is needed. Moreover, a better understanding of mechanisms to reduce or overcome barriers helps to improve the design of policy tools and strategies as well as the methodological foundations of policy evaluation.

Approaches to Model Policies

Most models have historically addressed policy through addressing the implementation costs of measures for energy efficiency improvement. The relatively simple modeling approaches included the effect of subsidies and energy taxes on the costs and the degree of implementation. Some models have included the effect of research, development, and demonstration policies by including learning-by-doing curves for energy conversion technologies. The latter modeling approach has not yet been used extensively for energy-efficient technologies; however, CIMS has included this function in its modeling set and used it in its latest round of analyses assessing the cost of GHG-emission reduction for Canada. Endogenous (or induced) technological change has also been included in some of the more aggregate models. However, the extent of endogenous technological change and the policy impact on this change remains an emerging research area, and studies to date reflect an emerging, rather than comprehensive, understanding of the interactions between policy, technological change, and energy efficiency (22). This demonstrates the need for a better representation of the effects of energy efficiency policies (23). Comprehensive evaluations of energy efficiency policies are necessary to improve modeling approaches. Especially, modeling of new policy developments, such as voluntary programs and nonfiscal policies, remain a challenge for the energy modeling community (24). When they are modeled, models may mimic voluntary approaches by lowering the discount rate from the normal (based on hurdle rates or the literature on ex post analyses of discount) as an approximation for voluntary initiatives. This supposes that we can represent voluntary initiatives using economic criteria as the primary driver for decision making.

CHALLENGES AND REQUIREMENTS

The previous section discussed the issues that need further attention in the future development of engineering economic models. In this section, we outline the main challenges faced by modelers as well as the model requirements.

Challenges

SCENARIO CONSTRUCTION AND BASIC ASSUMPTIONS In scenario construction, the reference scenario assumptions are critical (10, 25). These include all major variables, including the level of activity (i.e., economic growth), structural effects, and assumptions, concerning technology availability and progress. The choice of available technology under business-as-usual (BAU) conditions is critical (25, 26).

In studies focusing on longer-term scenarios, the assumptions about technology development under future policy conditions are even more important.

Structural change has been recognized as another major driver for change in overall energy intensity (27). Structural change can be separated into intersectoral (e.g., a change to a larger fraction of light industry in the economy) and intrasectoral (e.g., a change in feedstocks without a substantial effect on product quality). Most energy modeling efforts start with an economic scenario that incorporates elements of intersector structural change for the reference scenario. Generally, the same structural development pattern is assumed for all policy scenarios, even when the modeled policy changes may have a profound effect on the energy system (such as long-term GHG concentration stabilization scenarios). Although this makes it possible to compare the results of the policy scenarios in a systematic way, it underestimates the flexibility of economic responses to important challenges to the energy and economic system (28) and, hence, may overestimate the costs of policy scenarios. This latter one can be, in part, compensated for by integration with an equilibrium model. But even an equilibrium model cannot forecast the appearance or development of new industries or sectors that may not exist today.

TECHNOLOGY AND OPPORTUNITY REPRESENTATION Modelers try to capture the achievable potential for energy efficiency improvement given the economic and policy assumptions of each scenario. Many engineering economic models start with a database of options and a selection of economic criteria to estimate the achievable potential under different scenario conditions. One challenge faced by many modelers is the time-intensive construction of a sufficient database of energy-efficient measures, and another is to combine this with a more sophisticated method to estimate the share of measures that is implemented under different scenario conditions. The selection to estimate the achievable potential, however, is often done in a simplified way using a discount rate, varying from a social discount rate to one that closely matches hurdle rates. This method over simplifies the complexity of investment decision-making behavior in industry because it does not account for market, institutional, and cultural barriers (5) that affect the achievable potential. The problem faced by modelers is that there are limited experience and empirical data on how to translate qualitative knowledge on decision-making behavior for energy efficiency into quantitative parameters (29, 30).

Industry uses energy in myriad ways, making end-use classifications more complex than in other sectors. Energy-consuming equipment may be industry specific, process specific, and even site specific, and crosscutting technologies, such as motors, vary widely in application, size, and output. It is therefore not easy to classify industrial energy use by service demand nor to group technologies or equipment that can provide the services. However, it is important to capture the differences in production in the analysis (31). Some studies build on very detailed and well-researched databases [e.g., IKARUS and Materials Technologies for Greenhouse Gas Emission Reduction (MATTER)]. CIMS, Los Alamos U.S. MARKAL, and, to a lesser extent, NEMS determine the level of services a major process technology would require and can supply the service from a separate service node. The service, for example, pumping, requires motor drive and picks it up from the motor node. Each node is subject to competition to provide the services.

Although cogeneration [Combined Heat and Power (CHP)] is recognized in many countries as an important energy efficiency option and is the subject of specific policies in many countries, often the integration of CHP in the models is limited. Sometimes, CHP is an afterthought because models first assume implementation of cost-effective end-use measures before evaluating the use of CHP. Other models did not allow expansion of CHP due to modeling structure and limitations. Modelers need to find ways to reflect that CHP investments compete with end-use measures in the economic evaluation.

The assumptions regarding the actual performance of existing capacity and stock turnover are of equal importance. Some industrial technologies have long economic and technical lifetimes. Because relatively large energy efficiency improvements can be achieved when existing capacity is replaced by new technology, the assumptions on lifetime, age distribution, and turnover rate are essential (32). In reality, this may result in nonlinear retirement patterns without a direct relationship with the age of the equipment. A conceptual problem here is that, in practice, the distinction between retrofit and replacement is not always clear. In long-term models (>50 years), it may be assumed that a large part of energy-consuming production equipment will be replaced over the modeling period.

Furthermore, market penetration patterns of energy-efficient technologies may not be as smooth as the typical S curve may suggest. Market penetration patterns may vary because of differences in potential adopter characteristics. Mutual dependency between technologies at individual plants, technical lock in, or path dependency may limit the uptake of a technology over a certain period. This also implies that critical mass effects accelerate the uptake of technology. A few studies have addressed the learning-by-doing effects by incorporating cost-development curves for power generation equipment (33–36). Speed of adoption estimates using diffusion models have been made (37, 38), but these have not yet made much impact on energy models.

ECONOMIC EVALUATION OF ENERGY-EFFICIENT TECHNOLOGIES Tied in closely to decision-making behavior is the economic evaluation of energy-efficient technologies. Most models do not include a full description of the costs and benefits of energy efficiency measures but rely on limited economic information, such as average energy prices and stylized technology costs (see Table 2). The energy modeling community has recently given more attention to the roles of transaction and opportunity costs as some of the factors explaining the differences in results of top-down and bottom-up models (39). Definitions of transaction costs, however, vary in the literature, and it often remains difficult to tie these transaction and opportunity costs to technologies. Transaction costs are likely to decrease owing to learning effects, growing knowledge, and policy measures.

On the other hand, one key factor, not usually captured by models, is the effect of the investment on the company's profitability. It is generally believed that most firms are capital constrained and do not have the internal resources, e.g., cash flow, to make investments even when payback periods are short (40–42). Ancillary benefits for the firm's productivity make energy efficiency investments a much better sell. Some technologies have benefits that include increased productivity, capacity utilization, and product quality, accompanied by the energy efficiency benefits (33, 44). As a consequence most engineering economic models do not fully account for the nonenergy benefits in the financial accounting, which contributes to a systematic underestimation of the economic potential.

Finally, it is difficult to represent external costs of energy use in models. Despite many fuel-cycle studies there is no clear direction whether and how to incorporate external costs in a model.

POLICY MODELING Representation of policies and policy impacts remains a challenge for the models. Most standard economic models simulate price-based policies. By definition, this limits the modeling of nonprice-based policies, which have been introduced in many industrialized countries over the past years. Policy impacts on energy-related decision making and barrier removal need to be analyzed and underline the importance of a sound representation of company behavior. In addition, several other issues are

- Special attention is needed for the modeling of R&D policies because R&D investments will likely lead to improved performance of existing and new technologies. For example, in the steel industry, scrap preheating dramatically reduces electricity use and is available for existing and new electric arc furnaces. Challenges are the link between (current) R&D expenditures and the speed of R&D progress as well as future technology availability and performance. Some modelers have tied the benefits of R&D policies into technical learning curves, but only for energy supply technologies. Comparable work on end-use technologies is still missing. Increased empirical analysis of R&D investments, technology, and management performance is essential to improve modeling of the relations.
- Economic feedbacks can impact the effectiveness of energy efficiency policy (27). Most studies of the rebound effect have focused on nonindustrial energy use and show a limited impact on the achieved savings. Recycling of energy tax revenue through tax relief in other areas is a relatively new phenomenon and used in a few taxation schemes in Europe. Revenue recycling can take various forms with different impacts. Models have difficulty in estimating the potential impacts of these feedbacks unless they have a detailed representation of the macroeconomy and taxation.
- In policy scenarios, the program costs are often not fully considered because data on the effectiveness and efficiency of industrial energy policies are difficult to find (23). The costs of classical policies, such as investment subsidies, were relatively easy to estimate, but this is more difficult for information dissemination programs or the new set of voluntary or negotiated agreements. Some studies (e.g., 25) have included an average estimate of program costs

> based on the evaluation of program costs of selected programs. The simultaneous and parallel implementation of different programs may increase the overall effectiveness through synergies but makes it difficult to evaluate and model individual programs.

Pandey (45) addresses the additional needs of energy policy modeling for developing countries. Pandey makes the case that the policy priorities in developing countries, existing barriers to technology diffusion, uncertainties in the policy regime, and other characteristics specific to developing countries make meaningful policy modeling in these countries even more difficult.

OVERALL CHALLENGES Foremost is the uncertainty in data and data quality. Cost cutting in statistical data collection on energy use patterns has resulted in higher aggregation levels for available information. This is especially unfortunate at times when the energy policy challenges are driving a need for detailed information on energy consumption and emission patterns. Although many studies acknowledge problems with data quality, there seems to be no systematic analysis of the impact of uncertainties on the scenario results other than of the costs of the policy scenarios. Another aspect of uncertainty is in the model structure itself, i.e., the decision algorithms of simulation models. If they are created using statistical analysis, then the statistical properties of the parameters provide measures of uncertainty. Uncertainty in modeling is also implemented in the optimization approaches as evidenced by the stochastic versions of MARKAL. The computational challenges often do limit the types of uncertainty that can be included.

The problems of data quality and data use in the model are also related to the transparency of the model. A transparent model makes it easy for the user and policy maker to evaluate and value the quality of the scenario results. However, the increasing complexity of the relationships between energy use, environment, and economy makes it difficult to maintain transparency. The trade-off between transparency and complexity remains essential to evaluate the results.

Typically, models focus on regions or countries, whereas a few integrated models include the global economy (subdivided in a varying number of regions). With the changing dynamics of energy policy the system boundaries of these studies may not be sufficient. For example, emission trading or the clean development mechanism under the Kyoto Protocol will likely affect the costs of emission reduction for different regions, as demonstrated by many models.[1] Still, energy efficiency policy may only affect a specific region, and hence the user/policy maker may only be interested in the specific country or region for the assessment.

---

[1]It should be noted, that often the reduction in emission mitigation costs due to (international) emission trade or other flexible mechanisms, as defined under the Kyoto Protocol, is the result of simplified or uncertain assumptions on the costs of emission reduction opportunities in the other regions.

Directions/Issues in Modeling

In this section we focus on the main issues that need further attention in modeling efforts. We discuss the state-of-the-art models as well as promising directions taken by various modelers.

TECHNOLOGICAL FLEXIBILITY Early energy models estimate the costs of GHG emission reductions to be quite high. Often this was the result of a limited menu of technology options included in the models or the reliance on a (expensive) backstop technology. Edmonds et al. (46) demonstrated the importance of good representation of technology in models to estimate the potential of GHG emission reduction and the costs. Roop & Dahowski (26) used a model with a rich technology representation to assess the Annual Energy Outlook 2000 baseline scenario developed by the U.S. Energy Information Administration. They found that a technology-rich model produced a baseline scenario with lower energy use.

TECHNICAL LEARNING Several groups have started to incorporate mechanisms to simulate changes in technology performance as a function of development and deployment (47, 48). However, most engineering economic models have a static representation of technology, i.e., the costs of a technology do not change over the modeling period. Some studies (e.g., 48, 49) tried to address this by using exogenous assumptions for technology parameters based on expectations of future technology performance changes because of R&D and learning by doing effects. The notion of induced (endogenous) technical change, i.e., the response of technology performance to changing market and policy environments, is important. Different groups have tried to capture endogenous technological change in models (46, 50, 51). MARKAL modelers in the United States and Switzerland (52) have used a progress-ratio function to estimate the impact of increased production volumes on costs of renewable energy technologies.[2] Like MARKAL, CIMS uses a progress ratio to reduce the costs of new or upcoming technologies on the basis of their market penetration (53). Newell & Jaffe (54) provide an analysis focusing on residential energy technology. The assumed progress ratio is critical. Recent International Energy Agency reports (55, 56) found that only a few measurements of experience curves for energy technologies are publicly recorded, and those are concentrated in a few supply technologies. Laitner & Sanstad (57) demonstrated significantly different results when learning was limited to supply-side technologies compared to scenarios that included learning for both end-use and supply-side technologies. Although, experience curve studies of manufacturing sectors are numerous (e.g., 43, 59–64), none are related to energy-efficient technologies in industry. Some empirical work on price-induced change in industry

[2]The use of progress ratios or learning curves is especially important for modular technologies, such as renewable energy technologies and many energy efficiency technologies, in which mass production is an important factor in bringing down the costs.

is emerging. Celikkol & Stefanou (58) examined induced change in the food processing industry, but not for energy efficiency.

Zwaan et al. (51) incorporated endogenous technological change as a function of cumulative capacity and showed that this reduced the costs for CO_2 emission reduction considerably. Similarly, R&D is supposed to lead to reduced costs and improved performance of technology. R&D is generally seen as an investment with a high payback (65), but the risk of incomplete appropriation of the benefits leads to underinvestment in R&D (66). Although some modelers assume certain cost reductions or performance improvement, the modeling of R&D policies and effects is still uncharted territory (46). Goulder & Schneider (67) as well as Messner (68) have tried to include the effects of R&D in their model calculations by assuming a certain cost reduction as a function of public and private R&D investments. Few case studies exist of the development of industrial technologies and the assessment of R&D investments on technology performance (69). Similarly, studies (70, 71) that assess future technologies, their performance, and costs are needed.

MATERIAL FLOWS Product and material demand are the important drivers for industrial energy use. So far, these interrelations are often predetermined through scenario definition, limiting the system's flexibility to respond. Modelers have tried to incorporate the material system in energy models to include changes in material flows in the development of policy scenarios. The strong interaction between climate change, energy use, and materials use will likely drive climate change policy development to include materials in the set of policy instruments. Pioneered by groups in Canada and the Netherlands, several MARKAL models are available that include a representation of the materials system (in some form) (72). Generally, the models demonstrate that including material efficiency options in the models will lead to reduced costs of GHG emission reduction and increased potential. This corresponds to a form of economic flexibility that changes the characteristics of the product mix and economic structure of industry in response to policy changes.

ECONOMIC FLEXIBILITY In almost all studies, the model work starts from a reference scenario. The reference scenario assumes a certain economic development with a given structure. Policy scenarios are developed to achieve the same economic development pattern. However, assuming that climate change will have a profound effect on the future of the energy system and the related fundamental energy price patterns, society is likely to change economic development toward different paths. Jorgenson et al. (28) modeled the opportunities for substitution between economic sectors to provide a given level of welfare to simulate economic responsiveness of society. As a result of including the flexibility, they found that the costs for GHG emission reduction decreased compared to a scenario that assumed a rigid economic development path.

DISCOUNT RATES AND HURDLE RATES Discount rates are used in engineering economic models to reflect the (risk) preferences of consumers or society when evaluating (energy efficiency) investments. Typically, earlier engineering economic models used social discount rates (e.g., 4% to 8%) in the studies. The choice of discount rate depends on the approach (prescriptive versus descriptive) used. A prescriptive approach typically uses lower discount rates, especially for long-term issues like climate change. Lower discount rates (4% to 8%) may also be used to appraise public sector projects. A descriptive approach uses relatively high rates (5). Other studies use a descriptive approach by using discount rates between 10% and 30%. Howarth & Sanstad (73) have challenged the common belief of economists that high discount rates reflect a rational evaluation of risk associated with an investment and of efficient markets. Instead, the use of high discount rates may be a function of asymmetric information, bounded rationality, and transaction costs. As such, it is reasonable to assume that efficient policies may affect the implicit discount rate used by consumers. For example, the LIEF model (74) allows change in the capital recovery factor used by the model, which is a reflection of the used discount (or hurdle) rate, to mimic the effect of reduced barriers.

PROGRAM COST ESTIMATES The program costs may be an important variable in policy analysis. Program costs may vary widely, depending on the type of program, the success rate, and the efficiency with which it is administered. The Clean Energy Futures study (25) uses the average specific (administrative) program costs (i.e., dollars/unit of energy saved), based on a small number of policy evaluations. This average is used to estimate all program costs. It would be desirable to be able to estimate program costs for different types of policy programs or instruments to get a better understanding of the cost-effectiveness of policy measures (75). However, it is hard to estimate these costs on a disaggregated basis owing to a lack of evaluations, especially for industry.

INTEGRATION WITH ECONOMIC SYSTEM (EQUILIBRIUM OR PARTIAL EQUILIBRIUM) The desire to integrate engineering economic models into a macroeconomic forecasting model has important implications for policy modeling. This integration has been conducted at varying levels of detail, and the manner in which this integration occurs is under examination (76, 77). NEMS, MARKAL-MACRO, and more recently Netherlands Energy Demand Model (NEMO) and AMIGA all approach the integration in different ways. NEMS uses various engineering economic submodules within a detailed energy market partial equilibrium, which is embedded in a macroeconomic response surface model. The response surface model is derived from a more detailed commercially available econometric macromodel. MARKAL-MACRO combines a detailed energy optimization model with a neoclassical growth model. NEMO (78) uses ICARUS data to parameterize a simple computable general equilibrium model. AMIGA is a computable general equilibrium model, but it has a very high degree of sectoral and technology detail (79, 80). The more recent approaches to integration directly incorporate technology models into the equilibrium framework, rather than merge preexisting technology and economic system models.

Stochastic models Engineering economic models may treat costs and energy savings as known, but they may also be viewed as unknown, random variables. Howarth & Andersson (81) illustrate how uncertainty in the form of imperfect information regarding the performance of a technology results in suboptimal adoption. Models may represent this uncertainty regarding technology adoption explicitly with Monte Carlo simulations or with probability based diffusion models. Stochastic behavior reflected in the difference in costs and/or characteristics of adopter is conveniently modeled by discrete choice models. ENPEP, Industrial Technology and Energy Modeling System (ITEMS), CIMS, and ISTUM all use a logit function to apply market shares. Discrete choice models do not model the underlying process, but only the outcome. More direct treatments of stochastic costs can be implemented in optimization models such as MARKAL, but with substantial computational challenges. Option value models that account for uncertain future outcomes have been proposed as a justification for high discount rates, but detailed models or studies have been few and conclusions are mixed (73). Explicit treatment of uncertainty would substantially improve realism in engineering economic models.

Frontier production function models Many engineering economic models summarize the detailed technology information in the form of conservation supply curves (CSC). A CSC can be derived from parametric frontier production functions as a conditional factor of demand (82–84). The LIEF model can be viewed in this context because its CSCs are parametric. This approach reduces the burden imposed by collection of technology specific data and has the benefit of implicitly incorporating nonenergy benefits. However, the authors are not aware of any empirical CSCs derived from frontier production functions.

INCLUDING DIFFERENT DISCIPLINES IN MODELING Scientific disciplines look differently at complex problems, such as energy modeling. For example, although an engineer understands technology as being hardware, an economist typically sees technology as part of a mathematical production function. More and more, multidisciplinary teams are used in designing models, and scientific results from different disciplines are used in modeling. There are still many lessons to be learned from the varied disciplines, which include the following:

- Social psychology investigates individual behavior and the underlying determinants of action, including values, attitudes, and norms (85, 86). Together with empirical experience from *social marketing initiatives* that aim at influencing these parameters, results on individual preferences and decisions can be expected that may challenge traditional assumptions on economic behavior and technology transfer (87). Moreover, the same actor appears several times (e.g., as employee and driver or household member) in a model of the energy system, and the actors are subject to various policy interventions.
- Management science and organizational research have accumulated considerable knowledge on change processes in companies and institutions (88–91). For energy modeling, the impact of improved management skills on the rate of technology adoption is of special importance. In this regard, many positive synergies and benefits can be found between competitiveness, economic

performance, innovation strength, and ecological performance. This field has embraced the frontier production function framework for measuring efficiency. One principle tool developed in this literature is Data Envelopment Analysis (92).

- Marketing research offers know-how on possibilities and restrictions for opening up markets. This can contribute to a more appropriate segmentation of target groups or modeling market transformation processes.
- Innovation and diffusion research analyzes the conditions for the generation and diffusion of new solutions that model penetration rates more realistically (93). Related to this, *technology foresight studies* provide methodologies and information on how to assess future technology options that play an important role in long-term scenario analyses (e.g., 70, 71).
- Bayesian economics is now applied to technology choice and learning, market leaders, and imitators (94, 95). Insights into market structure and productivity behavior could generate new directions for energy modeling. The CIMS model tries to include Bayesian economic principles in the model structure.
- Evolutionary economics in the tradition of Nelson (65) and related work in systems theory/systems analysis provide insight into dynamic processes within complex nondeterministic systems (96). Putting special emphasis on the time dependency of developments, the work on technological trajectories and path dependency, for example, provides an understanding of the constraints for technical progress and structural change in industrial systems (97, 98).
- Agent-based model (ABM) simulations have emerged as important new social science and economics simulation tools to investigate the behavior of complex adaptive systems. By simulation, the behavior and interaction of individual agents provides insight into the behavior of organizations, and the associated implications for technology adoption and integrated assessments are revealed (99, 100). ABMs have been developed to study the U.K. (101) and the U.S. (102) deregulated electric markets, and there are also ABMs for natural gas markets and infrastructure interdependencies (102, 103).

PATHWAYS

Although the current work on models and methodologies offers some interesting results, practical advances in engineering economic modeling still remain. In this section, we identify and distill the directions and trends that can enhance the contribution of engineering economic models to energy analysis in order to meet the challenges depicted in the previous section (see Table 3). The diversity of challenges can be condensed to two problems.

- The first is the complex, dynamic nature of decision-making behavior, the related transformation effects in the market systems, as well as the impact of policy on the behavior.

TABLE 3 Matrix of challenges, recent advances in modeling and remaining open questions[a]

New approaches from research	**Enhanced technological flexibility**	**Endogenous technical learning**	**Incorporation of material flows**	**Enhanced economic flexibility**	**Adaptation of discount/ hurdle rates**	**Estimation of program costs**	**Macro-economic integration**	**Integration of stochastic elements**	**Integration of other disciplines**	***Open issues***
Challenges to modeling: scenario construction and basic assumptions										
Definition of business as usual		+	+	++					+	How much change/ flexibility is already in scenario?
Choice of available technology	++	++	+							What is the future set of options?
Representation of structural change	+		++	++			+		+	What are the drivers, trends, directions, and interdependencies?
Technology and opportunity representation										
Degree of technology specification	++		++							What degree is appropriate?
Cogeneration	+		+							How to give a complete picture of a business practice?
Market and institutional barriers	+	+	+		+				+	How do market actors interact?
Socioeconomic barriers	+	+			+				++	Why, when, and under what conditions is behavior changed?
Assumptions about actual performance	+	+			+			+	+	Actual treatment of technologies in business practice?

(*Continued*)

Market penetration patterns	+	+			+			+	How to aggregate individual adoption behavior?
Definition of costs and benefits	+	+	+	+	++			+	Nature, dimension, and persistence of costs/ benefits?
Representation of policies and instruments									
Barrier related instruments	+	+			+	+		++	What are the impacts, synergies, and persistence of effects?
Research & development	+	++	+	+	+	+		+	What are impacts, synergies, and persistence of effects?
Economic feedbacks		+	+	++	+	+	+	+	Role of energy efficiency as a source of economic change?
Program costs		+			+	++		+	Nature, dimension, and persistence of costs/benefits?
General aspects									
Data uncertainty	+		−		−	+	+		Scope and limits for better data?
Transparency	−	−	−	−	−				Trade-off between accuracy, complexity and simplification?
System boundaries	−		−				+		Appropriate choice of questions and tools?
Open issues	Treatment of technical complexity	Learning with energy efficient technologies	Modeling material flows		Representing economic behavior	Evaluation methodology		Transfer of knowledge	

[a]The meanings of the symbols used are as follows: +, a potential contribution; ++, a direct contribution; −, a problem or possible negative effect.

- The second is coping with the technical diversity and complexity of the industrial production system.

With regard to both challenges, new modeling approaches can mitigate existing deficiencies of economic-engineering modeling but cannot fully overcome conceptual limitations of modeling per se. Given this perspective, models will hardly be able to fully cover all relevant aspects of industrial energy policy, and important missing parameters need to be addressed by other tools. Accordingly, policy analysis needs to be grounded on a kind of heuristic competence that allows it to master a methodological diversity of tools with a limited scope (a network/cluster of micromodels) rather than striving toward even bigger megamodels that aim at integrating as many dimensions as possible. Moreover, the analysis process, the development of parameters, the application of the models, and the analysis of results, is at least as important as the models. Hence, the models need to be explicitly embedded in a more comprehensive analytical strategy that recognizes the limitations, strengths, and weaknesses of the tools. Two aspects are important for such a strategy.

- Sound specification of modeling tasks and system boundaries is required, i.e., an appropriate choice of analytical questions in relation to the capability of a modeling tool. Usually, models aim at a broad coverage of the economy to provide a framework for a broader policy debate. Given that the quality of sector representation differs significantly, an assessment of single policy instruments may lead to distorted results in such a model. A sound specification of policy questions and analytical tasks and the choice of a suitable modeling tool and its systems boundary are needed.
- Data quality is an essential element in any model. In certain areas, it is needed to develop the statistical foundation of modeling. At the same time, however, it has to be acknowledged that perfect data sets cannot be achieved. Given existing budget constraints, efforts need to concentrate on crucial areas. Empirical work should aim to accurately study and quantify the parameters that are of greatest relevance to sensitivity analysis. This will identify possible biases and prevent systematic over- and underestimation of parameters. Examples of such sensitive parameters are variables affecting the flexibility of policies and the representation of emerging technologies. Still, it will not be possible to reduce all uncertainties (104), and hence, presentation of modeling results that acknowledge the uncertainties is essential.

Better Use of Models in Policy Analysis

A critical assessment of the models, both by the modelers and the users of the results, will underline that not one single model is sufficiently equipped to answer all policy questions. Instead, modelers and users should try to jointly find ways to develop the right tools to answer the questions being asked. The development of new modeling approaches starts with a critical assessment of the policy needs and the impacts of these needs on the modeling tools. Also, the scenario design or definition of the policy background in the model is an essential starting point for each modeling exercise. The lessons learned of an improved interface between user and modeler include the following:

- The choice of an appropriate model structure and careful analysis of inputs and assumptions are essential. Focus on the interfaces of appropriate inputs, assumptions, and model structure, instead on the model itself. Model assumptions are often more important than the structure.
- There should be less emphasis on normative approaches in terms of optimization, owing to a relatively weak foundation for a strong message. Optimization model results are often based on the result of uncertain assumptions and inputs.
- More emphasis on simulation through quantitative assessment of impacts and interdependencies is required. Thorough analysis of diffusion patterns and policies will provide improved inputs for models and better simulate the effects of policies.
- Improved modeling of interaction mechanisms between scenario development and technology is needed. Policy scenarios reflect not only changes in energy demand and supply but also changes in the relationships with other scenario parameters. Increased energy efficiency policies driven by environmental concerns, for example, will affect purchases and production patterns and change development in directions other than BAU scenarios.
- Focus should not only be on the technical aspects of model improvement. A greater investment is needed in efforts to strengthen the "interpretative intelligence" of models through increased transparency and by relating results to questions, inputs, and assumptions.
- A multidisciplinary view of technology and its implementation mechanism in modeling will improve understanding of technology diffusion patterns and, hence, of the role that policy plays in shaping energy use.
- A more dynamic representation of technology, with an emphasis on technological learning and the side effects of technology, is another reflection of the policy environment of the scenarios assumed.

Improving Models

The results from new research fields will hardly fit directly into existing models. Moreover, adding more and more information to the models deteriorates the transparency, underlining the need for targeted exercises, e.g., based on micromodels suited to answer specific questions. The results of the different micromodels can be used to improve larger macromodels or integrated in megamodels using innovative computing techniques. Below, we discuss three pathways to improve modeling efforts.

TECHNOLOGY AND OPPORTUNITY REPRESENTATION To make better use of the technical diversity in industrial production models, a suggested research agenda includes

- Conducting empirical studies that investigate technical and economic aspects of energy efficiency to provide data to improve modeling assumptions and improve the basis for estimating more realistic model parameters;
- Emphasizing crosscutting technologies of rising importance that have been neglected so far;
- Including technological learning effects on the performance, costs, and diffusion of industrial energy technologies;
- Using detailed modeling of production functions to study the role of structural change within the economy, including the economic flexibility to respond to policy challenges; and
- Improving understanding of the assumptions in the reference scenario.

Current advances in research that hold particular promise in this area include incorporation of material flows, enhanced economic flexibility, learning effects, and integration of stochastic elements.

More transparent modeling techniques can allow the user a clear understanding of the modeling and technology assumptions. New computer techniques, for example object-oriented programming, may help improve the modularity of the model but still build on a clear understanding by the user of the limitations of the model and its assumptions (e.g., lack of opportunities, bad representation, and interrelations in the model). By designing a common framework for energy modeling, a language for linking micromodels can be developed. Such a framework could allow salvaging elements of existing models. These computing techniques have yet to be successfully implemented for energy efficiency models.

The energy-materials link Although physical production flows are often used implicitly to model technology, the explicit modeling of physical production allows for a more transparent analysis of the assumptions for technology and scenarios, including structural change (e.g., increased recycling and impact on primary resource consumption). Linking energy use with material flows, i.e., integrating assumptions on physical production levels, structural change effects, and related policy measures (such as recycling quota), will allow improved interaction between technology, scenario, and policy assumptions. In turn, the impact of energy policy strategies on material consumption and structural change effects needs to be investigated. All in all, such an integration of dimensions reflects the importance of integrated policy approaches that bridge the traditional separations between policy areas and administrative responsibilities.

Functional categorization of technologies In principle, models will benefit from more detailed information on technologies. As discussed, technology-rich models often provide different results than models with poor technology representation.

However, given the complexity of many models, there are clear practical and financial limits to incorporating a vast amount of technical information. To resolve this dilemma, more emphasis on smart categorization of technologies and target groups (i.e., users) can direct scarce resources to areas of particular importance. This will result in appropriate criteria and features for building typologies of technologies and opportunities that can be handled within modeling exercises. The challenges are to go beyond traditional sector definitions derived from statistical sector categorization and to shed light on policy-relevant distinctions, e.g., in terms of impact mechanisms and driving factors. The focus should be less on the richness of the technology options and more on qualities of those technologies and their potential to effect future energy use. For example, crosscutting technologies (e.g., a motor) are often selected and installed under different conditions than process-specific technologies (e.g., a distillation tower). Strategic investments, such as CHP, are evaluated differently than auxiliaries. However, in current models, technology choice and competition are often represented in a similar way, leading to potential misrepresentation of the role of technologies and the prospects for change. The technology groups must be established exogenous to the model on the basis of detailed policy-relevant technology assessments. For example, the Canadian iron and steel industry says it will never build a coke-based steel mill again. All future mills producing steel from ore will use direct reduced-iron processes. Others will focus on recycling and the use of electric arc mills. This suggests that a policy-relevant model (at least for the Canadian steel industry) should have only short lists of coke-based steel producing technologies, even though this is currently a significant energy consumer.

Multiple technology benefits Owing to the importance of cost information for modeling, sound definitions and comprehensive representations of cost variables are needed. Traditional flaws of current models include insufficient specification of cost-benefit ratios of energy-saving technologies, overlooking the multiple benefits of a technology, and biasing the representation of the economic performance of technology. Although discussed for years (44), this aspect has hardly been considered in models. Empirical work is needed to investigate the nature and dimension of the broad range of synergetic benefits of energy-efficient technology. The same holds for changes in energy management practice that may lead to better business performance, e.g., through higher motivation and better quality control.

Transaction and opportunity costs Engineering economic models are often criticized for the underestimation of transaction and opportunity costs. A thorough analysis of transaction costs and adoption of a common terminology will result in an improved model. A better understanding of opportunity and transaction costs may help explain the varied results of different models.

Learning curves of energy-efficient technology There is a strong need to account for learning effects in end-use energy-efficient technology modeling. New information is needed to get a realistic estimate of the future costs as well as an estimate of the trajectories of technical progress. Although there is an extensive body of literature on learning effects for energy supply technologies, empirical studies are specifically needed for end-use equipment.

BEHAVIORAL REPRESENTATION With regard to the behavior of decision makers and the development of markets, more insight is needed from (*a*) qualitative and quantitative studies on decision behavior, (*b*) the sociocultural background that determines the effectiveness of instruments and (*c*) improved understanding of technology diffusion and penetration patterns as a function of firm behavior. Advances in research to improve the understanding of decision-making behavior in firms, and modeling thereof, adaptation of discount rates and hurdle rates, analysis of technology diffusion patterns, evaluation of energy efficiency and other policies on technology diffusion, evaluation of the effectiveness and efficiency of energy policies, as well as estimating program costs contribute to this pathway.

Basic understanding of investment situation Energy models tend to describe the decision to invest in energy-efficient technology primarily as a choice driven by energy cost savings and financial gain. In reality, however, there is a permanent turnover of production equipment, i.e., the technology stock is already in motion. For the most part, investment decisions are mainly the result of technical reasons, market prospects, and productivity gains. With regard to energy efficiency, the question is often not whether to invest or not but what version of technology to choose (standard versus high efficiency). Developing a more dynamic understanding of decision-making behavior is likely to better model the direction of an investment decision toward a more energy-efficient alternative.

The diversity of socioeconomic interactions that determine corporate behavior should be condensed into a set of model parameters. This translation, however, must not distort the dynamics of real processes that take place in company social systems. Attention must be given to the representation of change in behavior through the spread of information, evolution of awareness, and organizational learning. New approaches must be found to model the parameters that describe the adoption of technologies by a company, considering the economic, social, and political context. At the same time, we acknowledge that any quantitative simulation of firm behavior is very difficult (105).

Diffusion processes A better understanding of the diffusion of innovations over time is needed. Starting from the rich body of innovation research (93), different methodologies have been developed to study the diffusion patterns of technology. Even if these achievements appear to be insufficient, most energy models do not include state-of-the-art features. To better model the impact of policy on diffusion processes, we need better knowledge concerning the interaction between policy incentives and the process of technology adoption (see below). Better understanding of the diffusion patterns is directly related to the discussions above, which recommend improvements in the characterization of technology by categorizing the technologies into functional groups.

POLICY REPRESENTATION A sufficient representation of policies and instruments demands a proper definition of policy instruments and a sound analysis of the features of policy implementation, including the following:

Realistic representation of the practice of implementation In energy models, policy instruments tend to be described in an idealistic, textbook-like manner. Real implementation practice, however, can vary significantly from the theoretical concept. In addition, the same instrument can work differently under different circumstances or with other target groups. Empirical research is needed to provide background information for the development of improved modeling assumptions on policy instruments and on their effectiveness.

Policy and program effects Research is needed to derive indicators concerning the degree of impact (i.e., to what extent are the target groups affected by the measure) and the response time, (i.e., the time lag between the policy intervention and the time when results can be observed). The last aspect may include a "cumulative impact curve" to represent the acceleration and accumulated dissemination of energy efficiency improvement because of a policy change. The typology of policy instruments is determined on the basis of different intervention modes and moments in the typical S-curve technology diffusion. This will also model nonmonetary policies.

Program costs To assess strategies for climate change abatement, better data on policy effectiveness and efficiency is needed. Generally, there is a lack of evaluation of (industrial) energy policies. This is a promising area for empirical research and should also include side effects (i.e., programs can suffer from a free-rider effect but can also have positive spillover effects).

Assessment of policy mixes In reality, programs are not implemented in isolation but as part of a larger set of policies and programs. The effect of single instruments within a portfolio cannot simply be added. Synergetic effects may improve the efficiency and effectiveness of one policy instrument or program, whereas other policy developments may reduce the effectiveness. On the basis of a series of empirical studies, it is important to better understand the synergies between programs to advance the modeling of policy mixes.

Representation of nonenergy policy background in scenario definition Most energy modeling efforts focus on energy policies, yet other policies will affect energy use patterns and diffusion of energy-efficient technologies. We need a more comprehensive representation of the policy landscape in which industry and energy policy is placed. Energy models tend to link investments to energy alone, and many other policies are not included. In reality, energy may play a minor role for strategic investments. Therefore, for example, the general investment-friendliness of the nonenergy scenario setting needs more attention because it is a major parameter for industry's response flexibility. The same holds for environmental requirements as a driver for replacement of older polluting (and often energy inefficient) technologies. Environmental (and regulatory) side benefits are also an important aspect of the model.

CONCLUSIONS AND RECOMMENDATIONS

The discussion of challenges and new requirements to engineering economic modeling revealed a fundamental shift needed in research priorities. In the past, models have been constructed principally as forecasting tools focused on energy market questions of what quantity and type of energy will be consumed in the future. Having origins in the economics of resource depletion and having grown in substantial use after the oil price shocks of the seventies, these models have price (costs) as their principle drivers. However, nonmonetary policies are becoming more and more important in the current policy debate. Formerly static parameters turn into policy variables that should change over time. Conventional modeling approaches designed for different tasks appear to be ill equipped to serve the new demand of policy analysis. At the same time, we acknowledge that models remain limited in scope and analytical power. Rather than aiming at a silver bullet, it appears to be more fruitful to strengthen the overarching framework of policy analysis in which models designed for specific tasks are placed.

Research Priorities

The development of a uniform but public modeling framework to integrate existing and future modules and models would be a major step forward. Similar to an open software development environment, it would allow for innovation in different parts (e.g., policy modeling) of the total model and allow easy integration in existing models. We propose to base this framework on object-oriented programming and modeling, allowing transparency and flexibility in modeling approaches. Research should determine a common structure and the information needed to facilitate communication between the different objects (or modules). At the same time, interaction with policy analysis can be strengthened by better linking specific modeling exercises with related research.

Technology representation has shown to be a key area in which short-term efforts can make an important impact. At issue are the full nature and the dynamics of the technology, including (*a*) nonenergy benefits in the quantitative description of a technology, (*b*) research in the learning effect of energy-efficient end-use technologies to accurately reflect the dynamics of technology development, (*c*) the level of disaggregation, and (*d*) smart categorization of technologies and target groups. With an increase in the number of technologies, there is increased need to derive appropriate criteria and features for technology typologies that can be handled by the models.

Research should aim to improve the understanding of the diffusion of technologies to better link technologies to the decision making and implementation trajectory. Current models apply a similar diffusion model to most energy-efficient technologies. In reality, other benefits than energy may drive implementation. This is linked to a proper quantification of the nonenergy benefits, but it is also linked to other nonenergy related regulation that may affect implementation of a specific technology. Improved understanding should lead to categories or groups of technologies with specific characteristics, allowing improved modeling of technology diffusion.

As the counterpart to the assessment of efficiency options, there is a need for policy evaluation of the effectiveness and efficiency of policy instruments. Full policy evaluations are rare in the field of industrial energy policy. Innovative ways are needed to translate the impact of policies on the micro- (or firm-) level to macrolevels of the technology diffusion process. It is important to account for synergies or unintended consequences of energy policy mixes and other policies. The efficiency of a policy instrument has to include the costs of implementing a policy (instrument) and potential synergies or rebound effects. This item is a plea to policy makers to include policy evaluation as an integral part of new policy development.

New modeling approaches for the decision-making framework (or behavioral representation) and process are needed that can be used in the economic-engineering models. These approaches need to include barrier representation (e.g., lack of information), decision-making behavior, as well as the effect of policies. The impact of nonmonetary policies and policies aiming to reduce barriers are especially important. Such modeling approaches need to translate behavior of individual firms to the larger model and economy. Innovative economic research may offer different potentially successful approaches, and the contribution of social sciences in the debate on firm behavior is needed to develop successful modeling approaches.

Short Term Collaborative Projects

On the basis of the research priorities and modeling directions discussed above, we identified three major areas in which collaborative projects are essential to warrant successful development of a commonly accepted modeling approach. The three areas focus on the modeling framework, technology representation, and policy evaluation. We stress that the projects should be the result of an international and multidisciplinary collaboration.

The framework should include the different modules, communication between modules, as well as outputs. It should allow for transparency and flexibility. An interdisciplinary workshop of key people is the preferred start for developing the framework.

Technology representation needs international and interdisciplinary collaboration on technology representation, typologies to categorize technologies (e.g., implementation trajectories and characteristics), the building and maintance of databases on technologies, and the assessment of emerging technologies. The International Energy Agency (IEA) has led an effort to improve the understanding of experience curves for energy supply technologies. A similar effort is urgently needed for demand-side technologies.

We have stressed the lack of policy evaluations, which are essential to improve modeling of policies and policy impacts. Several workshops have been organized in this area, but generally there is lack of attention for policy evaluation in the design and implementation of energy policies. Besides refinement of methods and increased attention and discussion among analysts, there is a strong need for increased attention on the policy front. This is a key area where a concerted effort by international agencies is essential for success.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and W-31-109-Eng-38. The review does not necessarily reflect the opinion of the U.S. Department of Energy or any other U.S. government agency. This review is based on an earlier contribution invited by the professional network for Engineering Economic Technology Analysis (EETA), and a summary presented at the 2003 ACEEE Summer Study on Energy Efficiency in Industry. EETA is coordinated by the IEA. EETA is a multidisciplinary worldwide network of professionals who use engineering economic analysis to investigate energy and climate change technologies and policies. EETA aims to improve the quality, relevance, and visibility of engineering economic assessments for energy and climate change policy making. Currently, representatives from over 20 leading institutions from around the world actively participate in EETA. The authors were chosen to represent a varied background in the economic, technical, and social sciences. Modelers represented in EETA have reviewed an earlier draft. A draft of this paper was reviewed by Kornelis Blok (Utrecht University, The Netherlands), Richard Cirillo (Argonne National Laboratory, United States), Jeff Dowd (U.S. Department of Energy), Ken Friedman (U.S. Department of Energy), Lorna Greening (New Mexico, United States), Susan Holte (U.S. Department of Energy), Skip Laitner (U.S. Environmental Protection Agency), John Nyboer (Simon Fraser University, Canada), Joe Roop (Pacific Northwest National Laboratory, United States), Leo Schrattenholzer (International Institute for Applied Systems Analysis, Austria), and Fridtjof Unander (IEA, France). Despite their efforts, the authors are solely responsible for any remaining errors.

LITERATURE CITED

1. Craig PP, Gadgil A, Koomey JG. 2002. What can history teach us? A retrospective examination of long-term energy forecasts for the United States. *Annu. Rev. Energy Environ.* 27:83–118
2. Zhang ZX, Folmer H. 1998. Economic modeling approaches to cost estimates for the control of carbon dioxide emissions. *Energy Econ.* 20:101–20
3. Laitner JA, DeCanio SJ, Koomey JG,

Sanstad AH. 2003. Room for improvement: increasing the value of energy modeling for policy analysis. *Util. Policy* 11:87–94
4. DeCanio SJ. 2003. *Economic Models of Climate Change—A Critique*. New York, NY: Palgrave Macmillan
5. Intergov. Panel Clim. Change. 2001. *Climate Change 2001: Mitigation*. Cambridge, UK: Cambridge Univ. Press
6. Bertoldi P. 1999. The use of long-term agreements to improve energy efficiency in the industrial sector: overview of the European experiences and proposal for a common framework. In *Proc. 1999 Am. Council Energy-Efficient Econ. Summer Study Energy Effic. Ind.* pp. 287–98. Washington, DC: Am. Council Energy-Efficient Econ.
7. Börkey P, Lévêque F. 1998. *Voluntary approaches for environmental protection in the European Union.* OECD Work. Doc. ENV/EPOC/GEEI(98)29/Final, Organ. Econ. Co-op. Dev., Paris, Fr.
8. Chidiak M. 1999. Voluntary agreements for energy efficiency in five EU countries. In *Proc. 1999 European Council for an Energy-Efficient Economy Summer Study*, May 31–June 4, Mandelieu, Fr.
9. Hansen K, Larsen A. 1999. Voluntary agreements in industry: a comparative description of the process and a normative analysis. *Proc. 1999 Am. Council Energy-Efficient Econ. Summer Study Energy Effic. Ind.* pp. 311–24. Washington, DC: Am. Council Energy-Efficient Econ.
10. Krarup S, Ramesohl S. 2000. *Voluntary Agreements in Energy Policy—Implementation and Efficiency: Final Report*. Inst. Local Gov. Studies (AKF), Copenhagen, Den.
11. Mazurek J, Lehman B. 1999. Monitoring and verification of long-term voluntary approaches in the industrial sector: an initial survey. *Proc. 1999 Am. Council Energy-Efficient Econ. Summer Study Energy Effic. Ind.*, pp. 299–310. Washington, DC: Am. Council Energy-Efficient Econ.
12. Newman J. 1998. Evaluation of energy-related voluntary agreements. *Proc. Workshop Int. Netw. Energy Demand Anal. Ind. Sect.*, pp. 53–62. (LBNL-42368.) Berkeley, CA: Lawrence Berkeley Natl. Lab.
13. Storey M. 1996. *Demand Side Efficiency: Voluntary Agreements with Industry, Policy and Measures for Common Action.* Paris, Fr.: Organ. Econ. Co-op. Dev.
14. Boyd G. 1996. *Impact of Voluntary Agreements on Greenhouse Gas Emission in US Industry*. Paris, Fr.: Organ. Econ. Co-op. Dev.
15. Ramesohl S. 2000. Social interactions and conditions for change in energy-related decision-making in SMCs—an empirical socio-economic analysis. See Ref. 106, pp. 207–28
16. Laitner JA, DeCanio SJ, Peters I. 2000. Incorporating behavioural, social and organizational phenomena in the assessment of climate change mitigation options. See Ref. 106, pp. 1–64
17. Neij L. 1999. *Dynamics of energy systems—methods of analysing technology change.* PhD thesis, Lund Univ., Lund, Swed.
18. Dowd J, Newman J. 1999. Challenges and opportunities for advancing engineering-economic policy analysis. *Proc. IEA Int. Workshop Technol. Reduce Greenh. Gas Emissions: Eng.-Econ. Analyses of Conserved Energy Carbon,* May 5–7. *Washington, DC.* http://www.iea.org/workshop/engecon
19. Lovins AB, Lovins LH. 1991. Least-cost climatic stabilization. *Annu. Rev. Energy Environ.* 16:433–531
20. Energy Technol. Syst. Anal. Programme (ETSAP). 1997. *New Directions in Energy Modeling, Summary of Annex V (1993–1995).* Petten, Neth.: Energy Research Cent. Neth.
21. Gielen DJ. 1995. Toward integrated energy and materials policies? A case study on CO_2 reduction in Netherlands. *Energy Policy* 23:1049–62
22. Grübler A, Nakicenovic N, Nordhaus

W, eds. 2002. *Technological Change and the Environment*. Laxenburg, Austria/Washington, DC: IIASA/RFF

23. Martin N, Worrell E, Sandoval A, Bode JW, Phylipsen D. 1998. Industrial energy efficiency policies: understanding success and failure. *Proc. Workshop Int. Netw. Energy Demand Anal. Ind. Sect.*, pp. 1–203 Berkeley, CA: Lawrence Berkeley Natl. Lab.
24. Worrell E, Price L, Ruth M. 2001. Policy modeling for energy efficiency improvement in US industry. *Annu. Rev. Energy Environ.* 26:117–43
25. Interlab. Working Group Energy-Effic. Clean-Energy Technol. 2000. *Scenarios for a Clean Energy Future*. Oak Ridge, TN/Berkeley, CA: Oak Ridge Natl. Lab./Lawrence Berkeley Natl. Lab.
26. Roop JM, Dahowski RT. 2000. Comparison of bottom-up and top-down forecasts: vision industry forecasts with ITEMS and NEMS. *Proc. 22nd Natl. Ind. Energy Technol. Conf. Apr. 5–6*, pp. 84–88. Houston, TX
27. Schipper L, ed. 2000. On the rebound: the interaction of energy efficiency, energy use and economic activity. *Energy Policy* 28:351–501
28. Jorgenson DW, Goettle RJ, Wilcoxen PJ, Ho MS. 2000. *The Role of Substitution in Understanding the Costs of Climate Change Policy*. Washington, DC: Pew Cent. Glob. Clim. Change
29. Velthuijsen JW. 1995. *Determinants of investment in energy conservation*. PhD thesis. Univ. Amsterdam, Amsterdam, Neth.
30. De Groot HLF, Verhoef ET, Nijkamp P. 2001. Energy saving by firms: decision-making, barriers and policies. *Energy Econ.* 23:717–40
31. Farla JCM. 2000. *Physical indicators of energy efficiency.* PhD thesis. Utrecht Univ., Utrecht, Neth.
32. Worrell E, Biermans G. 2004. Move over! Stock turnover, retrofit and industrial energy efficiency. *Energy Policy.* In press
33. Joskow PL, Rose NL. 1985. The effects of technology change, experience, and environmental regulation on the construction cost of coal-burning generating units. *RAND J. Econ.* 16:1–26
34. Zimmerman M. 1982. Learning effects and the commercialization of new energy technologies: the case of nuclear power. *Bell J. Econ.* 13:297–310
35. Lester R, McCabe M. 1993. The effect of industrial structure on learning by doing in nuclear power plant operation. *RAND J. Econ.* 24:418–38
36. Boyd GA, Molburg JC, Cavallo JD. 2002. Estimates of learning by doing in gas turbine electric power systems. *Energy Stud. Rev.* 10(2):85–99
37. Boyd GA. 2001. A Probit Model of Energy Efficiency Technology Decision Making. *Proc. 2001 ACEEE Summer Study Energy Effic. Ind.*, Tarrytown, NY, pp. 521–34. Washington, DC: Am. Council Energy-Efficient Econ.
38. Harrington W, Kopp R. 1999. *Public Policy, Technology Adoption, and Aggregate Energy Efficiency*. Washington, DC: Resour. Future
39. Jaffe A, Stavins R. 1994. The energy paradox and the diffusion of conservation technology. *Resour. Energy Econ.* 16:91–122
40. Ellsworth RR. 1983. Subordinate financial policy to corporate strategy. *Harv. Bus. Rev.* 61:170–82
41. Ross M. 1986. Capital budgeting practices of twelve large manufacturers. *Financ. Manag.* (Winter):15–22
42. Fazzari SM, Petersen BC. 1993. Working capital and fixed investment: new evidence on financing constraints. *RAND J. Econ.* 24:328–42
43. Boyd GA, Pang JX. 2000. Estimating the linkage between energy efficiency and productivity. *Energy Policy* 28:289–96
44. Worrell E, Laitner JA, Ruth MB, Finman H. 2003. Productivity benefits of industrial energy efficiency measures. *Energy* 28:1081–98
45. Pandey R. 2002. Energy policy modeling:

agenda for developing countries. *Energy Policy* 30:87–106
46. Edmonds J, Roop JM, Scott MJ. 2000. *Technology and the Economics of Climate Change Policy*. Washington, DC: Pew Cent. Glob. Clim. Change
47. Clarke LE, Weyant, JP. 2002. Modeling induced technological change: an overview. See Ref. 22, pp. 41–92
48. Löschel A. 2002. Technological change in economic models of environmental policy: a Survey. *Ecol. Econ.* 43:105–26
49. Worrell E, Bode JW, De Beer J. 1997. *Analysing Research and Technology Development Strategies: The 'ATLAS' Project, Energy Efficient Technologies in Industry*. Utrecht, Neth.: Dept. Sci. Technol. Soc. Utrecht Univ.
50. Van Vuuren DP, de Vries HJM. 2001. Mitigation scenarios in a world at sustainable development: the role of technology, efficiency and timing. *Clim. Policy* 1:189–210
51. van der Zwaan BCC, Gerlagh R, Klaassen G, Schrattenholzer L. 2002. Endogenous technological change in climate change modeling. *Energy Econ.* 24:1–19
52. Tseng P, Lee J, Kypreos S, Barreto L. 1999. Technology learning and the role of renewable energy in reducing carbon emissions. *Proc. IEA Int. Workshop Technol. Reduce Greenh. Gas Emissions: Eng. Econ. Anal. Conserv. Energy Carbon*, Washington, DC, May 5–7
53. Luciuk D. 1999. *The Price-Independent Trend in Energy Efficiency in Canada and the Potential Influence of Non-Price Policies.* Burnaby, BC: Simon Fraser Univ.
54. Newell R, Jaffe A, Stavins RA. 1999. The induced innovation hypothesis and energy saving technological change. *Q. J. Economics* 114(3):941–75
55. Int. Energy Agency. 2000. *Experience Curves for Energy Technology Policy.* Paris, Fr.: IEA
56. Int. Energy Agency. 2003. Experience curves: a tool for energy policy analysis and design. *Proc. Workshop Exp. Curves: Tool Energy Policy Anal. Design*, Jan. 22–24. Paris, Fr.: IEA
57. Laitner JS, Sanstad AH. 2003. Learning to capture progress on both the demand and the supply side: implications for electric utility investments. *Proc. Workshop Exp. Curves: Tool Energy Policy Anal. Design,* Jan. 22–24. Paris, Fr.: IEA
58. Celikkol P, Stefanou S. 1999. Measuring the impact of price-induced innovation on technological progress: application to the US food processing and distribution sector. *J. Prod. Anal.* 12:135–51
59. Lieberman MB. 1984. The learning curve and pricing in the chemical processing industries. *RAND J. Econ.* 15:213–28
60. Landau R, Rosenberg N. 1994. Innovation in the chemical procession industry. In *Exploring the Black Box: Technology, Economics, and History*, ed. N Rosenberg, pp. 190–202. Cambridge, Cambridge Univ. Press
61. Jarmin RS. 1994. Learning by doing and competition in early rayon industry. *RAND J. Econ.* 25:441–54
62. Yin JZ. 1994. Managing process innovation through incremental improvements: empirical evidence in the petroleum refining industry. *Technol. Forecast. Soc. Change* 47:265–76
63. Gruber H. 1992. The learning curve in the production of semiconductor memory chips. *Appl. Econ.* 24:885–94
64. Bahk BH, Gort M. 1993. Decomposing learning by doing in new plants. *J. Polit. Econ.* 101:561–83
65. Nelson RR, ed. 1982. *Government and Technical Progress*. New York, NY: Pergamon
66. Cohen LR, Noll RG. 1994. Privatizing public research. *Sci. Am.* 271(3):72–77
67. Goulder LH, Schneider SH. 1999. Induced technological change and the attractiveness of CO_2 abatement policies. *Resour. Energy Econ.* 21:211–53
68. Messner S. 1997. Endogenized technological learning in energy systems models. *J. Evol. Econ.* 7:291–313

69. Luiten EEM. 2001. *Beyond energy efficiency*. PhD thesis. Utrecht Univ. Utrecht, Neth.
70. De Beer J, Worrell E, Blok K. 1998. Future technologies for energy efficient iron and steelmaking. *Annu. Rev. Energy Environ.* 23:123–205
71. Martin N, Worrell E, Ruth M, Price L, Elliott RN, et al. 2000. *Emerging Energy-Efficient Industrial Technologies*. Berkeley, CA/Washington, DC: Lawrence Berkeley Natl. Lab./Am. Council Energy-Efficient Econ. (LBNL-46990)
72. Gielen DJ. 1999. *Materialising dematerialisation—integrated energy and materials system engineering for greenhouse gas emission mitigation*. PhD thesis. Delft Univ. Technol. Delft, Neth.
73. Howarth RB, Sanstad AH. 1995. Discount rates and energy efficiency. *Contemp. Econ. Policy* 13:101–9
74. Ross MH, Thimmapuram P, Fisher RE, Maciorowski W. 1993. *Long-term Industrial Energy Forecasting (LIEF) Model (18-Sector Version)*. (ANL/EIAS/TM-95.) Argonne, IL: Argonne Natl. Lab.
75. Blok K, de Groot H, Luiten EEM, Rietbergen MG. 2002. *The Effectiveness of Policy Instruments for Energy Efficiency Improvement in Firms*, Utrecht, Neth.: Dept. Sci. Technol. Soc., Utrecht Univ.
76. Bernow S, Rudkevich A, Ruth M, Peters I. 1998. *A Pragmatic CGE Model for Assessing the Influence of Model Structure and Assumptions in Climate Change Policy Analysis.* Boston, MA: Tellus Inst.
77. Peters I, Bernow S, Cleetus R, Laitner J, Rudkevich A, Ruth M. 2002. The Influence of Model Structure and Assumptions in Climate Change Policy Analysis: Explorations with a Pragmatic CGE Model. In *Critical Issues In International Environmental Taxation*, LA Kreiser, ed, pp. 503–22. Riverwoods, IL: CCH Inc.
78. Koopmans C, Velde D. 2001. Bridging the energy efficiency gap: using bottom-up information in a top-down energy demand model. *Energy Econ.* 23:57–75
79. Hanson D, Laitner J. 2000. An economic growth model of investment, energy savings, and CO_2 reductions. *Proc. Air Waste Manag. Assoc. 93rd Annu. Meet.*, Salt Lake City, UT. June
80. Hanson D, Laitner J. 2000. Energy-economy interactions revisited within a comprehensive sectoral model. In *Energy 2000: The Beginning of a New Millennium*, ed. P. Catania, B Golchert, C Zhou, pp. 742–46. Lancaster, PA: Balaban/Technomic
81. Howarth RB, Andersson B. 1993. Market barriers to energy efficiency. *Energy Econ.* 15:262–72
82. Stoft SE. 1995. The economics of conserved-energy "supply" curves. *Energy J.* 16:109–37
83. Blumstein C, Stoft S. 1995. Technical efficiency, production functions, and conservation supply curves. *Energy Policy* 23:765–68
84. Huntington HG. 1994. Been top down so long it looks like bottom up. *Energy Policy* 22:833–39
85. Banks N. 1999. Causal models of household decisions to choose the energy efficient alternative: the role of values, knowledge, attitudes and identity. In *Energy Efficiency and CO_2 reduction: the Dimensions of the Social Challenge. Proc. 1999 Summer Study of the European Council for an Energy Efficient Economy*, Part 2, Pap. (III. 24). Paris, Fr.: Agence Environ. Maitrise Energy (ADEME)
86. Bandura A. 1986. *Social Foundations of Thought and Action—A Social Cognitive Theory.* Englewood Cliffs, NJ: Prentice-Hall
87. Shove E. 1998. Gaps, barriers and conceptual chasms: theories of technology transfer and energy in buildings. *Energy Policy* 26:1105–12
88. Malik F. 1992. *Strategie des Managements Komplexer Systeme—Ein Beitrag zur Management-Kybernetik Evolutionärer Systeme.* Bern, Switz.: Haupt. 4th ed.

89. Dar-El E. 2000. *Human Learning: From learning Curves to Learning Organizations*. Dordrecht, Neth.: Kluwer Acad.
90. Senge P. 1994. *The Fifth Discipline—The Art and Practice of the Learning Organization*. New York, NY: Currency Doubleday
91. Argyris C. 1977. Double loop learning in organizations. *Harv. Bus. Rev.* 55(5):115–25
92. Cooper W, Seiford L. 1999. *Data Envelopment Analysis: A Comprehensive Text with Models, Applications, References, and DEA-Solver Software*. Dordrecht, Neth.: Kluwer Acad.
93. Rogers EM. 1995. *The Diffusion of Innovations*. New York, NY: Free Press
94. Jovanovic B, Nyarko Y. 1996. Learning by doing and the choice of technology. *Econometrica* 64:1299–1310
95. Kleit A, Terrell D. 2001. Measuring potential efficiency gains from deregulation of electricity generation: a Bayesian approach. *Rev. Econ. Stat.* 83:523–30
96. Weidlich W, Braun M. 1992. The master equation approach to nonlinear economics. *J. Evol. Econ.* 2:233–65
97. Erdmann G. 1990. Evolutionäre Ökonomik als Theorie ungleichgewichtiger Phasenübergänge. In *Studien zur Evolutorischen Ökonomik*, ed. U Witt, 195:135–61. Berlin, Ger.: Schriften Vereins Socialpolitik
98. Dosi G. 1988. The nature of the innovative process. In *Technical Change and Economic Theory*, ed. G. Dosi, C. Freeman, R. Nelson, G. Silverberg, L. Soete, pp. 77–93. London, UK: Pinter
99. DeCanio S, Dibble C, Amir-Atefi K. 2000. The importance of organizational structure for the adoption of innovations. *Manag. Sci.* 46:1285–99
100. DeCanio S, Dibble C, Amir-Atefi K. 2001. Organizational structure and the behavior of firms: implications for integrated assessment. *Clim. Change* 48:487–514
101. Bower J, Bunn DW. 2000. A model-based comparison of pool and bilateral market mechanisms for electricity trading. *Energy J.* 3:1–29
102. North MJ. 2002. Multi-agent social and organizational modeling of electric power and natural gas markets. *Comput. Math. Organ. Theory J.* 7:331–37
103. North MJ. 2001. Agent-based infrastructure modeling. *Soc. Sci. Comput. Rev.* 20:307–21
104. Beck MB, Ed. 2002. *Environmental Foresight and Models: A Manifesto*. Amsterdam, Neth./New York, NY: Elsevier
105. Gillissen M, Opschoor JB, Farla JCM, Blok K. 1995. *Energy Conservation and Investment Behaviour of Firms.* Amsterdam, Neth.: Dep. Environ. Econ., Free Univ.
106. Jochem E, Sathaye J, Bouille D, eds. *Society, Behaviour, and Climate Change Mitigation.* Dordrecht, Neth.: Kluwer Acad.