THE POTENTIAL FOR INDUSTRIAL ENERGY EFFICIENCY TECHNOLOGY TO REDUCE U.S. GREENHOUSE GAS EMISSIONS

Madeline G. Woodruff, Pacific Northwest National Laboratory[1]
Gale A. Boyd, Argonne National Laboratory
Joseph M. Roop, Pacific Northwest National Laboratory

INTRODUCTION

This paper describes the industrial portion of a Department of Energy (DOE) study that assessed the potential for energy-efficient technologies to reduce energy consumption and greenhouse gas emissions in the United States. The objectives of this portion of the study were 1) to assess the contribution that an "invigorated effort" to move efficient technology into the industrial market could make to reducing greenhouse gas emissions by 2010, and 2) to describe the role of research and development (R&D)in providing a stream of advanced technologies after 2010 that can continue to reduce industrial energy intensity and greenhouse gas emissions.

In this paper, we first provide some background information on our approach to the assessment and how that approach is shaped by the complexities of the U.S. industrial sector and the limitations of the available analytical tools for this sector. We then discuss the preliminary results of a model-based analysis through 2010. The study from which this paper is drawn (Boyd et al. 1997) supplements these results with descriptions of examples of technologies that, were they to come into widespread use in the U.S. industrial sector before 2010, could achieve the model scenario results. It also describes examples of advanced technologies that, with continued R&D, could contribute to saving energy and reducing greenhouse gas emissions beyond 2010. In this paper we include a summary table of the technology examples described in the study.

APPROACH

The industrial sector is extraordinarily complex and heterogeneous. By definition, it includes all manufacturing activities as well as agriculture, mining, and construction activities. The manufacturing industries range from those that transform raw materials into more refined forms, such as the primary metals and petroleum refining industries, to those that produce highly finished products, such as the food processing, pharmaceuticals, and electronics industries. Hundreds of different processes are used to produce thousands of different products. Even within a manufacturing industry, individual firms vary greatly in the outputs they produce and how they produce them.

This complexity makes it impossible to conduct this assessment in a "bottom-up" fashion that looks in detail at each specific technology that might contribute to reducing industrial greenhouse gas emissions by 2010. Instead, we rely on publicly-available, computer-based models that allow us to develop rough estimates of the potential for increased investment in energy efficiency more generally. We supplement these estimates with examples of technologies that, if adopted under an invigorated effort to move them into the market, could achieve the modelled results.

Scenario Analysis

For the scenario portion of the analysis, the preferred analytical tool would be an industrial model that is publicly-available, complete, and up-to-date and that has a stock-adjustment mechanism as well as detailed, technology-specific conservation supply curves for all important industrial processes that are affected by changes in energy prices, capital recovery rates, and other economic parameters. We would also like to be able to relate the modeling results to those reported in the U.S. DOE's Annual Energy Outlook 1997 (DOE 1997), which is prepared by the Energy Information Administration using the National Energy Modeling System (NEMS).

No existing modeling tool has all of these features. Instead, we employ two modeling tools that, when used together, provide us with the features we need: the Long-Term Industrial Energy Forecasting (LIEF) model, which provides a mechanism for evaluating general investment in conservation technology as a function of energy prices, capital recovery rates, and other parameters, and the NEMS Industrial Module (NEMS-IM), which captures the effects on energy intensity of groups of specific technologies, but does not model investment in these technologies as functions of energy prices or any other factors.

We used these two models to develop three scenarios: a business as usual (BAU) case, an Efficiency case, and an High Efficiency case. Our general approach was to use the 1997 Annual Energy Outlook (AEO97) reference case (developed using the NEMS model) as our BAU case. Using the macroeconomic and energy price assumptions in the AEO97 reference case, we adjusted the LIEF model's base case slightly to more closely approximate the overall energy forecast in the AEO. We then ran the adjusted LIEF model to obtain an Efficiency and an High Efficiency case. We computed the difference between the LIEF BAU case and the LIEF Efficiency case ("delta one"), and between the LIEF BAU case and the LIEF High Efficiency case ("delta two"). We applied the LIEF model "deltas" to the NEMS (AEO 1997 base) results to compute our final estimates for potential greenhouse gas emissions reductions. We also used the NEMS model to explore the extent to which capital stock turnover and technology performance would have to increase to correspond to "delta one" and "delta two."

Technology Examples and R&D

The technology and R&D discussions presented in the full study focus on seven energy-intensive industries that are either modelled in detail by the NEMS-IM and LIEF models or are the focus of the DOE Office of Industrial Technologies' Industries of the Future process: forest products (a subset of the pulp and paper industry), glass, iron and steel, metal casting, aluminum, chemicals, and petroleum refining. In the study, we also look at cross-cutting technologies (such as energy-efficient motors) that affect all industries.

SCENARIOS FOR 2010: ENERGY SAVINGS AND GREENHOUSE GAS EMISSIONS REDUCTIONS

The LIEF model contains conservation supply curves for various industries that describe the extent to which industry is willing to invest in energy conservation as a function of energy prices. These curves have been calibrated to historical industry data using an implicit Capital Recovery Factor (CRF) of 33%. CRFs and associated discount rates at this level or higher - representing a requirement that these investments pay back the capital outlay within a few years - have been found to characterize much of the decision-making in industry on investments in energy efficiency technologies and on similar investments. At the same time, firms have another class of investment decisions - termed "strategic" investments - that are characterized by a lower CRF (or discount rate), so that the initial investments are allowed to be paid back in operational savings over a longer period (see Ross 1990). One way, then, to simulate an increased investment in energy-efficient technology is to postulate a policy or set of policies that would lead industry to apply something like this more "strategic" discount rate to energy efficiency investments. This effect could be induced via policies that served to decrease the first cost of such investments or that resulted in increased annual cost savings.

Another way to simulate such an increase in technology investment is to directly increase the factor that represents the penetration rate of new technologies. The penetration rate parameter in LIEF provides a measure of the rate at which industry adopts conservation projects. Firms do not immediately adopt all technologies that meet their criteria for cost-effectiveness and other factors. Delays may represent a lack of capital, other priorities for the use of available capital funds, scheduling concerns, or simply a lack of awareness of the technologies. An increase in the adoption rate for new technology, or an increase in the turnover rate for old capital equipment, reflects a higher priority placed on energy conservation by industry as well as better information dissemination (Ross et al. 1993).

We have used both of these factors to simulate the Efficiency case and the High Efficiency case for the industrial sector. We assume that either the discount rate or the penetration rate is affected in the Efficiency case, and that both may be affected in the High Efficiency case.

Business as Usual Case

Our business as usual (BAU) case is the AEO97 reference case. Under this case, national economic output, measured by gross domestic product (GDP), is projected to increase by 2.1% annually to the year 2010. Within this overall growth, the manufacturing sector growth rate is projected at 2.1% per year, with energy-intensive industries growing at half the rate of non-energy-intensive industries (1.3% versus 2.6%). The leading growth sectors within manufacturing are projected to be industrial machinery, electronic equipment, and transportation equipment. Of all the manufacturing subsectors, electronic equipment is expected to have the highest growth rate, twice that of the manufacturing sector as a whole.

Total energy use intensity is projected to decline by 1.1% per year through 2010. Among industry sectors, the largest declines in total energy use intensity are projected for the pulp and paper and glass industries, with the cement industry third. Electricity use intensity is projected to decline by 0.5% overall but with considerable inter-industry variation. The largest decline, 1.1%, occurs in the pulp and paper industry and contrasts with an increase of the same magnitude in the iron and steel industry. The distribution of primary energy consumption among end uses is expected to remain stable, with more than two-thirds of industrial sector use accounted for by manufacturing heat and power requirements and the remaining third split about equally among non-manufacturing heat and power applications and use as process feed-stocks. For manufacturing heat and power, the largest energy consuming industries are petroleum refining, chemicals, and pulp and paper production. The long-term trend of declining energy intensity in manufacturing is expected to continue, representing an 18% energy savings between 1995 and 2010. This trend is due to both adoption of energy-efficient technologies and relatively lower growth rates in the more energy-intensive industries. The effects of industry mix shifting toward less energy-intensive industries is stronger than the efficient-technology effect on the overall rate of change in energy intensity.

The AEO97 reference case is an appropriate BAU case for this study, since it assumes that there are no changes in federal energy or environmental policies over the forecast period. To the extent that the NEMS model reflects recent historical trends of industrial technology R&D performance, availability, and introduction, this means that current and future private and government R&D funding for new and emerging technologies that is consistent with recent history is, in part, responsible for the reference case decline in energy intensity.

Efficiency and High Efficiency/Low Carbon Cases

The industrial sector forecasts for the Efficiency and High Efficiency/Low Carbon (HE/LC) cases use the AEO97 energy prices and macroeconomic activity forecasts as a starting point. We assume no changes in economic activity that might arise from changes in energy markets. Moreover, we assume no changes in the energy prices that could occur under conditions of lower energy demand. Energy markets adjust to changes in demand. This means that reduced demand in the efficiency cases would lead to lower energy prices, thereby reducing incentives for efficiency gains.

The Efficiency case assumes that industrial firms apply a "strategic" discount rate (or hurdle rate) to energy-savings investments. We simulate the former effect in LIEF by changing the Capital Recovery Factor (CRF) from 33% to 15% to reflect the lower hurdle rate. Since not all cost effective technologies are assumed to instantaneously penetrate the market, the High Efficiency/Low Carbon case is based on the assumption that the penetration rate of the technologies that are cost effective under a CRF of 15% doubles on average. The preliminary results are shown in Table 1 for ten major economic sectors of U.S. industry. The results are expressed in terms of a percentage change in sectoral energy intensity compared with the BAU case. The Efficiency case reduces total energy intensity growth by 0.28%. The High Efficiency case reduces the growth in energy intensity by more than one half of one percent (0.55%) relative to the BAU case and reduces the growth in electricity use by even more.

Table 1. LIEF Results: Change in Energy Intensity 1997-2010 Compared with the Business as Usual Case (average annual percent change)

	Efficiency Case CRF = 15% Penetration = Normal			High Efficiency/Low Carbon Case CRF = 15% Penetration = Double		
	Electric	Fuels	Total Energy	Electric	Fuels	Total Energy
Heavy Manufacturing	**-0.23%**	**-0.18%**	**-0.20%**	**-0.46%**	**-0.39%**	**-0.41%**
Pulp & Paper	-0.23%	-0.18%	-0.20%	-0.47%	-0.39%	-0.42%
Bulk Chemicals	-0.26%	-0.18%	-0.21%	-0.52%	-0.39%	-0.45%
Petroleum	-0.31%	-0.18%	-0.20%	-0.51%	-0.39%	-0.41%
Glass	-0.26%	-0.19%	-0.22%	-0.46%	-0.37%	-0.41%
Cement	-0.18%	-0.18%	-0.18%	-0.43%	-0.42%	-0.42%
Iron & Steel	-0.28%	-0.19%	-0.22%	-0.51%	-0.37%	-0.41%
Aluminum	-0.10%	-0.19%	-0.10%	-0.20%	-0.36%	-0.20%
Other	-0.23%	-0.18%	-0.20%	-0.49%	-0.41%	-0.45%
Light Manufacturing	**-0.56%**	**-0.40%**	**-0.50%**	**-1.14%**	**-0.75%**	**-1.01%**
Non-Manufacturing	**-0.43%**	**-0.14%**	**-0.19%**	**-0.82%**	**-0.27%**	**-0.35%**
ALL INDUSTRY	**-0.42%**	**-0.20%**	**-0.28%**	**-0.83%**	**-0.39%**	**-0.55%**

Table 2 translates these changes in energy intensity into percentage changes in energy consumption over the 13-year period from 1998 to 2010. In the HE/LC case, overall energy consumption decreases by 6.9% in 2010 relative to the BAU case, while the decrease in the Efficiency case is 3.6%. The results for individual industries vary; the declines in energy intensive industries are close to the average for all of industry, but non-energy intensive sectors show percentage declines of about twice that of heavy industry. This is because energy is a very small part of the costs in these sectors so that energy efficiency investment is often overlooked. The LIEF model represents this by a large difference between the average light manufacturing plants and the most efficient ones. The high growth sectors in light manufacturing have relatively larger opportunities to make significant percentage reductions than do their energy intensive counterparts, who have already done so in response to rising energy prices in the seventies. In addition, light industries' energy use is dominated by electricity. Electricity savings in light manufacturing comes largely from computer controls and the use of efficient motor systems, supplemented by contributions from improvements in lighting and heating, ventilation, and air conditioning systems. This difference between light and heavy manufacturing is a major source of the difference in the energy savings (on a percentage basis) between fossil fuels and electric energy. One should note that, while these percentage savings vary, the majority of the energy savings in absolute terms still come from reduced fossil fuel use in heavy industry: the heaving industry reduction is 5.2% while the reduction for all of industry is 6.9%.

Table 2. LIEF Results: Energy Savings in the Year 2010 Compared with the Business as Usual Case (percent reduction)

	Efficiency Case CRF = 15% Penetration = Normal			High Efficiency/Low Carbon Case CRF = 15% Penetration = Double		
	Electric	Fuels	Total Energy	Electric	Fuels	Total Energy
Heavy Manufacturing	**3.0%**	**2.4%**	**2.6%**	**5.7%**	**4.9%**	**5.2%**
Pulp & Paper	2.9%	2.4%	2.6%	5.9%	4.9%	5.3%
Bulk Chemicals	3.3%	2.4%	2.8%	6.6%	5.0%	5.6%
Petroleum	3.9%	2.4%	2.6%	6.4%	5.0%	5.1%
Glass	3.3%	2.4%	2.8%	5.8%	4.6%	5.2%
Cement	2.3%	2.3%	2.3%	5.4%	5.3%	5.4%
Iron & Steel	3.6%	2.4%	2.9%	6.4%	4.6%	5.3%
Aluminum	1.3%	2.5%	1.3%	2.5%	4.6%	2.6%
Other	2.9%	2.3%	2.6%	6.1%	5.2%	5.6%
Light Manufacturing	**7.0%**	**5.0%**	**6.3%**	**13.8%**	**9.3%**	**12.3%**
Non-Manufacturing	**5.5%**	**1.9%**	**2.4%**	**10.1%**	**3.4%**	**4.4%**
ALL INDUSTRY	**5.3%**	**2.5%**	**3.6%**	**10.2%**	**4.9%**	**6.9%**

Table 3 translates the results reported in Table 2 into changes in the energy consumption levels forecast by the AEO97. The first two columns show the overall change in energy use between 1997 and 2010 for the BAU case for fossil fuels and electricity use (including system conversion losses). The next two columns show the effects of the Efficiency case and the High Efficiency case, as forecast by LIEF, on the AEO97 BAU case. The High Efficiency/Low Carbon case approaches zero growth with energy use increasing by only 2.3 Quads (7%) between 1997 and 2010, in spite of an output increase of 30% over this period.

Table 3. Total Industrial Energy Use: AEO 97 Business as Usual Case and LIEF Forecasts (quads).

	AEO 97		LIEF	
	1997	Bus. As Usu. Case 2010	Efficiency Case 2010	High Efficiency/ Low Carbon Case 2010
Fossil Fuels	21.4	24.2	23.6	23.0
Electricity (incl. related losses)	11.3	13.2	12.5	11.8
Total	**32.6**	**37.4**	**36.1**	**34.9**

Table 4 provides greenhouse gas emissions estimates for 2010 in million metric tons. Because LIEF does not model fossil fuel choice, the greenhouse gas emissions reductions estimates are based on the fossil fuel mix and emission factors in NEMS. There are two ways to compute greenhouse gas emissions reductions from reduced fossil fuel use. The first is to assume that efficiency affects fuel reductions through the average fuel mix, such that greenhouse gas emissions reductions are proportional to fossil fuel reductions. The second is to assume that most energy efficiency reductions operate on the margin - i.e., they affect those fuels that constitute the growth in the BAU forecast.

An examination of the change in the fossil fuel mix in industry in the AEO97 found that no fuel's share changed by more than 1%. Therefore, using the average industrial fossil fuel mix from the AEO97 is a reasonable approach to computing the change in greenhouse gas emissions. However, an analysis of the fuel mix in the electric utility industry shows that natural gas has a growing share, so that this same approach would yield an upper bound estimate for carbon emissions reductions arising from electricity savings. Therefore, the emissions reductions resulting from decreased electricity use were computed using the marginal carbon emission rates rather than the average rates.

Table 4. Carbon Emissions Estimates (Million Metric tons per Year)

	AEO 97		LIEF	
	1997	Business as Usual Case 2010	Efficiency Case 2010	High Efficiency/ Low Carbon Case 2010
Electricity	171.7	200.5	194.2	191.0
Fossil Fuels	310.7	333.6	325.1	317.2
Total	482.4	534.1	519.3	508.2

The LIEF model conservation supply curves can be used to compute the investment implied by the forecast energy savings. These estimates, shown in Table 5, represent the additional investment required to achieve the energy savings presented above. Due to the long-lived nature of industrial capital goods, this cumulative investment in more efficient and productive industrial plant and equipment continues to generate energy and costs savings, relative to the base case, after the 2010 time horizon.

Table 5. Cumulative Incremental Investment (1998-2010) for Energy Efficiency Implied by the LIEF Model to Achieve the Forecast Energy Savings (billion $1997)

	Efficiency Case	High Efficiency/Low Carbon Case
Fossil Fuels	7.4	15.2
Electricity	15.8	32.0
Total	**23.2**	**47.2**

LIEF projects that this level of investment would be profitable given the forecast energy prices and a CRF of 15%, implying that the energy savings would provide about a 7-year payback on the initial investment. Since savings continue to accrue over the lifetime of the equipment, this is an investment with a profitable return. However, it is important to understand the magnitude of the up-front costs, since this may be an issue in designing policies to spur this enhanced technology penetration.

To put this level of investment in energy efficiency into context, the investment can be compared with total investment in manufacturing. If the cumulative investment in energy efficiency is spread out evenly over the 13 year time period, the High Efficiency case would require a $3.6 billion total annual investment in fossil and electricity efficiency. In 1992, total investment in manufacturing (not including agriculture, construction, and mining) was $110.1 billion (1995$). Thus the incremental annual investment needed to achieve the High Efficiency case represents a 3.3% increase over the level of manufacturing investment for 1992.

Comparison with the NEMS Model

The NEMS model provides a different approach to and perspective on the Efficiency and High Efficiency cases. The NEMS model uses a stock turnover approach to project the change in energy use. New technology is projected to be more efficient, so as capital is replaced the overall energy requirements in the industry decline. To compare the scenarios, the NEMS industrial model was run under alternative assumptions and compared to those corresponding industry sectors in LIEF (see Table 6). When the retirement rate of capital is doubled in the NEMS industrial model, total energy use declines between 1 and 8%, depending on the sector. For four out of six comparable industries, this is comparable to the Efficiency and High Efficiency case forecasts.

Table 6. Total Energy Savings in Year 2010 Relative to the Business as Usual Case in the NEMS and LIEF Models

	LIEF		NEMS	
	Efficiency Case	High Efficiency/ Low Carbon Case	Doubled Retirement Rate	Doubled Technology Performance
Paper	2.6%	5.3%	4.9%	7.5%
Chemicals	2.8%	5.6%	1.3%	5.0%
Glass	2.8%	5.2%	3.6%	9.9%
Cement	2.3%	5.4%	5.7%	3.6%
Iron and Steel	2.9%	5.3%	8.2%	2.9%
Aluminum	1.3%	2.6%	1.2%	7.8%

On the other hand, when the performance of new technology is assumed to double, i.e. new technology's relative energy intensity declines twice as fast as the BAU case, three out of the six sectors exceed the savings from the High Efficiency case, while the remaining three fall within the range of energy savings of the Efficiency and High Efficiency cases. These parametric variations in the NEMS model illustrate, in rough magnitude, what rate of technology improvement or stock turnover would be consistent with the Efficiency and High Efficiency cases.

The Historical Context of Energy Efficiency in Industry

Over time, both the "what" and the "how" of industry output changes. Buggies and whips have disappeared, but automobile production has taken their place. And while the Model T was mass-produced, today's methods of production are only vaguely reminiscent of Henry Ford's assembly line. Energy use in manufacturing and other industry sectors has changed due to both product and process transformation. While much of the change occurs because of energy efficiency improvements over time, another substantial part of overall energy use changes occur because of changes in the mix of industries. Rough approximation of the importance of these two factors indicates that efficiency accounts for about two-thirds of the change, while the shift in the mix of industries accounts for about one-third of the change. Put into historical perspective, the forecasts of potential changes in energy use and energy intensity changes derived in this analysis are modest changes, and, we argue, more than just possibilities. With appropriate and effective policy measures to accelerate the adoption of technologies that are currently, or will soon be, available, the efficiency gains and energy and carbon savings projected could easily be achieved.

A study published by DOE (1995) illustrates how rapidly energy intensity in the industrial sector can decline. From 1972, the last full year prior to the effect of the first oil price shock, and 1985, when energy prices fell, the rate of decline in energy intensity in industry was 2.74% per year. During the period of the most rapid decline, from 1975 to 1983, industrial sector energy intensity fell by 3.12% per year. These numbers show that when industry has a major incentive to reduce energy use, it will do so. By the same token, when the incentives are reduced, so too do the improvements. Between 1984 and 1991, energy intensity in the industrial sector declined by less than 1% per year, and in four of these years, the intensity actually increased. Of the energy savings that occurred in the industrial sector between the mid 1970s and the early 1990s, this report suggests that about one-third of the total was attributable to compositional shifts (i.e., shifts from highly energy-intensive industries to industries with lower energy intensity). The remainder was attributable to reductions in energy intensity within industries.

In the BAU forecast, total energy intensity declines at about 1.1% per year, with more than half of this decline (.6%) attributable to projected composition effects. If one takes the efficiency component of 0.5% per year forecast of total intensity decline from the BAU case and adds the additional 0.55% per year from the High Efficiency/Low Carbon case, the High Efficiency/Low Carbon case has a rate of energy intensity decline that is slightly below the historical rate over the period 1972-1991 (1.89%). This would be quite an achievement with energy prices remaining at current levels.

TECHNOLOGY EXAMPLES

Although our forecasting methodology does not draw directly from detailed representation of individual technologies, the forecast savings that are expected in each sector will be drawn from a variety of sources of new technologies and business practices. In addition, with further R&D, additional technologies will be available for additional energy savings and emissions reductions beyond the forecast period. Table 7 is a summary table of the technology examples described in the study from which this paper is drawn. Proven industrial technologies and near-commercial technologies are identified as contributing to saving energy and reducing greenhouse gas emissions by 2010, while those that will require continuing R&D and will be available after the forecast period (i.e., after 2010) are identified as contributing to saving energy and reducing emissions by 2020. A rough categorization into incremental (I) or fundamental (F) improvements has been made for the technologies listed. Many of the underlying concepts in these examples apply to more than one industrial sector, while others are very process specific. This identification is also made in the table.

Some of the technologies in Table 7 recover or reduce the production of waste heat in high-temperature applications; others optimize the process load to the energy using equipment. Many of the most successful technologies have multiple benefits, including environmental- or productivity-enhancing features. A technology that reduces product loss or increases process throughput will often reduce labor or material costs as well as energy costs. While we feel these technologies are representative and have the potential to be readily accepted by industry, the estimates of energy savings provided in the study from which this paper is drawn do not represent any industry consensus of the relative difference between the new technology and average practice. Instead we rely on available, published literature that assesses the performance of these technologies and business practices.

The diversity of industries, businesses, plants, and processes imply that not all of these examples will be universally cost effective, or even applicable. Site- or plant-specific constraints may prevent the use or economic acceptability of a technology for retrofit applications that would be readily accepted in a new plant design. In many of the most energy intensive process industries, few green-field plants are being built in this country, further limiting some applications. While we do not consider explicitly the economics of when to replace old equipment, we understand that a variety of considerations enter into this business decision, including:

- How learning curves tend to continually lower the costs (including energy costs) as cumulative production experience with new technology is gained
- Countervailing factors like "wear and tear" that tend to increase costs over time
- How the introduction of new equipment can alter the economics of existing equipment
- Available design trade-offs between capital and other costs, especially energy costs.

New and replacement capacity will be put into place at many existing plants based on these and other decision variables. The opportunity for new technology to be adopted occurs at the point in time when these decisions are made. It is at this point that energy prices and capital discount rates can influence the decision to purchase new technology and thus the adoption of technologies such as those listed in Table 7.

Many of these technology example exhibit energy savings of more than the 4-7% relative to current average practice, but the slow turnover of the capital stock in the energy and capital intensive industries require that our projections take this into account. In 13 years many of the technologies listed for 2010 (and the many others not listed here) are capable of reaching higher levels of penetration, but most will not achieve 100% penetration. In addition, the technology examples often account for only a fraction of the energy use in that sector. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives. Therefore, these examples help establish the technical plausibility of the projections.

Details on the technology examples can be found in the original study (Boyd et al. 1997).

Table 7. Summary of Technology Examples

Example Taken From	Technology Example	Year	Type of Change	Concept Applicable to Other Sectors?	Saves Fossil or Electric Energy
Metal Casting	Computer-Aided Casting Design	2010	I	Y	EF
Iron and Steel	Process Controls	2010	I	Y	EF
Iron and Steel	Hot Connection	2010	I	Y	F
Iron and Steel	Scrap Preheating	2010	I	Y	EF
Aluminum	Improve Furnace Efficiency	2010	I	Y	EF
Aluminum	Materials Recycling	2010	I	Y	E
Glass	Glass Batch/Cullet Preheated Technology	2010	I	Y	F
Glass	Advanced Burner Technology	2010	I	Y	F
Petroleum Refining	Utility System Improvements	2010	I	Y	F
Chemicals	Pinch Analytical Techniques	2010	I	Y	F
Pulp and Paper	On-Machine Sensors for Paper Properties	2010	I	Y	F
Cross-cutting	Cogeneration	2010	I	Y	EF
Cross-cutting	Motor Systems	2010	I	Y	E
Iron and Steel	Process Controls and Sensors	2020	I	Y	EF
Glass	Producing Oxygen More Efficiently	2020	I	Y	E
Glass	Recovering Waste Heat	2020	I	Y	F
Glass	Maximizing Combustion Efficiency	2020	I	Y	F
Pulp and Paper	Biomass Gasification	2020	I	Y	EF
Metal Casting	Optimized Coreless Induction Melting	2010	I	N	E
Iron and Steel	Use of DC, Rather than AC, Electric Arc Furnaces	2010	I	N	E
Aluminum	Improving Hall-Heroult Cell Efficiency	2010	I	N	E
Glass	Oxy-Fuel Process	2010	I	N	F
Petroleum Refining	Process/Equipment Modifications	2010	I	N	F
Chemicals	Advanced Distillation Control Techniques	2010	I	N	F
Pulp and Paper	Multiport Cylinder Drying	2010	I	N	F
Pulp and Paper	Impulse Drying	2010	I	N	F
Metal Casting	Electromagnetic Stirring	2020	I	N	EF
aluminum	Titanium Diboride Cathodes	2020	I	N	E
Aluminum	Inert Anodes	2020	I	N	E
Glass	Optimizing Electric Boost	2020	I	N	F
Pulp and Paper	Black Liquor Gasification	2020	I	N	EF
Petroleum Refining	Development of Improved Catalysts	2020	F	Y	F
Iron and Steel	Coal or Natural Gas Injection	2010	F	N	F
Iron and Steel	Direct Smelting/Reduction	2010	F	N	F
Metal Casting	Electromagnetic Casting	2020	F	N	EF
Iron and Steel	Direct Smelting and Thin Strip Casting	2020	F	N	EF
Aluminum	Aluminum Chloride Process	2020	F	N	E
Aluminum	Carbothermic Reduction Process	2020	F	N	E
Chemicals	Flexible Chemical Processing of Polymers	2020	F	N	F
Chemicals	Biological/Chemical Caprolactam Process	2020	F	N	F
Pulp and Paper	Sulfur Free Pulping	2020	F	N	EF
Pulp and Paper	Polyoxometalate Bleaching	2020	F	N	EF

CONCLUSIONS

This analysis presents an approach to assessing the potential for efficiency to reduce energy use in the most diverse sector of the economy, the industrial sector, that is a compromise between the desire for technology detail and the need to evaluate sector-wide energy use. The approach uses two publicly available models, Argonne's LIEF model and the Energy Information Administration's NEMS-IM, to simulate a plausibly optimistic set of scenarios for additional energy savings relative to an established base case, the AEO 1997. The models are used to project what energy savings could arise from an "invigorated effort" to put currently available or near commercial technologies into practice in industry. This invigorated effort is loosely characterized as either a combination of new policy initiatives or a more serious consideration of efficiency as a strategic concern of industrial decision makers.

Two efficiency cases are presented which project that overall reductions in energy use by 2010. A reduction of 4-7% is projected to be technically feasible, given adequate policies or other incentives to expand the adoption of cost effective measures. This is about two and a half quads in the high case. The LIEF model projects that these reductions could arise from cost effective investments defined by a capital recovery factor (CRF) of 15%, which is equivalent to about a 7 year pay-back period. The LIEF model does not assume that in every case all energy efficiency investments are made, but an increased penetration rate of efficiency investment is assumed relative to the base case as a result of this "invigorated effort." For many of the energy intensive industrial sectors, these projected energy savings are consistent with roughly doubling the current rates of capital stock replacement or doubling the rate of energy technology efficiency improvement that is currently represented in the NEMS model.

Since the models used to conduct the scenario analysis do not have a detailed, technology-specific representation of each major industrial sector, illustrative examples of technologies for most of the energy intensive industries are provided in the study from which this paper is drawn and are listed in this paper. These examples are technologies which have the potential to reduce energy use relative to current practices if widely adopted. These technologies exhibit substantial energy savings relative to current industry practice, so they reinforce the fact that the model results are feasible. But one cannot expect these technologies to be adopted widely unless there is some invigorated effort to encourage their adoption. The slow turnover of the capital stock in the energy and capital intensive industries requires is one reason that this invigorated effort would be needed.

The efficiency case projections also show that, on a percentage basis, there are more savings in "light" non-energy intensive industry vs. the "heavy," energy intensive sectors. This result arises from the LIEF model scenarios, but, due to the structure of the model, does not have an analog in NEMS. Because the share of total production costs attributable to energy use in the non-energy intensive sectors is very low (the manufacturing average is about 3% and most light industry is less) it is not surprising that the range of energy performance is quite broad. Energy efficient technologies, in the form of motor systems as well as lighting and HVAC represent cost effective investment opportunities in light manufacturing. However, there may not have been a managerial or technical focus on energy efficiency in those industries. An "invigorated effort" could provide this focus. On the other hand, in heavy industry, where considerable attention to efficiency has already been paid, low capital turnover rates and difficulty in financing medium to large sized investments may be the major impediments to accelerated improvements in energy utilization. The "'invigorated effort" in these sectors might require tax incentives, alternative financing arrangements, new developments that lower first costs, or demonstrations focusing on lowering perceived risk. The diversity among these broad categories of industry implies that the mix of policies required to achieve the High Efficiency case may differ for the various types of industries, their current business and technical practices, and current domestic and international market conditions.

For all of these industries discussed above, further progress in energy efficiency beyond 2010 requires further developments in technology. These developments may be incremental improvements, such as sensors, controls, and system/process modeling, or may be fundamental breakthroughs, such as catalysts, direct smelting, or bio-processing. Incremental improvements need not be associated with "small" efficiency changes. The ability to sense and adjust a process to achieve optimal operating condition can have large effects on productivity and energy consumption. However, the search for totally new methods to produce a product with fundamental breakthroughs in chemistry, metallurgy, or biology offers another route to enhance productivity and lower energy use. These two avenues of R&D to create the manufacturing sector of 2020 are both being sought by private and private/public partnerships.

The range and types of technological solutions in industrial applications is quite large. Since energy represents a cost and energy efficiency a potential source of profit, these technical solutions can be consistent with the economic goals of businesses. With the right incentives, higher industrial energy efficiency of the magnitude projected here is an achievable goal.

REFERENCES

Boyd, G.A., J.M. Roop, and M.G. Woodruff. 1997. "The Industrial Sector." Draft chapter in *The Potential for Energy Efficiency Technologies to Reduce Greenhouse Gas Emissions in the United States.* Forthcoming. U.S. Department of Energy, Washington, DC.

DOE. See U.S. Department of Energy.

Ross, M. 1990. "Capital Budgeting Practices of Twelve Large Manufacturers." In Philip Cooley, ed., *Advances in Business Financial Management.* Dryden Press, Chicago.

Ross, M., P. Thimmapuram, R. Fisher, and W. Maciorowski. 1993. *Long-Term Industrial Energy Forecasting (LIEF) Model (18-Sector Version).* ANL/EAIS/TM-95. Argonne National Laboratory, Argonne, IL.

U.S. Department of Energy (DOE). 1997. *Annual Energy Outlook 1997, with Projections to 2010.* DOE/EIA-0383(97). Energy Information Administration, Washington, D. C.

ENDNOTES

1. Now with the International Energy Agency.