

# **EMERGING ENERGY-EFFICIENT INDUSTRIAL TECHNOLOGIES**

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## ABBREVIATIONS

ACEEE	American Council for an Energy-Efficient Economy
AEO	<i>Annual Energy Outlook</i>
ASD	adjustable speed drive (motors)
BOF	basic oxygen furnace (steel making)
Btu	British thermal unit
CADDET	Center for the Analysis and Dissemination of Demonstrated Energy Technologies
CHP	combined heat and power
CO <sub>2</sub>	carbon dioxide
DOE	U.S. Department of Energy
EAF	electric arc furnace (steel making)
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EJ	exajoule
GDP	gross domestic product
GJ/t	gigajoule per metric ton
HVAC	heating ventilation and airconditioning
IEC	Iowa Energy Center
kW	kilowatt (electric)
kWh	kilowatt-hour (electric)
LBNL	Lawrence Berkeley National Laboratory
LPG	liquid petroleum gas
MW	megawatt (electric)
MBtu	million Btu
MBtu/ton	million Btu per short ton
NEMS	National Energy Modeling System
NO <sub>x</sub>	oxides of nitrogen
NYSERDA	New York State Energy Research and Development Authority
NEEA	Northwest Energy Efficiency Alliance
OIT	U.S. DOE Office of Industrial Technologies
PG&E Co.	Pacific Gas and Electric Company
PJ	petajoule
Quads	quadrillion Btu
R&D	research and design
RD&D	research, development, and demonstration
TBtu	trillion Btu
ton	short ton (2000 pounds mass)
t	metric ton
TWh	terawatt-hour (electric)





## EXECUTIVE SUMMARY

U.S. industry consumes approximately 37 percent of the nation's energy to produce 24 percent of the nation's GDP. Increasingly, industry is confronted with the challenge of moving toward a cleaner, more sustainable path of production and consumption, while increasing global competitiveness. Technology will be essential for meeting these challenges. At some point, businesses are faced with investment in new capital stock. At this decision point, new and emerging technologies compete for capital investment alongside more established or mature technologies. Understanding the dynamics of the decision-making process is important to perceive what drives technology change and the overall effect on industrial energy use.

The assessment of emerging energy-efficient industrial technologies can be useful for:

- identifying R&D projects;
- identifying potential technologies for market transformation activities;
- providing common information on technologies to a broad audience of policy-makers; and
- offering new insights into technology development and energy efficiency potentials.

With the support of PG&E Co., NYSERDA, DOE, EPA, NEEA, and the Iowa Energy Center, staff from LBNL and ACEEE produced this assessment of emerging energy-efficient industrial technologies. The goal was to collect information on a broad array of potentially significant emerging energy-efficient industrial technologies and carefully characterize a sub-group of approximately 50 key technologies. Our use of the term “emerging” denotes technologies that are both pre-commercial but near commercialization, and technologies that have already entered the market but have less than 5 percent of current market share. We also have chosen technologies that are energy-efficient (i.e., use less energy than existing technologies and practices to produce the same product), and may have additional “non-energy benefits.” These benefits are as important (if not more important in many cases) in influencing the decision on whether to adopt an emerging technology.

The technologies were characterized with respect to energy efficiency, economics, and environmental performance. The results demonstrate that the United States is not running out of technologies to improve energy efficiency and economic and environmental performance, and will not run out in the future. We show that many of the technologies have important non-energy benefits, ranging from reduced environmental impact to improved productivity and worker safety, and reduced capital costs.

## Methodology

The assessment began with the identification of approximately 175 emerging energy-efficient industrial technologies through a review of the literature, international R&D programs, databases, and studies. The review was not limited to U.S. experiences, but rather we aimed to produce an inventory of international technology developments. We devised an initial screening process to select the most attractive technologies that had: (1) high potential energy savings; (2) lower comparative first costs relative to existing technologies; and (3) other significant benefits. While some technologies scored high on all of these characteristics, most had a mixed score. We formalized this approach in a very simple rating system. Based on the literature review and the application of initial screening criteria, we identified and developed profiles for 54 technologies. The technologies ranged from highly specific ones that can be applied in a single industry to more broadly crosscutting ones that can be used in many industrial sectors.

Each of the selected technologies has been assessed with respect to energy efficiency characteristics, likely energy savings by 2015, economics, and environmental performance, as well as what's needed to further the development or implementation of the technology. The technology characterization includes a one to two-page description and a one-page table summarizing the results for the technology.

## Summary of Results

Table ES-1 provides an overview of the 54 emerging energy-efficient industrial technologies. We evaluated energy savings in two ways. The third column of Table ES-1 (Total Energy Savings) shows the amount of total manufacturing energy that the technology is likely to save in 2015 in a business-as-usual scenario. The fourth column (Sector Savings) reflects the savings relative to expected energy use in the particular sector. We believe that both metrics are useful in evaluating the relative savings potential of various technologies.

Economic evaluation of the technology is identified in the summary table by simple payback period, defined as the initial investment costs divided by the value of energy savings less any changes in operations and maintenance costs. We chose this measure since it is frequently used as a shorthand evaluation metric among industrial energy managers. Payback times for the technologies range from the immediate to 20 years or more. Of the 54 technologies profiled, 31 have estimated paybacks of 3 years or less, with six paying back immediately

Energy savings are most often not the determining factor in the decision to develop or invest in an emerging technology. Over two-thirds of technologies not only save energy but yield non-energy benefits. We separated these non-energy benefits into environmental and other categories. We assessed how important the environmental benefits are to the technology adoption decision and listed the nature of the other benefit(s). We include an assessment of the importance of these non-energy benefits.

Technologies do not seamlessly enter existing markets immediately after development. The acceptance of emerging technologies is often a slow process that entails active research and development, prototype development, market demonstration, and other activities. In Table ES-1 we summarize the recommendations for the primary activities that could be undertaken to increase the technologies' rate of uptake. Over half of these technologies have already been developed to prototype stage or are already commercial but require further demonstration and dissemination.

Each technology is at a different point in the development or commercialization process. Some technologies still need further R&D to address cost or performance issues, some are ready for demonstration, and others have already proven themselves in the field and the market needs to be informed of the benefits and market channels needed to develop skills to deliver the technology. Our outlining of recommended actions in Table ES-1 is not an endorsement of any particular technology. Technology purchasers and users will ultimately decide regarding future development. However, the actions specified are intended to help identify whether a technology is both technically and economically viable and whether it is robust enough to accommodate the stringent product quality demands in various manufacturing establishments.

Seventeen emerging technologies could benefit from additional R&D. We suggest further R&D for several primary metal technologies, and several cross-cutting motor and utility technologies. In addition to private research funds, several of the identified technologies have received some R&D support from DOE or other public entities, including federal and state agencies.

There are also a large number of technologies that already have made some headway into the marketplace or are at the prototype testing stage, and therefore are candidates for demonstration for potential customers to gain comfort with the technology. While we recommend further demonstration and dissemination of these technologies, it was often difficult to understand what is limiting their uptake without more comprehensive investigation of market issues. Some of the technologies in this category are common in European countries or Japan but have not yet penetrated the U.S. market. Others are being newly developed in the United States and face challenges in reducing the risks perceived by potential purchasers. Two technologies, motor system optimization and pump efficiency improvement, are opportunities for training programs similar to those developed by DOE for the compressed air system management. For advanced industrial CHP turbine systems, the major recommended activity is removal of policy barriers. For other technologies, their unique markets will dictate the form of the educational and promotional activities. We urge the reader to follow up on any details in the specific technology profiles provided in Section VI of this report .

**Table ES-1. Summary of Profiled Emerging Energy-Efficient Industrial Technologies**

Technology	Sector	Total <sup>1</sup> Energy Savings	Sector <sup>2</sup> Savings	Simple Payback	Environ. Benefits	Other <sup>3</sup> Benefits	Suggested Next Steps	Likelihood of Success
Advanced forming	Aluminum	Medium	Medium	Immediate	None	P	R&D	High
Efficient cell retrofit designs	Aluminum	High	High	2.7	Somewhat	P	Demo	High
Improved recycling technologies	Aluminum	Medium	Medium	4.5	Significant	P	Demo	Medium
Inert anodes/wetted cathodes	Aluminum	High	High	4.0	Significant	P, Q	R&D	Medium
Roller kiln	Ceramics	Medium	High	1.9	Significant	P	Demo	Medium
Clean fractionation—cellulose pulp	Chemicals	Low	Low	1.9	Significant	P, O	Demo	Medium
Gas membrane technologies—chem.	Chemicals	Low	Low	10.2	Significant	Q, O	Dissem.	High
Heat recovery technologies—chem.	Chemicals	Medium	Medium	2.4	None	P, O	Dissem., Demo	Medium
Levulinic acid from biomass	Chemicals	Low	Low	1.5	Significant	P, O	Demo	High
Liquid membrane technologies—chem.	Chemicals	Low	Low	11.2	Significant	O	Dissem.	Medium
New catalysts	Chemicals	Medium	Medium	7.9	Somewhat		R&D	Medium
Autothermal reforming—ammonia	Chemicals	High	High	3.7	Significant	P	Dissem	Medium
Plastics recovery	Plastics	Medium	Medium	2.8	Compelling	P	Demo	High
Continuous melt silicon crystal growth	Electronics	Medium	High	Immediate	Somewhat	P, Q	R&D	High
Electron beam sterilization	Food	High	High	19.2	None	P, Q	R&D	Low
Heat recovery—low temperature	Food	Medium	Medium	4.8	None	P, Q	Dissem.	Low
Membrane technology—food	Food	High	High	2.2	Somewhat	P, Q	Dissem., R&D	Medium
Cooling and storage	Food	Medium	Medium	2.6	Somewhat	O	Dissem., Demo	Medium
100% recycled glass cullet	Glass	Medium	High	2.0	Significant		Demo	High
Hi-tech facilities HVAC	Crosscutting	Medium	High	4.0	None	P	Dissem.	Medium
Advanced lighting technologies	Crosscutting	High	High	1.3	None	P, Q, O	Dissem., Demo	High
Advanced lighting design	Crosscutting	High	High	3.0	None	P, Q, O	Dissem., Demo	Medium
Variable wall mining machine	Mining	Low	Low	10.6	None	P, S	Demo	Low
Advance ASD designs	Crosscutting	High	Medium	1.1	None	P, Q	R&D	High
Advanced compressor controls	Crosscutting	Medium	Low	0.0	None	P, Q	Dissem.	Medium
Compressed air system management	Crosscutting	High	High	0.4	None	P, Q	Dissem.	Medium
Motor diagnostics	Crosscutting	Low	Low	Immediate	None	P, Q	Dissem., Demo	High
Motor system optimization	Crosscutting	High	High	1.5	Somewhat	P, Q	Dissem., Train	Medium
Pump efficiency improvement	Crosscutting	High	High	3.0	None	P, Q	Dissem., Train	Medium
Switched reluctance motor	Crosscutting	Medium	Low	7.4	None	P, Q	R&D	Medium
Advanced lubricants	Crosscutting	Medium	Medium	0.1	Significant	P, Q	Dissem.	Medium
Anaerobic waste water treatment	Crosscutting	Medium	Low	0.8	Significant	O	Dissem., Demo	High
High-efficiency/low NO <sub>x</sub> burners	Crosscutting	High	Low	3.1	Significant	P	Dissem., Demo	Medium
Membrane technology wastewater	Crosscutting	High	Medium	4.7	Somewhat	P	Dissem., R&D	High
Process integration (pinch)	Crosscutting	High	Low	2.3	Somewhat	P	Dissem.	Medium
Sensors and controls	Crosscutting	High	Medium	2.0	Somewhat	P, Q	Dissem., R&D, demo	High

**Table ES-1. Summary of Profiled Emerging Energy-Efficient Industrial Technologies (continued)**

Technology	Sector	Total <sup>1</sup> Energy Savings	Sector <sup>2</sup> Savings	Simple Payback	Environ. Benefits	Other <sup>3</sup> Benefits	Suggested Next Steps	Likelihood of Success
Black liquor gasification	Pulp & paper	High	High	1.5	Somewhat	P, S	Demo	High
Condebelt drying	Pulp & paper	High	Medium	65.2	None	P, Q	Demo	Low
Direct electrolytic causticizing	Pulp & paper	Low	Low	N/A	Somewhat	P, Q	R&D	Medium
Dry sheet forming	Pulp & paper	Medium	Medium	48.3	Somewhat	Q	R&D, demo	High
Heat recovery—paper	Pulp & paper	High	Medium	3.9	Somewhat	P, S	Demo	Medium
High consistency forming	Pulp & paper	Medium	Medium	Immediate	Somewhat	P, Q	Demo	Medium
Impulse drying	Pulp & paper	High	Medium	20.3	None	P, Q	Demo	Medium
Biodesulfurization	Pet. Refining	Medium	Medium	1.8	None	Q	R&D, demo	High
Fouling minimization	Pet. Refining	High	High	N/A	None	P	R&D	Low
BOF gas and sensible heat recovery	Iron & steel	Medium	Medium	14.7	Significant	P	Dissem.	Low
Near net shape casting/strip casting	Iron & steel	High	High	Immediate	Somewhat	P, Q	R&D	High
New EAF furnace processes	Iron & steel	High	High	0.3	Somewhat	P	Field test	High
Oxy-fuel combustion in reheat furnace	Iron & steel	High	Medium	1.2	Significant	P	Field test	High
Smelting reduction processes	Iron & steel	High	High	Immediate	Significant	P	Demo	Medium
Ultrasonic dyeing	Textile	Medium	Medium	0.3	Compelling	P, Q	Demo	Medium
Advanced CHP turbine systems	Crosscutting	High	High	6.9	Significant	P, Q	Policies	High
Advanced reciprocating engines	Crosscutting	High	High	8.3	Limited	P, Q, O	R&D, demo	Medium
Fuel cells	Crosscutting	High	High	58.6	Significant	P, Q	Demo	Medium
Microturbines	Crosscutting	High	Medium	Never	Somewhat	P, Q, O	R&D, demo	Medium

**Notes:** 1. “High” could save more than 0.1% of manufacturing energy use by 2015, “medium” saves 0.01 to 0.1%, and “low” saves less than 0.01%.

2. “High” could save more than 1% of sector energy use by 2015, “medium” saves 0.1 to 1%, and “low” saves less than 0.1%.

3. “P”=productivity, “Q”=quality, “S”=safety, and “O”=other.

We assess the technology’s likelihood of success in the marketplace. While our study evaluates each technology in relation to a given reference technology, the reality of the market is that technologies compete for market share. We made a judgement (based on the energy savings, cost-effectiveness, importance of non-energy benefits, market conditions, data reliability, and potential competing technologies) as to the likelihood that the technology would succeed in the marketplace.

From a national energy policy perspective, it is important to understand which technologies have both a high likelihood of success and a high energy-savings. While various audiences may be interested in sector-specific or regional-specific technologies, the technologies listed in Table ES-2 are intended to provide guidance to those interested in the impact of energy-saving technologies on a more national level. This table also identifies the recommended next steps appropriate for each technology.

**Table ES-2. Technologies with High Energy Savings and a High Likelihood of Success**

Technology	Code	Total Energy Savings	Likelihood of Success	Recommended Next Steps
Efficient cell retrofit designs	Alum-2	High	High	Demonstration
Advanced lighting technologies	Lighting-1	High	High	Dissemination, demonstration
Advance ASD designs	Motorsys-1	High	High	R&D
Membrane technology wastewater	Other-3	High	High	Dissemination, R&D
Sensors and controls	Other-5	High	High	R&D, demonstration, dissemination
Black liquor gasification	Paper-1	High	High	Demonstration
Near net shape casting/strip casting	Steel-2	High	High	R&D
New EAF furnace processes	Steel-3	High	High	Field test
Oxy-fuel combustion in rehear furnace	Steel-4	High	High	Field test
Advanced CHP turbine systems	Utilities-1	High	High	Policies
Autothermal reforming-ammonia	Chem-7	High	Medium	Dissemination
Membrane technology - food	Food-3	High	Medium	Dissemination, R&D
Advanced lighting design	Lighting-2	High	Medium	Dissemination, demonstration
Compressed air system management	Motorsys-3	High	Medium	Dissemination
Motor system optimization	Motorsys-5	High	Medium	Dissemination, training
Pump efficiency improvement	Motorsys-6	High	Medium	Dissemination, training
High efficiency/low NO <sub>x</sub> burners	Other-2	High	Medium	Dissemination, demonstration
Process integration (pinch analysis)	Other-4	High	Medium	Dissemination
Heat recovery - paper	Paper-5	High	Medium	Demonstration
Impulse drying	Paper-7	High	Medium	Demonstration
Smelting reduction processes	Steel-5	High	Medium	Demonstration
Advanced reciprocating engines	Utilities-2	High	Medium	R&D, demonstration
Fuel cells	Utilities-3	High	Medium	Demonstration
Microturbines	Utilities-4	High	Medium	R&D, demonstration
Inert anodes/wetted cathodes	Alum-4	High	Medium	R&D
Advanced forming	Alum-1	Medium	High	R&D
Plastics recovery	Chem-8	Medium	High	Demonstration
Continuous melt silicon crystal growth	Electron-1	Medium	High	R&D
100% recycled glass cullet	Glass-1	Medium	High	Demo
Anaerobic waste water treatment	Other-1	Medium	High	Dissemination, demonstration
Dry sheet forming	Paper-4	Medium	High	R&D, demonstration
Biodesulfurization	Refin-1	Medium	High	R&D, demonstration

\*note – technologies in this table are listed in alphabetical order based on industry sector

## Conclusions and Recommendations for Future Work

For this study, we identified about 175 emerging energy-efficient technologies in industry, of which we characterized 54 in detail. While many profiles of individual emerging technologies are available, few reports have attempted to impose a standardized approach to the evaluation of the technologies. This study provides a way to review technologies in an independent manner, based on information on energy savings, economic, non-energy benefits, major market barriers, likelihood of success, and suggested next steps to accelerate deployment of each of the analyzed technologies.

There are many interesting lessons to be learned from further investigation of technologies identified in our preliminary screening analysis. The detailed assessments of the 54 technologies are useful to evaluate claims made by developers, as well as to evaluate market potentials for the United States or specific regions. In this report we show that many new technologies are ready to enter the market place, or are currently under development, demonstrating that the United States is not running out of technologies to improve energy efficiency and economic and environmental performance, and will not run out in the future. The study shows that many of the technologies have important non-energy benefits, ranging from reduced environmental impact to improved productivity. Several technologies have reduced capital costs compared to the current technology used by those industries. Non-energy benefits such as these are frequently a motivating factor in bringing technologies such as these to market.

Further evaluation of the profiled technologies is still needed. In particular, further quantifying the non-energy benefits based on the experience from technology users in the field is important. Interactive effects and intertechnology competition have not been accounted for and ideally should be included in any type of integrated technology scenario, for it may help to better evaluate market opportunities.

While this report focuses on the United States, state- or region-specific analysis of technologies may provide further insights into opportunities specific for the region served. Regional specificity is determined by the type of users (i.e., industrial activities) in the region, as well as the available technology developers. Combining the region-specific circumstances with the technology evaluations offered in this report may lead to varying policy choices for regional entities such as state governments, state or regional agencies, or utilities.

Our selection of a limited set of 54 technologies was an arbitrary constraint based on the funding available. A number of the initial technologies screened appeared very interesting and warrant further study, but were eliminated due to resource constraints. In addition, the initial list of candidate technologies should not be viewed as all-encompassing. The authors are aware that other promising existing technologies exist, and that by their nature new technologies will be continually emerging. Ideally, the effort reflected in this report should be the start of a continuing process that identifies and profiles the most promising emerging energy-efficient industrial technologies and tracks the market success for these technologies. An interactive database may be a better choice for it would allow the continuous updating of information, rather than providing a static snapshot of the industrial technology universe.

This report identifies and profiles many promising emerging energy-efficient industrial technologies, which can achieve high energy-savings, and have a good likelihood of success due to their economic, environmental, product quality, and other benefits. We recommend next steps that product developers and policy-makers could undertake for each of the most promising technologies. Follow-up assessments are needed to identify additional emerging technologies, and to track the emergence of the technologies profiled in this report.







## I. INTRODUCTION

Whether one is the general manager of a manufacturing plant looking to increase productivity or an environmentalist seeking to reduce greenhouse gas emissions, it is evident that technology plays a critical role in the nation's economy. From a policy-making perspective, the better we understand technology developments the more effective we will be in utilizing our future research dollars and in undertaking sound strategy development.

As just one example, few economic models today provide a reasonable characterization of both existing and emerging technologies. But even models with only a limited characterization of technology tend to forecast significantly different energy consumption patterns than those that reflect actual technology choices confronted by consumers and businesses (Laitner 2000a). Inappropriate characterization of technologies can lead to poor analysis and eventually less than optimal policy choices. Getting a clearer picture about emerging technologies will help to:

- Identify new R&D projects;
- Identify potential technologies for market transformation activities;
- Provide common information on technologies to a broad audience of policy-makers; and
- Offer new insights into technology development and energy efficiency potentials

The development of this report emerged from a desire across several research, development, and policy-making agencies to improve our common understanding of the status of emerging energy-efficient technologies in the industrial sector. Although many technologies save energy, often the driver for their adoption is reductions in capital costs and other non-energy benefits. It is important to better understand the developmental stories and drivers behind the emerging technologies. With the support of PG&E Co.,<sup>1</sup> NYSERDA, DOE, EPA, NEEA, and IEC, staff from LBNL and ACEEE produced the current report. The sponsors are not responsible for the report's content, or any errors or omissions.

This report focuses on key emerging energy-efficient technologies in the industrial sector. Our goal is to identify and assess these technologies from the viewpoint of both energy and non-energy benefits. While we focus on technologies that show a strong potential for energy savings, we also account for the non-energy benefits associated with such technologies, since often these non-energy benefits can be the key driver in overall technology adoption. We hope that this assessment further identifies the significant potential available in the United States and other countries for further advancement toward "greener" production.

This work complements the 1998 study, *Emerging Energy-Saving Technologies and Practices for the Buildings Sector* (Nadel et al. 1998), which provided data on technologies with the largest potential savings, including likely costs, savings, and date of commercialization. Similar to the 1998 report, the goal of this current effort has been to collect information on a broad array of potentially significant emerging energy-efficient industrial technologies and carefully characterize a sub-group of 54 emerging technologies.

The characterization of an emerging, energy-efficient technology is somewhat difficult. What was emerging a decade ago may now be standard practice. In this report our use of the term "emerging" denotes technologies that are both pre-commercial but near commercialization and technologies that have already entered the market but have less than 5 percent of current market share. We also have chosen technologies that are energy-efficient (i.e., use less energy than existing technologies and practices to produce the same product) as well as technologies that often have other non-energy benefits associated with their use.

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<sup>1</sup> The PG&E Co. program is funded by California utility customers and is administered by PG&E Co. under the auspices of the California Public Utilities Commission.

## II. OVERVIEW OF U.S. INDUSTRIAL ENERGY USE

### Introduction

Energy is a key input for our modern U.S. economy. In 1998, the United States consumed 94 Quadrillion Btu (99 EJ)<sup>2</sup> of primary energy or 25 percent of world primary energy use (EIA 2000).<sup>3</sup> Within the various sectors of the United States, the industrial sector remains a significant energy user, consuming nearly 40 percent of primary energy resources (Table 1). The industrial sector is extremely diverse and includes agriculture, mining, construction, and manufacturing. Table 1 identifies historical industrial energy consumption in relation to U.S. total primary energy consumption.

**Table 1. Historical Share of Industrial Primary Energy Use in the United States**

	Units	1950	1970	1990	1998
Total U.S.	Quads (EJ)	34.6 (36.5)	67.9 (71.6)	84.1 (88.7)	94.2 (99.4)
Total Industry	Quads (EJ)	16.2 (17.1)	29.6 (31.3)	32.1 (33.9)	35.4 (37.4)
Percent share	%	47%	44%	38%	38%

Source: EIA 2000

Energy is necessary to help our industries create useful products; however, we are increasingly confronted with the challenge of moving our economy and society toward a cleaner, more sustainable path of production and consumption. The development and use of cleaner, more energy-efficient technologies can play a significant role in limiting the environmental impacts associated with many industries while enhancing productivity and reducing manufacturing costs.

### Industry in Context

#### *Economic Output*

Industrial activities are still a key component of U.S. economic output. In 1997, industrial activities accounted for 24 percent of gross domestic product (GDP), which that year was \$8,300 billion, and employed 27 million full and part-time employees (BEA 2000). Within the industrial sector, manufacturing activity (consisting of all industrial activity outside of agriculture, mining, and construction) accounts for 70 percent of industrial value added (BEA 2000). Table 2 identifies the distribution of value added by various manufacturing activities throughout the United States. The table also provides aggregated totals for the four U.S. regions that correspond to the regions that are used in the reporting of manufacturing energy statistics.

<sup>2</sup> In this report we present energy consumption and energy intensity information in both english units (Btus) and standard international units (joules), as the latter is the unit of international communication on energy issues. When appropriate we do note conversion factors. One quadrillion Btu ( $10^{15}$ ) equals 0.95 EJ and one metric tonne equals 0.907 short tons.

<sup>3</sup> Primary energy reflects the losses associated with the conversion, transmission and distribution of electricity. For the U.S. economy as a whole we use an electricity conversion efficiency of 33 percent. For calculation of primary energy savings in 2015 for the technology evaluation we assume a conversion efficiency of 40 percent accounting for the future efficiency improvement in power generation by 2015 (due to increased use of combined cycles and combined heat and power by 2015).

**Table 2. Manufacturing Value Added by Sector, 1997**

	Total	Food & kindred products	Textile & apparel	Lumber and wood	Paper products	Chemical	Petro. products	Stone, clay, & glass	Primary metals	Fabric. metals & machin.	Electron. Equip.	Transprt. equip.	Other
<b>West</b>	18%	20%	13%	26%	11%	8%	25%	16%	11%	18%	36%	16%	18%
Alaska	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Arizona	1%	1%	0%	1%	0%	1%	0%	1%	1%	1%	5%	2%	1%
California	11%	11%	11%	7%	5%	5%	18%	8%	4%	12%	17%	7%	12%
Colorado	1%	2%	1%	1%	0%	0%	0%	1%	0%	1%	1%	1%	2%
Hawaii	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Idaho	0%	1%	0%	2%	0%	0%	0%	0%	0%	0%	1%	0%	0%
Montana	0%	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Nevada	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%
New Mexico	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	4%	0%	0%
Oregon	2%	1%	0%	8%	1%	0%	0%	1%	2%	1%	8%	1%	1%
Utah	1%	1%	0%	0%	1%	1%	1%	1%	1%	1%	0%	1%	1%
Washington	2%	2%	1%	5%	2%	0%	2%	2%	2%	1%	1%	5%	1%
Wyoming	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
<b>South</b>	32%	32%	59%	43%	40%	42%	43%	37%	28%	26%	26%	26%	30%
Alabama	2%	1%	5%	5%	5%	1%	1%	2%	4%	1%	1%	1%	1%
Arkansas	1%	2%	1%	3%	2%	1%	1%	1%	2%	1%	1%	1%	1%
Delaware	0%	0%	0%	0%	1%	2%	0%	0%	0%	0%	0%	1%	0%
District of Col.	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Florida	2%	3%	2%	3%	2%	2%	1%	4%	1%	1%	3%	2%	3%
Georgia	3%	4%	11%	6%	6%	2%	0%	4%	2%	1%	2%	3%	3%
Kentucky	2%	2%	3%	1%	2%	2%	2%	2%	3%	2%	1%	4%	2%
Louisiana	1%	1%	1%	2%	3%	4%	9%	1%	0%	1%	0%	1%	0%
Maryland	1%	2%	1%	0%	1%	1%	0%	1%	2%	1%	1%	0%	1%
Mississippi	1%	1%	2%	4%	1%	1%	2%	1%	1%	1%	1%	1%	1%
North Carolina	4%	2%	15%	5%	3%	6%	0%	5%	2%	2%	4%	1%	6%
Oklahoma	1%	1%	0%	1%	1%	0%	4%	1%	1%	1%	1%	1%	1%
South Carolina	2%	1%	8%	2%	4%	3%	0%	2%	1%	2%	1%	1%	1%
Tennessee	2%	2%	3%	3%	3%	2%	0%	3%	2%	2%	1%	3%	2%
Texas	7%	6%	4%	6%	4%	10%	20%	8%	4%	9%	10%	3%	4%
Virginia	2%	3%	3%	3%	3%	3%	0%	2%	1%	1%	1%	2%	4%
West Virginia	0%	0%	0%	1%	0%	2%	0%	1%	2%	0%	0%	0%	0%
<b>Midwest</b>	30%	34%	8%	21%	29%	26%	15%	29%	45%	39%	20%	48%	26%
Illinois	5%	7%	1%	2%	4%	5%	5%	4%	6%	8%	5%	3%	5%
Indiana	4%	2%	1%	4%	1%	4%	2%	3%	11%	4%	2%	7%	3%
Iowa	1%	3%	1%	1%	1%	1%	0%	2%	1%	2%	1%	1%	1%
Kansas	1%	1%	0%	1%	1%	1%	1%	1%	0%	1%	0%	2%	1%
Michigan	5%	3%	2%	2%	3%	3%	1%	5%	7%	7%	1%	16%	4%
Minnesota	2%	3%	0%	3%	5%	1%	1%	2%	1%	3%	2%	1%	3%
Missouri	2%	4%	1%	1%	1%	3%	1%	2%	1%	2%	1%	5%	2%
Nebraska	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%
North Dakota	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ohio	6%	5%	1%	4%	5%	6%	4%	8%	14%	8%	4%	10%	4%
South Dakota	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Wisconsin	3%	4%	1%	3%	9%	1%	0%	2%	3%	5%	2%	2%	3%
<b>Northeast</b>	19%	15%	19%	10%	20%	24%	17%	18%	17%	17%	18%	10%	26%
Connecticut	2%	1%	1%	0%	2%	2%	1%	1%	1%	2%	2%	2%	2%
Maine	0%	0%	0%	1%	3%	0%	0%	0%	0%	0%	0%	0%	0%
Massachusetts	2%	1%	2%	1%	2%	1%	1%	1%	1%	3%	4%	1%	4%
New Hampshire	1%	0%	1%	1%	1%	0%	0%	0%	1%	1%	1%	0%	1%
New Jersey	3%	3%	3%	0%	3%	9%	10%	2%	1%	2%	1%	0%	3%
New York	5%	5%	8%	2%	4%	4%	3%	5%	3%	4%	4%	3%	11%
Pennsylvania	5%	5%	4%	4%	5%	7%	3%	7%	9%	5%	6%	3%	4%
Rhode Island	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%
Vermont	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
<b>U.S. Total</b>	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
<b>U.S. Total</b>	1,378.9	118.5	53.9	42.8	55.0	158.8	35.2	33.7	53.2	258.2	157.3	136.1	276.4
<b>(Billion current)</b>													

Note: Other manufacturing includes: tobacco products (SIC 21), furniture and fixtures (SIC 25), printing and publishing (SIC 27), rubber and plastics (SIC 30), leather products (SIC 31), instruments and related products (SIC 38), and miscellaneous manufacturing (SIC 39). Source: BEA 2000

As the table indicates, the South and Midwest accounted for nearly two-thirds of total manufacturing output in 1997. On a state level, the largest contributors to manufacturing GDP were California, Texas, Ohio, New York, Pennsylvania, Illinois, and Michigan, which together accounted for 40 percent of manufacturing output in 1997.

### *Energy Consumption*

Energy expenditures between 1994 and 1996, the most recent years for available statistics, fluctuated between \$60 and \$70 million, which accounted for about 2 percent of total costs, although in some industries the share could have been as high as 6 percent (Census 1998). EIA produces periodic detailed statistics on energy consumption in the U.S. manufacturing sector.<sup>4</sup> The most recent detailed data available are from 1994. Table 3 summarizes historical energy consumption by fuel between 1985 and 1994.

**Table 3. U.S. Manufacturing Energy Consumption and Fuel Share by Fuel Type, 1985, 1994**

Fuel	1985		1994		% change
	TBtu (PJ)	Fuel share	TBtu (PJ)	Fuel share	
Net electricity	2,173 (2,293)	16%	2,656 (2,802)	16%	22%
Residual fuel oil	505 (532)	4%	441 (465)	3%	-13%
Distillate fuel oil	185 (195)	1%	152 (160)	1%	-18%
Natural gas	4,647 (4,903)	34%	6,141 (6,479)	37%	32%
LPG	96 (101)	1%	99 (104)	1%	3%
Coal	1,304 (1,376)	10%	1,198 (1,264)	7%	-8%
Coke and breeze	590 (623)	4%	703 (742)	4%	19%
Other	4,102 (4,328)	30%	5,126 (5,408)	31%	25%
Total final energy	13,615 (14,365)	100%	16,515 (17,424)	100%	21%
Total primary energy*	18,027 (19,020)		23,113 (24,386)		21%

Source: EIA 1988, 1997

We used an electricity efficiency factor of 33 percent to convert from final to primary energy.

As the table indicates, energy use increased by 21 percent between 1985 and 1994, which translates into a growth of about 2 percent per year, slower than the rate of manufacturing economic growth over the same period. There has been a slow transition to more flexible fuels (natural gas, electricity), and the use of other fuels (primarily waste gas and biomass-derived fuels), which combined account for over 80 percent of the total fuel use in manufacturing. The use of oil and coal has declined even though overall energy consumption grew.

<sup>4</sup> We discuss manufacturing energy use in detail in this section due to availability of data. Manufacturing accounts for roughly 70 percent of total industrial energy use.

**Table 4. 1994 Manufacturing Energy Consumption by Process and Fuel (TBtu)**

	Electricity	Residual fuel oil	Distillate fuel oil	Natural gas	LPG	Coal	Coke & other	Total
Boilers	28	313	42	2,396	15	875	2,381	6,050
Total Process Use	2,075	106	51	2872	54	302		5,460
Process heating	284	103	29	2702	49	299	687	4,153
Process cooling	138			21	2			161
Machine drive	1,367	3	18	95	3	3		1,489
Electro-chemical	271							271
Other process use	15		4	53	1			73
Non Process Use	457	14	49	726	25	8		1,279
HVAC	217	5	7	351	5	3		588
Lighting	185							185
Facility support	46	3	1	30	1			81
On-site transport	4		35	1	19			59
Conventional electricity generation		5	4	335	1	6		351
Other	4	1	2	9		0		16
Not allocated	96	9	9	148	4	13	2,760	3,039
Total	2,656	441	152	6,141	99	1,198	5,828	16,515

Source: EIA 1997

These fuels are used to operate a variety of manufacturing operations including process heating, cooling, motor drive, and providing general utilities (e.g., power or steam). Table 4 provides information on the breakdown of fuel use by process for manufacturing in 1994. Based on recent LBNL analysis (Einstein et al. 2000), we reallocated some of the coke/other fuels that were previously not allocated to boiler inputs and coke for process use in the metals industry. As the table indicates, the production of steam in boilers for electricity generation<sup>5</sup> and process use accounts for the largest end-use within manufacturing, followed by process heating and machine drive. Process energy efficiency measures that reduce process steam consumption (e.g., drying measures in the pulp and paper industry) can also reduce boiler fuels use, as do direct boiler efficiency measures. The majority of natural gas is used in boilers and for process heating (e.g., furnaces), while half the electricity use is used for machine drive. When total motor systems are accounted for, a recent study found that process motor use accounted for 63 percent of all electricity use in industry in 1994 (Xenergy 1998).

The consumption of energy for various processes is not equally divided among all industries. Rather, within manufacturing, there exist a set of activities in which the energy requirements to produce a unit of output are significantly higher than average energy requirements for manufacturing overall. These “energy-intensive” sectors account for 80 percent of primary energy use in manufacturing but only a third of manufacturing value added. Energy-intensive sectors include paper; chemicals; petroleum and stone, clay, and glass products; primary metals; and food and kindred products.<sup>6</sup> These industries are often a prime target for emerging energy-saving technologies since they tend to better leverage energy savings. At the same time, some of the energy intensive sectors are growing more slowly and are less likely to make new capital investments as compared to some of the faster growing industries such as electronics and metal fabrication. In both cases, non-energy benefits associated with the investment in energy-saving technologies can be a key factor in justifying the expenditures on new equipment.

Table 5 identifies the regional distribution of manufacturing energy use in 1985 and 1994 with a breakdown of manufacturing sectors into energy-intensive and other manufacturing. Similar to the trends in manufacturing value-added, the South and Midwest accounted for the majority (three-fourths) of the

<sup>5</sup> Cogeneration or CHP is an important aspect of industrial process use that is not fully captured in Table 4. In 1994, 128 TWh of electricity was produced by cogeneration in manufacturing, as compared to a net purchased amount of 778 TWh. Over a third of cogenerated electricity was produced by steam turbines connected to boilers or high-temperature processes.

<sup>6</sup> Food and kindred products is normally included in energy-intensive since it too consumes a large amount of energy due to the high volume of product throughput even though the manufacturing processes themselves are less energy-intensive than the other energy-intensive sectors.

country's manufacturing energy use. The energy intensive sectors' share of energy consumption was roughly three or more times greater than less-intensive sectors in all U.S. regions.

**Table 5. Manufacturing Primary Energy Consumption by Region: 1985, 1994**

	1985		1994	
<b>NORTHEAST</b>	<b>TBtu (PJ)</b>	<b>Percent</b>	<b>TBtu (PJ)</b>	<b>Percent</b>
Energy-intensive	1,664 (1,756)	9%	1,662 (1,754)	7%
Other	657 (694)	4%	740 (781)	3%
<b>MIDWEST</b>				
Energy-intensive	3,793 (4,002)	21%	4,732 (4,993)	20%
Other	1,122 (1,184)	6%	1,545 (1,630)	7%
<b>SOUTH</b>				
Energy-intensive	6,859 (7,236)	38%	9,294 (9,806)	40%
Other	1,348 (1,423)	7%	1,954 (2,062)	8%
<b>WEST</b>				
Energy-intensive	2,075 (2,189)	12%	2,536 (2,676)	11%
Other	508 (536)	3%	650 (686)	3%
<b>US TOTAL</b>				
Energy-intensive	14,381 (15,172)	80%	18,224 (19,228)	79%
Other	3,647 (3,848)	20%	4,888 (5,158)	21%
<b>Total</b>	<b>18,027 (19,020)</b>	<b>100%</b>	<b>23,113 (24,386)</b>	<b>100%</b>

Source: EIA 1988, 1997

Note: assuming an electricity conversion efficiency of 33 percent for both 1985 and 1994.

## Technology Change in Industry

The demand for energy to produce manufactured products is related to the volume of production as well as the efficiency of the equipment used in the manufacturing processes. A broad proxy for efficiency is its inverse, energy intensity, or the amount of energy required to produce a unit of output. Research about the United States has shown that since the first oil price shock in 1973, manufacturing energy consumption would have been significantly higher were it not for decreases in energy intensity.<sup>7</sup>

As long as they can remain competitive, businesses will often choose to operate existing equipment and technology throughout its useful lifetime, which can run for 20 years or more for large pieces of equipment such as cement kilns or blast furnaces. At some point, however, businesses are faced with investment in new capital stock. At this decision point, new and emerging technologies compete for capital investment alongside more established or mature technologies. Even if a standard technology is chosen, it is likely to be more efficient than the equipment it is replacing. Understanding the dynamics of the decision-making process is important to better perceive what drives technology change and its overall effect on industrial energy use.

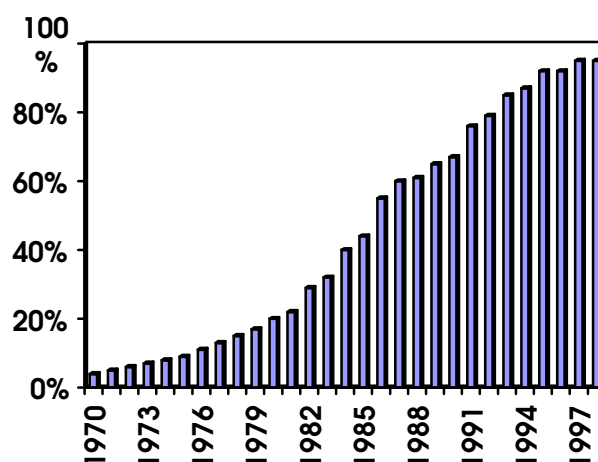
Barriers for technology transfer in the industrial sector include corporate decision-making rules (e.g., high hurdle rates, split incentives between various parts of a company), lack of information, limited capital or technology availability, shortage of trained personnel (especially in small and medium-sized enterprises), low energy prices, perceived risk, and the "invisibility" of energy savings.

Many new technologies follow a traditional "S" curve adoption path whereby a small segment of the industry, known as early adopters, embraces a new and unproven technology despite high costs and potential risks. As the technology becomes more common, the perceived risks decrease and the cost of the technology declines. The period needed to achieve a significant market share may vary and depends on the technology characteristics, as well as characteristics of the market and the particular sector. De Canio and

<sup>7</sup> Golove and Schipper (1996) performed a long-term analysis of the U.S. manufacturing sector from 1958 to 1991, which found that "declines in energy intensity played the dominant role in limiting actual energy consumption." Belzer et al. (1995) also found that energy intensity declines accounted for over half of the energy savings in the industrial sector.

Laitner (1997) point out that the current approaches to model technology diffusion tend to underestimate the rate since they do incorporate cost information (i.e., an investment approach) but lack the representation of the influence of time and the impact of an increasingly critical mass of technology adopters (De Canio and Laitner 1997). Figure 1 shows a typical “S” curve of the adoption of continuous casting technology in the U.S. iron and steel industry. Although the technology eventually reached saturation during the 30-year period, it took much longer in the United States than in other steel producing countries.<sup>8</sup> Many innovation and energy policies focus on accelerating the rate of adoption of specific technologies by reducing the costs or perceived risks of the technology.

**Figure 1. Continuous Casting Use in the United States (1970-1998)**



Source: IISI 2000a

Various programs try to reduce several barriers to adoption. A wide array of policies to increase the implementation rate of new technologies has been used and tested in the industrial sector in industrialized countries with varying success rates. We do not discuss general programs and policies in this report but refer to the literature (see Alliance et al. 1997; Bernow et al. 1999; Martin et al. 1999; Interlaboratory Working Group 2000; and Worrell, Bode, and de Beer 1997). With respect to technology-diffusion policies, there is no single instrument to reduce barriers; instead, an integrated policy accounting for the characteristics of technologies, stakeholders, and countries addressed is needed. RD&D projects often reduce risk and lower initial investment costs. Technology procurement programs such as the “golden carrot” lower the initial risk to technology developers by subsidizing the research and product development for more efficient technologies. “Demand-pull” programs seek to organize buyer groups to create a more ready market for emerging technologies. Financial incentive programs such as tax credits or other financial instruments seek to underwrite the first cost of the investment by the purchaser. All of these policies aim to more rapidly increase the share of the technology than would have been the case in the absence of a policy instrument (Worrell, Bode, and de Beer 1997).

## The Future Of Energy Use In Industry

In recent years, several studies have been undertaken related to modeling and forecasting the future of industrial or manufacturing energy use in the United States. EIA uses the National Energy Modeling System (NEMS) model to develop base case and alternative scenarios for energy consumption in various economic sectors, including industry. Other forecasting studies have incorporated various levels of policies usually working off of the NEMS baseline as the business-as-usual case. Table 4 identifies some of the main characteristics of industrial energy use forecasting studies developed in recent years.

<sup>8</sup> In Italy, South Korea, and Japan, for example, 96 percent or more of steel was continuously cast by 1993, whereas only 85 percent was continuously cast in the United States at that time (IISI 1996).

**Table 6. U.S. Industrial Energy Use Forecasting Studies**

Study	Model	Key Policies
Annual Energy Outlook 2000 (AEO 1999)	NEMS	Reference case incorporates existing policy trends. Includes sensitivity cases to low and high economic growth and low and high oil prices.
Scenarios for a Clean Energy Future (Interlaboratory Working Group 2000)	NEMS (with modified baseline and policy inputs)	Voluntary agreements, information programs, investment-enabling programs, regulations, R&D programs, cap and trade system (advanced scenario)
Energy Innovations (Alliance to Save Energy, et al. 1999)	NEMS (with the use of LIEF model to estimate policy impacts)	Incentives, increased R&D, increased use of recycled feedstock, overcoming barriers to combined heat and power production
America's Global Warming Solutions (Bernow et al. 1999)	LIEF (benchmarked in 1998 to NEMS)	Technical assistance, information programs, tax credits, R&D

In its *Annual Energy Outlook*, the EIA main reference case forecasts that primary industrial energy consumption will grow by 0.9 percent per year between 1998 and 2020 from 35.0 Quads (36.9 EJ) to 42.2 Quads (44.5 EJ) (EIA 1999). Similar conclusions are reached with the baseline or business-as-usual forecasts from the *Scenarios for a Clean Energy Futures*, *Energy Innovations*, and *America's Global Warming Solutions*, which all forecast baseline growth rates from 0.7 to 0.9 percent per year, even though the initial consumption levels vary by study. Others argue that the rise of the "Internet economy" is more rapidly supplanting our demand for traditional manufactured goods than we currently acknowledge and we may begin to see much slower growth in the business-as-usual case.<sup>9</sup>

In the three policy change forecasts, there is a consensus that through various policy instruments and further reducing industrial energy consumption, various policies can make a difference in accelerating the rate of technology adoption. All three suggest that it is possible to achieve a future in which industry consumes the same energy as today but has managed to continue to grow economically. The models used to forecast industrial energy use do not include methodologies for technological choice; instead, they include estimated parameters that simulate technological improvements. Therefore, the approaches taken by these models have limited use in exploring how policies can accelerate technology adoption, but can provide useful information on the impacts of accelerated adoption. Enhancing the models to incorporate technology choice is a fertile area for future research.

Not all efficiency technologies are potential future winners. Increasing the rate of adoption of efficient technologies often requires additional investment of time and resources to identify, assess, and integrate these new technologies into the marketplace. Our report contributes to this process by identifying what we believe to be some of the *key emerging energy-efficient technologies* that have the potential to help accelerate U.S. industry towards a more rapid improvement of energy efficiency than would be the case in business-as-usual circumstances. These technologies also can help transition our industrial base to the clean production approaches needed in the near future. The selected emerging energy-efficient industrial technologies would be in the start of the S-curve, as depicted in Figure 1.

<sup>9</sup> Laitner (2000b) argues in particular argue that "mainstream forecasts may be overestimating U.S. energy and carbon dioxide emissions in the year 2010 by up to 5 percent—while significantly underestimating overall U.S. economic growth." In the industrial sector, the production of materials needed for construction (stone, clay, and glass materials) and paper production are particularly likely to face growing competition from the Internet.



### III. METHODOLOGY AND APPROACH

As we noted in the introduction, emerging technologies are defined as those technologies that are either currently under development, but close to commercialization (i.e., could be reasonably expected to enter the marketplace by 2005), or have a low market penetration (i.e., it is commercialized but has achieved a less than 5 percent market share) or are pre-commercial. The set of emerging technologies evolves over time as industry continues to learn about newer and more improved manufacturing methods, and new technologies emerge from the laboratory and enter the marketplace.

#### Preliminary Screening of Technologies

The first step in our technology assessment was to collect limited information on a broad “universe” of potential technologies. Our key sources of information included the U.S. Department of Energy, Office of Industrial Technologies; the Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET); LBNL and ACEEE reports; and information from the sponsors of the project. Due to time constraints we did not attempt to collect any primary data on technology performance. It is important to note that it is likely that promising technologies were over looked.

Oftentimes, no one source provided all of the information we sought for our assessment (energy use, energy savings compared to average current technology, investment cost, operating cost savings, lifetime, etc.). We therefore made our best effort to combine readily available information along with expert judgement where necessary.

Our three key preliminary screening criteria, described in detail below, were:

- Potential for energy savings
- Ratio of first costs of new technology to replacement cost for existing processes
- Other benefits

From these screening criteria we developed an initial scoring rating—with a maximum rating of 100 points—to help select technologies for final screening. We also noted whether a technology has a low market penetration or whether the technology is pre-commercial. Below we discuss the rating criteria and scoring criteria, and we then present our initial screening results in Table 8.

#### Rating Criteria

##### *Potential for Energy Savings*

We sought to identify technologies that could have a large potential impact in terms of saving energy. These may be technologies that are specific to one process or one industry sector, or so-called “cross-cutting” technologies that are applicable to a variety of sectors. *High energy savings* technologies were rated as those whose primary energy savings in 2010 could be 0.1 percent or greater of primary energy consumption in 1994. We chose 1994 as our energy base-year since that is the year in which the most recent detailed manufacturing energy consumption statistics were published (EIA 1997)<sup>10</sup>. *Medium energy savings* are those in which the industry-wide potential energy savings in 2010 could be between 0.01 percent and 0.009 percent of primary industrial energy consumption. *Low energy savings* are those in which potential savings could be below 0.009 percent.

In estimating primary energy savings, we first identified the *specific energy savings* of each technology by comparing the energy used by the emerging technology to the energy required by current processes. Our second step was to “scale up” this savings estimate to see how much energy savings—for industry overall—this technology would achieve by 2010. For the most part, we derived specific energy savings information from various technology assessment studies noted above.

In scaling up the technology-specific energy savings to achieve a rough national estimate of energy savings, we relied on our general knowledge of the various industrial processes to which this technology could be applied. We also took into account *structural limitations* to the penetration of the technology. For example, a mechanical pulping technology is limited by the total throughput of pulp to which the measure

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<sup>10</sup> 1998 energy data will not be available from EIA until after the conclusion of this project.

can be applied. Additionally, we recognized that market penetration, in the absence of significant policy support, can take time given the slowness of stock turnover in many industrial facilities.

Our estimate of national energy savings is merely meant to be indicative of the relative impact of any particular technology on a national scale. Given time and resource constraints, our goal in calculating potential energy savings in the pre-screening stage was simply to estimate the relative impact (high, medium, low) of any particular technology, not specifically to provide a highly detailed calculation of energy savings.

#### *Investment Cost for New Technology/Replacement Cost for Existing Processes*

Because of the time-consuming nature of collecting detailed cost data, our goal for the preliminary screening was to develop a shorthand indicator of the relative expense of investing in the emerging technology. An emerging technology that's first cost was estimated to be 1 to 5 times or more expensive than replacement using existing practices was given a rating of "3," while a technology that's first cost was estimated as the same or cheaper was rated as "2" or "1," respectively.

While such an approach can be useful as a pre-screening device, we realize that it has limitations, primarily that a more expensive technology may still be a good investment particularly if it can provide significant energy savings over a long period of time. Thus we have further quantified the economic benefits of each technology, using metrics such as the cost of conserved energy and the internal rate of return.

#### *Other Benefits*

Usually, energy-efficient technologies are not purchased solely for their energy benefits but also because of other, non-energy benefits accrued from their use. We grouped these non-energy benefits into four categories: environmental, productivity, product quality, and safety (see below for details). These additional benefits—and not the energy savings—can often be the determining factor in deciding to purchase the technology. We judged how these other non-energy benefits would affect the technology choice decision. For technologies where these non-energy benefits were thought to be the dominant factor in selecting the technology, a rating of “compelling” was used. For a technology with non-energy and energy benefits that were judged of equal importance, a rating of “significant” was applied. For technologies with non-energy benefits, but energy savings drove the technology decision, a rating of “somewhat” was used. If the technology has no significant non-energy benefits that would influence the technology selection, a rating of “none” was applied. This terminology was also used in evaluating the non-energy benefits in the final profiles.

*Environmental benefits* refer to reductions in air emissions (e.g., sulfur dioxide, nitrogen oxides, particulate matter, dust) or reductions in waste streams that result from the use of the emerging technology. *Productivity improvements* can often result if the emerging technology reduces down-time required for operation and maintenance, reduces operation and maintenance costs, or increases yield. *Product quality improvements* and *safety benefits* often result from the fact that process energy requirements are more carefully controlled and monitored. In the preliminary screening we noted any other benefits that accompanied a particular technology or measure, but did not attempt to quantify them. We included the presence of other benefits in our rating system.

### **Rating Preliminary Technologies**

Based on the initial screening process, the most attractive technologies are those that: (1) have a high potential energy savings; (2) have lower relative first costs compared to existing technologies; and (3) have other significant benefits. While some technologies score high on all of these characteristics, most have a mixed score. We formalized this approach in a very simple rating system shown in Table 7 below.

**Table 7. Preliminary Screening Rating System**

	Energy Savings	Cost	Other Benefits
High	40	10	30
Medium	20	20	20
Low	10	30	10
None	N/A	N/A	0

As the rating system above indicates, a technology with high potential energy savings, low cost, and the presence of other high or compelling other benefits would be given a rating of 100. The lowest score a technology can receive is "20," where energy savings is low ("10"), cost is high ("10") and there are no other benefits ("0"). Table 8 below identifies all the technologies considered in our preliminary screening. In some cases we abbreviated the technology description for space considerations.

### Detailed Assessment of Selected Emerging Energy-Efficient Industrial Technologies

After establishing a preliminary selection of technologies based on the preliminary screening, our next step in the technology assessment process was to convene a workshop that brought together the research staff and sponsors to review the preliminary technology selection and to refine the criteria for the detailed assessment. Our aim was to develop a broad enough range of criteria that would allow for a thoughtful evaluation and presentation of the technologies, while at the same time not trying to "dilute" the evaluation with too many data points, which often may rely on too much speculative information.

The workshop was held in Washington, D.C. on April 27, 2000, and helped the research and sponsor group develop a consensus for moving forward with the detailed assessment of the short list of technologies. The detailed assessment consists of a 1-2 page write-up of the technology or measure and a final evaluation table detailing 8 main areas:

- Market and sectoral information
- Base-case information
- New measure information
- Energy savings information and analysis
- Cost information and analysis
- Key non-energy factors
- Evaluation
- Sources and Contacts

The write-up describes the measure, including the issues surrounding the analysis of energy savings and cost-effectiveness, key non-energy factors, and background on the evaluation of the technology, and recommends next steps advance the technology.

*Market information* includes a description of the industries to which the technology/measure is applicable (e.g., cement, iron and steel, Crosscutting). We also provide information on the end-uses for the technology (i.e., process, process heating, process cooling, electrochemical processes, utilities, ventilation and space conditioning, lighting, motor and drives), the principal energy types used by the technology (i.e. electricity, gas, oil, coal, biomass, waste fuel, fuels [multiple fossil fuels], other), and the primary market segment (i.e., retrofit, new, replace on failure, original equipment manufacturers). There may be more than one market segment for which the technology is applicable; we used our judgement to identify the most predominant segment. Finally, we also included a key output driver or the energy consumption for our 2015 base-case related to that sector. For example, a steel furnace technology would have as a 2015 base-case reference value the expected steel output for that year.

*2015 Base-case* includes a description of the current technology or practice, the volume of production or annual operating hours associated used in the baseline and savings analysis, and baseline energy consumption for the existing process (i.e., fuels, electricity, primary).

*New measure information* includes a description of the new technology, energy consumption information (i.e., fuel, electricity, primary energy), information on the current status of the technology (i.e., commercialized, field testing, prototype, research), the expected date of commercialization (if known), and the lifetime of the technology.

**Table 8. Technologies and Measures Considered in Preliminary Screening Analysis**

Technology/Measure	Sector	Technology/Measure	Sector
1 Ceramic Filters	Mining	56 Oxy-Burners (Chemicals)	Chemicals
2 Ramex Tunneller	Mining	57 Silicones From Sand	Chemicals
3 Variable Wall Mining Machine	Mining	58 Chlorate Cathodes for ClO <sub>2</sub>	Chemicals
4 Vibration Fluidized Bed	Mining	59 Electrodeionization	Chemicals
5 Membrane Technology - Food	Food Processing	60 Advanced Chlorine Cells	Chemicals
6 Electron Beam Sterilization	Food Processing	61 Advanced Cleanroom HVAC	Cross-Cutting
7 Heat Recovery - Low Temp.	Food Processing	62 Selective Cracking-Ethylene	Chemicals
8 Cooling And Storage	Food Processing	63 Catalytic Autothermal Oxydehydrogenization	Chemicals
9 Heat Recovery Food – High Temp.	Food Processing	64 Advanced Reactor Design-Methanol	Chemicals
10 Freeze Concentration	Food Processing	65 Advanced Recovery-Fractionation	Chemicals
11 Supercritical Extraction	Food Processing	66 Melt Crystalization-Benzene	Chemicals
12 Controlled Atmosphere Packaging	Food Processing	67 Alkane Functionalization Catalysts	Chemicals
13 4 Or More Effect Evaporator	Food Processing	68 Dividing Wall Column-Olefins	Chemicals
14 Efficient Cooling Systems	Food Processing	69 Autothermal Reforming-Ammonia	Chemicals
15 Condi-Cyclone Dryers	Food Processing	70 Membrane Reactor /Ammonia	Chemicals
16 Heat Pump Dryer	Food Processing	71 Adiabatic Pre-Reformer (Ammonia)	Chemicals
17 Ultrasonic Drying	Textile	72 Ammonia Process Control	Chemicals
18 Suction Slot Dewatering	Textile	73 Membrane Reactor/Steam Reforming	Chemicals
19 Direct Contact Water Heating	Textile	74 Ammonia Synthesis Using Sorbents	Chemicals
20 Textile Heat Recovery	Textile	75 Biodesulfurization	Refining
21 Dyeing Vacuum System	Textile	76 Fouling Minimization	Refining
22 Automated Dyebath Reuse	Textile	77 Liquid Membranes In Refining	Refining
23 Membrane Technology Textiles	Textile	78 Low Profile FCC	Refining
24 Improved Drying Systems	Lumber And Wood	79 Ammonia Absorption Refrigeration	Refining
25 Direct Electrolytic Causticizing	Pulp And Paper	80 Hydrogen Purification	Refining
26 High Consistency Forming	Pulp And Paper	81 Froth Flotation Plastics Recovery	Plastics
27 Black Liquor Gasification	Pulp And Paper	82 Heat Recovery In Plastics	Plastics
28 Impulse Drying	Pulp And Paper	83 Water As Cooling Refrigerant	Plastics
29 Heat Recovery - Paper	Pulp And Paper	84 Fluidized Bed/Plastics Recovery	Plastics
30 Dry Sheet Forming	Pulp And Paper	85 Tunnel Kiln – Plastics	Plastics
31 Condebelt Drying	Pulp And Paper	86 Roller Kiln	Ceramics
32 Flotation Deinking/Stickies Removal	Pulp And Paper	87 Innovative Tunnel Kiln	Bricks/Tiles
33 Bacterial Reduction Of Sulfur	Pulp And Paper	88 Process Control-Glass Tanks	Glass
34 Press Drying	Pulp And Paper	89 Ion-Exchange System - Float Glass	Glass
35 Biopulping	Pulp And Paper	90 New Glass Melting Technologies	Glass
36 Fluidized Bed For Biomass Waste	Pulp And Paper	91 Efficient Burners For Glass Furnaces	Glass
37 Air/Steam Impingement Drying	Pulp And Paper	92 Pre-Heat Technologies-Glass	Glass
38 Freeze Concentration Mill Effluent	Pulp And Paper	93 Electric Forehearth/Indirect Cooling	Glass
39 Fiber Loading Equipment/PCC	Pulp And Paper	94 100 percent Recycled Glass Cullet	Glass
40 Thermodyne Pulp Dryer	Pulp And Paper	95 Cogen--Exhaust Gas Drying Of Blast Furnace Slag For Blended Cements	Cement
41 Pressurized Groundwood-Super	Pulp And Paper	96 New Refractory Materials - Cement	Cement
42 Direct Drying Cylinder Firing	Pulp And Paper	97 Fluidized Bed Kiln	Cement
43 Molten Metal Paper Dryer	Pulp And Paper	98 Mineral Polymers	Cement
44 Multi-Port Drying Cylinder	Pulp And Paper	99 Heat Recovery For Cogeneration	Cement
45 Fluidized Bed Heat Exchanger	Pulp And Paper	100 Advanced Communion	Cement
46 New Refractory Materials	Pulp And Paper	101 High Efficiency Roller Mills	Cement
47 Heat Recovery -Printing	Printing	102 Near Net Shape Casting/Strip Casting	Iron and Steel
48 New Catalysts	Chemicals	103 New EAF Furnace Processes	Iron and Steel
49 Clean Fractionation	Chemicals	104 Smelt Reduction Processes	Iron and Steel
50 Levulinic Acid From Biomass	Chemicals	105 Oxy-Fuel/Reheat Furnace	Iron and Steel
51 Liquid Membranes	Chemicals	106 BOF Gas/Sensible Heat Recovery	Iron and Steel
52 Gas Membranes	Chemicals	107 High Levels Of PCI	Iron and Steel
53 Heat Recovery Technologies	Chemicals	108 Coke Oven Gas Cogeneration	Iron and Steel
54 Oxidation Of Benzene To Phenol	Chemicals	109 "Pickliq" HCL Regeneration	Iron and Steel
55 Corn Fiber Fractionation	Chemicals	110 Intelligent Inductive Processing	Iron and Steel

**Table 8. Technologies And Measures Considered In Preliminary Screening Analysis (Continued)**

Technology/Measure	Sector	Technology/Measure	Sector
111 Improved EAF Refractories	Iron and Steel	143 Pump Efficiency	Cross-Cutting
112 Coke Dry Quenching	Iron and Steel	144 Pinch Analysis	Cross-Cutting
113 Non-Recovery Coke Ovens	Iron and Steel	145 Switched Reluctance Motor	Cross-Cutting
114 Waste Oxides Recycling In	Iron and Steel	146 Advanced Lighting	Cross-Cutting
115 Heat Recovery In Sinter Plants	Iron and Steel	147 Anaerobic Waste Water Treatment	Cross-Cutting
116 Scrap Pre-Heating	Iron and Steel	148 Motor System Optimization	Cross-Cutting
117 Recuperative Burners	Iron and Steel	149 Fuel Cells	Cross-Cutting
118 Steel Strapping/Mini-Mill	Iron and Steel	150 Microturbines	Cross-Cutting
119 Improved Recycling	Aluminum	151 Metalax Stress Relief Method	Cross-Cutting
120 Efficient Cell Designs	Aluminum	152 Energy Management Systems	Cross-Cutting
121 Inert Anodes	Aluminum	153 Clean Energy Systems	Cross-Cutting
122 Advanced Forming	Aluminum	154 Heat Pumps	Cross-Cutting
123 Pot Lining Additive	Aluminum	155 Written Pole Motor	Cross-Cutting
124 Improve Casting Furnace	Aluminum	156 Heat Recovery Turbine	Cross-Cutting
125 Fy-Gem Grain Refinement	Aluminum	157 Copper Rotor Motor	Cross-Cutting
126 Twin Chamber Pulp Lifter	Alumina	158 Permanent Magnet Motor	Cross-Cutting
127 Solvent Recovery Using Nitrogen	Chemicals	159 Efficient Transformers	Cross-Cutting
128 Continuous Melt Silicon	Electronics	160 General Heat Recovery	Cross-Cutting
129 Advanced Polysilicon	Electronics	161 Molten Metal Filtering	Cross-Cutting
130 Adv. Electroplating	Autos	162 GFX Drainwater Heat Recovery	Cross-Cutting
131 Advanced Coating Processes	Autos	163 High-Efficiency Welding	Cross-Cutting
132 Sensors And Controls	Cross-Cutting	164 Furnace Process Modeling	Cross-Cutting
133 Low NO <sub>x</sub> Burners	Cross-Cutting	165 Unconventional Yield Improvement	Cross-Cutting
134 Advanced Lubricants	Cross-Cutting	166 Simulation Programs	Cross-Cutting
135 Motor Diagnostics	Cross-Cutting	167 New Metal Heating	Cross-Cutting
136 Compressed Air Management	Cross-Cutting	168 Thermal Storage Cooling	Cross-Cutting
137 Advanced CHP Turbines	Cross-Cutting	169 Low Friction Working Fluids	Cross-Cutting
138 Advance ASD Designs	Cross-Cutting	170 Recuperative Burners	Cross-Cutting
139 Advanced Recip. Engines	Cross-Cutting	171 Oxy-Fuel Burners	Cross-Cutting
140 Advanced Compressor Controls	Cross-Cutting	172 Copper Motor Rotors	Cross-Cutting
141 Advanced Lighting Design	Cross-Cutting	173 Tube Feeder	Cross-Cutting
142 Membranes- Wastewater	Cross-Cutting		

*Savings information* identifies electricity, fuel, and primary energy savings for a typical application of the new technology relative to the reference technology. The analyst made an assessment of the rate at which the technology is expected to penetrate the market. We used a simplified, uniform penetration rate to represent a plausible estimate of the market penetration of each measure during the analysis period. We assigned measures to one of three standard penetrations rates (high, medium, and low). These rates are tied to assumptions how readily is the market likely to adopt the measures. In general, the penetration rates assume successful programs, and that the technologies compete against the reference technology but not against each other for the market share. While the market diffusion will be sigmoid as discussed in Section II: Overview of U.S. Industrial Energy Use, we assumed linear penetration. Thus, when the market requires a high level of intervention to successfully adopt the measure, annual market-penetration rate was assumed to be 5 percent, with an ultimate penetration of 30 percent in 2015. For measures that require medium market intervention required, the annual market-penetration rate was assumed to be 7.5 percent, for an ultimate penetration of 45 percent in 2015. Where the intervention is low (i.e., the technology is likely to be adopted with little intervention), we assume that market penetration rates will be high: 10 percent per year to an ultimate penetration of 60 percent in 2015.

These penetration rates begin in the first year after commercialization, or 2001 for those technologies that are already commercialized. For measures with retrofit as the predominate mode of market deployment, the portion of the market that can be impacted by a technology is assumed to be 100 percent. For replacement (i.e., replace on failure), the portion is assumed to be the period of the study (15 years) divided by the measure life. For new construction, it is the growth in capital investment for the target industry divided by the anticipated total installed capital value in 2015.

Finally we estimated the share applications that the technology captures by 2015 (e.g., for which the measure is technically feasible and cost-effective to the end-user on a life-cycle cost basis). “Feasible applications” refers to the percentage of the total market that the technology is estimated to capture by 2015. Any other key assumptions for savings potential are noted in the spreadsheet and profiles narrative, and the total 2015 fuels, electricity, and primary energy savings is calculated. Our 2015 energy savings estimate is relative to the 2015 base-case information identified in the market information section of the table.

*Cost information and analysis* provides an estimate of the technology or measure’s investment cost (\$/unit output), whether that investment is incremental or full cost, and any change in operations and maintenance cost (\$/unit output) for adopting the technology. We include three measures of cost-effectiveness: cost of conserved energy<sup>11</sup> for electricity, fuels, and primary energy, simple payback<sup>12</sup> for the investment relative to the reference technology (years), and internal rate of return (IRR percent).<sup>13</sup> Simple payback and internal rate of return are metrics that are often used by industries and financial analysts, while cost of conserved energy has been useful as a cost-effectiveness indicator for the policy community.<sup>14</sup>

*Key non-energy factors* are those factors that can significantly affect the decision to purchase a technology. These include the presence of other benefits (productivity, quality, environmental, other [i.e. safety]), and to what extent the technology is currently being promoted.

In the *evaluation* section of this table, researchers identify the major market barriers that could impede the successful implementation of this technology. The technology’s likelihood of success (high, medium, and low) is rated based on its cost-effectiveness, key non-energy factors, and major market barriers. We suggest what next steps are appropriate to accelerate the deployment of the technology. Finally, the analyst

<sup>11</sup> The cost of saved energy is calculated by:  $(ACAP + O\&M)/E$  where: ACAP is the capital cost of technology annualized as a loan for the life of the measure, at the default discount rate (i.e., 15 percent), O&M is the change in annual operating cost, and E is the annual non-energy energy savings.

<sup>12</sup> The simple payback is calculated by:  $CAP/(EC - O\&M)$  where: CAP is the capital cost of the technology, EC is cost of the energy saved based on 2015 projected national energy price (EIA 1999), and O&M is the change in annual, non-energy operating cost.

<sup>13</sup> The IRR is calculated from a analysis based on the initial capital cost and the annual cash flow of energy cost savings and change in non-energy O&M for the life of the measure discounted at a rate of 15 percent.

<sup>14</sup> While we calculate a general IRR and cost of conserved energy based on average energy savings, we realize that the attractiveness of the investment is very plant specific and that the attractiveness of an individual investment may look different from the technology viewed in national terms.

provides an assessment of the overall quality of the data used in the analysis using a rating of excellent, good, fair or poor.

Finally, we provide information on *sources* for the key data collected and principal *contacts* for those interested in follow up analysis.

### *Treatment of Utility Technologies*

A slightly different approach was used to analyze the power generating technologies in this study. Each of the utility technologies has a unique capacity characteristic, ranging from microturbines with an electric generation capacity of below 300 kW to industrial CHP turbine systems with capacities approaching 50 MW. Therefore a methodology was developed using as a reference the primary energy required to generate 1kWh of grid-supplied electricity at an average delivered efficiency the projected 2015 grid efficiency of 33.4 percent (EIA 1999). This reference case was compared with the fuel and primary energy required to generate 1 kWh of electricity from utility technologies based on the efficiency of the technology. For each of the measures, the electricity savings is 1 kWh (the amount of electricity that would otherwise have been purchased from the grid). The fuel and primary energy savings are dependent on the respective efficiency of each measure. Using this approach, the relative energy savings of each technology was determined on a consistent basis.

In determining the cost-effectiveness of the utility technologies, an average industrial electricity price of \$0.039/kWh was used. This value is the projected 2015 industrial price for electricity in the AEO 2000 reference case (EIA 1999). Electricity prices vary wildly by region, service provider, and industrial segment. In reality, industrial facilities can pay a price of anywhere between \$0.01 to \$0.14 on average. This price is determined by any agreements that are established between a manufacturing facility and the local power supplier. The actual rate also depends on several other factors such as time of day (peak demand charges). The electricity price profoundly effects the economics of on-site electricity generation technologies. For example, a 65 percent efficient 800 kW gas reciprocating engine has a simple payback period of 8 years when compared to purchased grid electricity at \$0.039/kWh. At a purchased electricity price of \$0.12/kWh, the simple payback drops to less than a year.

Ancillary benefits can make electric generating technologies more economically attractive as well. Certain industrial sectors, such as the pharmaceutical, semiconductor and microelectronics sectors, demand high-quality power, often with a reliability target of six-nines (i.e., 99.9999 percent). While the average reliability of the U.S. electric grid hovers near 99 percent, this is not reliable enough for many of these applications. Many of these industries must employ stand-by power systems to meet their requirements. No accepted methodology exists for determining this ancillary reliability benefit of an on-site power generating technology. In principle this can be determined by calculating the revenues that would be lost during a grid outage. This value however is highly site specific. In high-value applications, such as semiconductor or pharmaceutical manufacturing and data-centers where loss revenues can easily exceed \$1 million/hour, this consideration can make generating technologies, even with high initial capital costs, economically attractive (Elliott and Spurr 1999).

All the utilities, except for industrial CHP turbine systems, were evaluated in electricity generation only mode. It is also worth noting that all of the utility technologies in this study become more efficient when operated with heat recovery (cogeneration or CHP mode). The increased efficiency allows for a higher rate of return as well as lower combustion-related emissions per unit of generated energy. This option is particularly attractive in industries with high large process heat or space conditioning demands such as the food, chemicals, paper, and microelectronics industries.

In conclusion, it should be noted at times the lack of reliable data (especially if the technologies are pre-commercial) can impede a thorough assessment. When this is the case, we note this and do not attempt to stretch the analysis beyond its ability to be supported by the underlying data. Our goal is to provide as thorough an assessment of the various emerging technologies as possible, given the available information.

## IV. SUMMARY OF FINDINGS

### Introduction

The industrial sector is a significant energy user, consuming nearly 40 percent of U.S. primary energy resources and producing about a quarter of GDP. The development and use of cleaner, more energy-efficient technologies can help limit the negative environmental impacts associated with many industries while enhancing productivity and reducing manufacturing costs. This study aims to identify and evaluate emerging energy-efficient technologies for use in the industrial sector.

In this section we rank these technologies by overall energy savings, electricity savings, fuel savings, share of sector savings, and environmental benefits. We conclude with suggested actions to support the development of these technologies and evaluations of the likelihood of technologies to succeed in the marketplace.

### Summary of Technology Characterizations

Based on a comprehensive literature review and the application of some basic initial screening criteria (see Section 3:Methodology and Approach), we identified and developed profiles for 54 technologies. The technologies themselves range from highly specific technologies that can be applied in a single industry to more broadly Crosscutting technologies, which can be used in many industrial sectors. Table 14 summarizes the results of the individual analyses.

We evaluated energy savings in two different ways. The third column in Table 14, Total Energy Savings, shows the amount of total manufacturing energy that the technology is likely to save in 2015 in a business-as-usual scenario. The fourth column, Sector savings, shows the savings relative to expected energy use in the particular sector. We believe that both metrics are useful in evaluating the relative savings potential of various technologies.

Economic evaluation of the technology is identified in the summary table as Simple Payback, defined as the initial investment costs divided by the value of energy savings less any changes in operations and maintenance costs. We chose this measure since it is frequently used as a shorthand evaluation metric among industrial energy managers. Payback periods for the technologies range from the immediate to 20 years or more. Of the 54 technologies profiled, 31 have estimated paybacks of 3 years or less, with six paying back immediately. The individual profiles also include estimations of internal rate of return and cost of saved energy.

Energy savings are often not the determining factor in the decision to develop or invest in an emerging technology. Over two-thirds of these technologies not only save energy but yield environmental or other non-energy benefits. These non-energy benefits include: increases in productivity, worker safety, product quality, and capacity; and reduced capital and operating costs.

Technologies are not simply developed and then seamlessly enter existing markets. The acceptance of emerging technologies is often a slow process that entails active research and development, prototype development, market demonstration, and other activities. In Table 14 we summarize the recommendations for the primary activities that should be undertaken to increase the rate of uptake of these technologies. Over half have already been developed to prototype stage or are already commercial but require further demonstration and dissemination.

While data on many of the technologies were readily available and appeared reliable and self-consistent, for some technologies the analyst faced significant challenges. Each analyst judged the relative quality of data ranging from poor to excellent. The data quality judgement is also given in Table 14 for each technology.

Below we review the key parameters in greater detail. In the following sections we evaluate how the technologies can be grouped relative to each parameter of interest.



**Table 9. Summary of the Profiled Energy-Efficient Emerging Industrial Technologies**

Technology	Sector	Total Energy Savings <sup>1</sup>	Sector Savings <sup>2</sup>	Est. Life	Simple Payback <sup>3</sup>	Environ. Benefits	Other <sup>4</sup> Benefits	Next Steps	Data Quality
Advanced forming	Aluminum	Medium	Medium	15	Immed.	None	P	R&D	Good
Efficient cell retrofit designs	Aluminum	High	High	15	2.7	Somewhat	P	Demo	Fair
Improved recycling technologies	Aluminum	Medium	Medium	15	4.5	Significant	P	Demo	Good
Inert anodes/wetted cathodes	Aluminum	High	High	10	4.0	Significant	P, Q	R&D	Good
Roller kiln	Ceramics	Medium	High	30	1.9	Significant	P	Demo	Fair
Clean fractionation - cellulose pulp	Chemicals	Low	Low	15	1.9	Significant	P, O	Demo	Good
Gas membrane technologies-chem	Chemicals	Low	Low	15	10.2	Significant	Q, O	Dissem	Good
Heat recovery technologies – chemi	Chemicals	Medium	Medium	10	2.4	None	P, O	Dissem, demo	Fair
Levulinic acid from biomass	Chemicals	Low	Low	20	1.5	Significant	P, O	Demo	Good
Liquid membrane technologies-chem	Chemicals	Low	Low	10	11.2	Significant	O	Dissem	Good
New catalysts	Chemicals	Medium	Medium	20	7.9	Somewhat		R&D	Fair
Autothermal reforming-Ammonia	Chemicals	High	High	30	3.7	Significant	P	Dissem	Fair
Plastics recovery	Plastics	Medium	Medium	20	2.8	Compelling	P	Demo	Fair
Continuous melt silicon crystal growth	Electronics	Medium	High	7	Immed.	Somewhat	Q, P	R&D	Excellent
Electron beam sterilization	Food	High	High	10	19.2	None	P, Q	R&D	Fair
Heat recovery - low temperature	Food	Medium	Medium	25	4.8	None	P, Q	Dissem	Fair
Membrane technology - food	Food	High	High	10	2.2	Somewhat	P, Q	Dissem, R&D	Fair, Poor
Cooling and storage	Food	Medium	Medium	15	2.6	Somewhat	O	Dissem, demo	Fair
100% recycled glass cullet	Glass	Medium	High	25	2.0	Significant		Demo	Good
Black liquor gasification	Pulp & Paper	High	High	30	1.5	Somewhat	P, S	Demo	Excellent
Condebelt drying	Pulp & Paper	High	Medium	20	65.2	None	P, Q	Demo	Good
Direct electrolytic causticizing	Pulp & Paper	Low	Low	10	N/A	Somewhat	P, Q	R&D	Good
Dry sheet forming	Pulp & Paper	Medium	Medium	20	48.3	Somewhat	Q	R&D, demo	Good
Heat recovery – paper	Pulp & Paper	High	Medium	20	3.9	Somewhat	P, S	Demo	Good
High Consistency forming	Pulp & Paper	Medium	Medium	20	Immed.	Somewhat	P, Q	Demo	Fair
Impulse drying	Pulp & Paper	High	Medium	20	20.3	None	P, Q	Demo	Good
Biodesulfurization	Pet. Refining	Medium	Medium	15	1.8	None	Q	R&D, demo	Excellent
Fouling minimization	Pet. Refining	High	High	15	N/A	None	P	R&D	Fair
BOF gas and sensible heat recovery	Iron & Steel	Medium	Medium	30	14.7	Significant	P	Dissem	Good
Near net shape casting/strip casting	Iron & Steel	High	High	20	Immed.	Somewhat	P, Q	R&D	Good
New EAF furnace processes	Iron & Steel	High	High	40	0.3	Somewhat	P	Field test	Fair
Oxy-fuel combustion in rehear furnace	Iron & Steel	High	Medium	10	1.2	Significant	P	Field test	Fair
Smelting reduction processes	Iron & Steel	High	High	40	Immed.	Significant	P	Demo	Good
Ultrasonic drying	Textile	Medium	Medium	10	0.3	Compelling	P, Q	Demo	Fair
Variable wall mining machine	Mining	Low	Low	25	10.6	None	P, S	Demo	Fair
Hi-tech facilities HVAC	Crosscutting	Medium	High	20	4.0	None	P	Dissem.	Fair
Advanced lighting technologies	Crosscutting	High	High	4	1.3	None	Q, P, O	Dissem, demo	Excellent
Advanced lighting design	Crosscutting	High	High	20	3.0	None	P, Q, O	Dissem, demo	Good
Advance ASD designs	Crosscutting	High	Medium	15	1.1	None	P, Q	R&D	Good
Advanced compressor controls	Crosscutting	Medium	Low	15	0.04	None	P, Q	Dissem	Good
Compressed air system management	Crosscutting	High	High	1.5	0.4	None	P, Q	Dissem	Good
Motor diagnostics	Crosscutting	Low	Low	15	Immed.	None	P, Q	Dissem, demo	Good
Motor system optimization	Crosscutting	High	High	10	1.5	Somewhat	P, Q	Dissem, train	Good
Pump efficiency improvement	Crosscutting	High	High	10	3.0	None	P, Q	Dissem, train	Good
Switched reluctance motor	Crosscutting	Medium	Low	15	7.4	None	P, Q	R&D	Good
Advanced lubricants	Crosscutting	Medium	Medium	0.5	0.1	Significant	P, Q	Dissem.	Good
Anaerobic waste water treatment	Crosscutting	Medium	Low	20	0.8	Significant	O	Dissem, demo	Good+
High efficiency/low NO <sub>x</sub> burners	Crosscutting	High	Low	20	3.1	Significant	P	Dissem, demo	Poor
Membrane technology wastewater	Crosscutting	High	Medium	10	4.7	Somewhat	P	Dissem, R&D	Fair, Poor
Process Integration (pinch analysis)	Crosscutting	High	Low	15	2.3	Somewhat	P	Dissem.	Fair
Sensors and controls	Crosscutting	High	Medium	10	2.0	Somewhat	P, Q	R&D, demo, dissem	Fair
Advanced CHP turbine systems	Crosscutting	High	High	10	6.9	Significant	P, Q	Policies	Excellent
Advanced reciprocating engines	Crosscutting	High	High	7	8.3	Limited	P, Q, O	R&D, demo	Excellent
Fuel cells	Crosscutting	High	High	7	58.6	Significant	P, Q	Demo	Good
Microturbines	Crosscutting	High	Medium	7	Never	Somewhat	P, Q, O	R&D, demo	Good

**Notes:** 1. "High" could save more than 0.1% of manufacturing energy use by 2015, medium is 0.01 to 0.1%, and low is less than 0.01%.

2. "High" could save more than 1% of sector energy use by 2015, medium is 0.1 to 1%, and low is less than 0.1%.

3. "Immed" is immediate.

4. "P" is productivity, "Q" is quality, "S" is safety, "O" is other.

## Energy Savings

Depending on the particular technology and application, the technologies will reduce electricity consumption, fuel consumption, or both. Table 15 presents the 28 technologies having “high” total energy savings, rated according to their primary energy savings (i.e. accounting for losses in the production and delivery of electricity). These savings represent the estimated 2015 implemented savings under a business-as-usual scenario (i.e. excluding policy efforts to stimulate adoption of a specific technology). As would be expected, the Crosscutting technologies (motor systems, lighting, utilities) save the largest amount of primary energy, followed by selected specific technologies in energy-intensive sectors (steel, petroleum, paper, aluminum, and chemicals). However, this does not mean that sector-specific technologies should be overlooked, as many of these may save substantial amounts of energy in a particular sector, or may have important additional benefits (see below).

**Table 10. Projected 2015 Implemented Primary Energy Savings Potential**

Technology	Code	Sector	Primary Energy TBtu (EJ)
Motor system optimization	Motorsys-5	Crosscutting	1502 (1585)
Advanced reciprocating engines	Utilities-2	Crosscutting	777 (820)
Compressed air system management	Motorsys-3	Crosscutting	563 (594)
Pump efficiency improvement	Motorsys-6	Crosscutting	502 (530)
Advanced CHP turbine systems	Utilities-1	Crosscutting	484 (510)
Advanced lighting design	Lighting-2	Crosscutting	408 (430)
Advanced lighting technologies	Lighting-1	Crosscutting	231 (244)
Fuel cells	Utilities-3	Crosscutting	185 (195)
Near net shape casting/strip casting	Steel-2	Iron and steel	138 (146)
Sensors and controls	Other-5	Crosscutting	136 (143)
Fouling minimization	Refin-2	Petroleum refining	123 (130)
Membrane technology—wastewater	Other-3	Crosscutting	118 (125)
Microturbines	Utilities-4	Crosscutting	67 (71)
Black liquor gasification	Paper-1	Pulp and paper	64 (68)
Efficient cell retrofit designs	Alum-2	Aluminum	46 (49)
Process Integration (pinch analysis)	Other-4	Crosscutting	38 (40)
Autothermal reforming—Ammonia	Chem-7	Chemicals	38 (40)
Condebelt drying	Paper-2	Pulp and paper	34 (36)
Electron beam sterilization	Food-1	Food processing	34 (36)
Inert anodes/wetted cathodes	Alum-4	Aluminum	34 (36)
Smelting reduction processes	Steel-5	Iron and steel	32 (34)
Impulse drying	Paper-7	Pulp and paper	30 (32)
Membrane technology—food	Food-3	Food processing	27 (28)
Advance ASD designs	Motorsys-1	Crosscutting	25 (26)
New EAF furnace processes	Steel-3	Iron and steel	24 (25)
Heat recovery—paper	Paper-5	Pulp and paper	22 (23)
High efficiency/low NO <sub>x</sub> burners	Other-2	Crosscutting	21 (22)
Oxy-fuel combustion in reheat furnace	Steel-4	Iron and steel	21 (22)

Electricity is a unique energy source, with significant emissions and a large infrastructure supporting its generation and delivery. Many industries, including electric utilities, will find it important to focus on technologies that save electricity. Table 16 identifies the top 20 technologies in terms of electricity savings. Our estimate of savings is based on an economically feasible market penetration in 2015 under business-as-usual conditions. As Table 16 indicates, the Crosscutting technologies concerning motor systems, lighting, and utilities are expected to have the most significant impact in terms of savings along with selected sector-specific technologies. The most important sector-specific technologies are black liquor gasification (a potentially large self-generation technology in the pulp and paper sector) and technologies that reduce electricity use in the aluminum and electric arc furnace/secondary steel sectors. According to EIA, the total forecast of electricity use for the U.S. industrial sector in 2015 is 13,000 TWh (EIA 1997). While the top technology only represents 1 percent of total forecast electricity use, this is still a significant amount, representing \$7 billion in electricity expenditures alone. Since electricity is one of the most high-quality and expensive energy inputs, small reductions in electricity expenditures can have a large impact on reductions in operating costs for various manufacturing establishments.

**Table 11. Projected 2015 Implemented Electricity Savings Potential**

Technology	Code	Sector	Electricity Twh
Motor system optimization	Motorsys-5	Crosscutting	176
Advanced reciprocating engines	Utilities-2	Crosscutting	156
Advanced CHP turbine systems	Utilities-1	Crosscutting	79
Advanced ASD designs	Motorsys-1	Crosscutting	72
Compressed air system management	Motorsys-3	Crosscutting	66
Fuel cells	Utilities-3	Crosscutting	65
Pump efficiency improvement	Motorsys-6	Crosscutting	59
Advanced lighting design	Lighting-2	Crosscutting	48
Advanced lubricants	Motorsys-8	Crosscutting	46
Microturbines	Utilities-4	Crosscutting	40
Advanced lighting technologies	Lighting-1	Crosscutting	27
Black liquor gasification	Paper-1	Pulp and paper	10
Advanced compressor controls	Motorsys-2	Crosscutting	9
Switched reluctance motor	Motorsys-7	Crosscutting	7
Near net shape casting/strip casting	Steel-2	Iron and steel	6
Efficient cell retrofit designs	Alum-2	Aluminum	5
Inert anodes/wetted cathodes	Alum-4	Aluminum	4
New EAF furnace processes	Steel-3	Iron and steel	3
Electron beam sterilization	Food-1	Food processing	3
Biodesulfurization	Refin-1	Pet. Refining	2

Table 17 identifies the top 14 technologies in terms of fuel savings. Unlike the electricity savings, the technologies highlighted in this table are primarily sector-specific; although Crosscutting technologies (membranes, sensors, process integration) show strong potential for fuel savings. The fuel savings below tend to reflect better utilization of low-quality or by-product fuels, improved heat recovery, or better direct application of process heating. Similar to electricity savings, no one technology represents an overwhelming proportion of industrial fuel consumption in 2015 (estimated at 31,960 TBtu), but each of the technologies in Table 17 represent a savings in energy expenditures between \$30 and \$900 million per year.

**Table 12. Projected 2015 Implemented Fuel Savings Potential**

Technology	Code	Sector	Fuel Savings TBtu (PJ)
Membrane technology wastewater	Other-3	Crosscutting	276 (292)
Fouling minimization	Refin-2	Pet. Refining	123 (130)
Sensors and controls	Other-5	Crosscutting	111 (117)
Near net shape casting/strip casting	Steel-2	Iron and steel	86 (91)
Impulse drying	Paper-7	Pulp and paper	64 (67)
Autothermal reforming-Ammonia	Chem-7	Chemicals	38 (40)
Process Integration (pinch analysis)	Other-4	Crosscutting	37 (39)
Membrane technology—food	Food-3	Food processing	36 (37)
Condebelt drying	Paper-2	Pulp and paper	34 (36)
Smelting reduction processes	Steel-5	Iron and steel	32 (34)
Dry sheet forming	Paper-4	Pulp and paper	28 (30)
Oxy-fuel combustion in reheat furnace	Steel-4	Iron and steel	23 (24)
High efficiency/low NO <sub>x</sub> burners	Other-2	Crosscutting	21 (23)
Heat recovery—paper	Paper-5	Pulp and paper	20 (21)

The presentation in the last three tables focuses on aggregate energy savings. These technologies are dominated by measures that are applicable in a broad range of industries (e.g., Crosscutting) or in the dominant energy-intensive industries. In Table 18 we identify those technologies that offer important energy savings to their industry sector. These technologies have a high share of energy savings relative to energy use within the specific sector, where we define high as having a greater than 1 percent share of sectoral primary energy use. While the savings for a given technology may be modest in absolute terms, it may be important to the limited sector in which it is applicable. As noted in Section 2: Overview, there is significant regional variation in the distribution of industry. Many of the energy-intensive industries are concentrated in a few states. The industrial sector in some other states may be dominated by less energy-

intensive industries. Thus, states with concentrations of these industries may find these technologies of significant interest.

**Table 13. Implemented Savings Share of Sector Projected 2015 Energy**

Technology	Code	Sector	Share of sectoral savings
Continuous melt silicon crystal growth	Electron-1	Electronics	20.0%
Motor system optimization	Motorsys-5	Crosscutting	11.5%
Roller kiln	Ceramics-1	Ceramics	8.2%
Hi-tech facilities HVAC	HVAC-1	Crosscutting	7.4%
Efficient cell retrofit designs	Alum-2	Aluminum	6.6%
Near net shape casting/strip casting	Steel-2	Iron and steel	6.4%
Advanced reciprocating engines	Utilities-2	Crosscutting	5.9%
Inert anodes/wetted cathodes	Alum-4	Aluminum	4.9%
Compressed air system management	Motorsys-3	Crosscutting	4.3%
Pump efficiency improvement	Motorsys-6	Crosscutting	3.8%
Advanced CHP turbine systems	Utilities-1	Crosscutting	3.7%
Fouling minimization	Refin-2	Pet. Refining	3.4%
Advanced lighting design	Lighting-2	Crosscutting	3.1%
Electron beam sterilization	Food-1	Food processing	2.0%
Black liquor gasification	Paper-1	Pulp and paper	1.8%
Advanced lighting technologies	Lighting-1	Crosscutting	1.8%
Membrane technology—food	Food-3	Food processing	1.6%
100% recycled glass cullet for container glass	Glass-1	Glass	1.5%
Smelting reduction processes	Steel-5	Iron and steel	1.5%
Fuel cells	Utilities-3	Crosscutting	1.4%
New EAF furnace processes	Steel-3	Iron and steel	1.1%
Autothermal reforming—Ammonia	Chem-7	Chemicals	1.0%

## The Economics of Energy Savings

As we noted earlier in the section, payback is frequently used as a shorthand evaluation metric among industrial energy managers. For evaluating technologies from the perspective of cost-effective energy savings we use cost of saved energy as our metric.

Thirty technologies have a cost of saved electricity of less than 4.6¢/kWh (the average industrial electricity price in 1996), with thirteen technologies having a net negative cost (i.e. costs of saved electricity is less than zero). Most of these were measures that achieved significant immediate energy savings while costing less than the reference technologies or not requiring significant capital outlays.

Twenty-nine technologies had costs of saved fuel of less than \$2.8/MBtu (the estimated average fuel price for industry in 1996), with 19 with values of zero or less than zero. These technologies share much in common with the top electricity savings technologies, and in fact 16 of the technologies appear on both lists.

**Table 14. Technologies with the Lowest Cost of Saved Electricity**

<b>Technology</b>	<b>Code</b>	<b>Cost of Saved Electricity \$/kwh</b>
Advanced forming/near net shape technology	Alum-1	< 0
Levulinic acid from biomass (biofine)	Chem-4	< 0
Cooling and storage	Food-4	< 0
Advance ASD designs	Motorsys-1	< 0
Advanced lubricants	Motorsys-8	< 0
Anaerobic waste water treatment	Other-1	< 0
Dry sheet forming	Paper-4	< 0
High Consistency forming	Paper-6	< 0
Impulse drying	Paper-7	< 0
BOF gas and sensible heat recovery	Steel-1	< 0
Near net shape casting/strip casting	Steel-2	< 0
New EAF furnace processes	Steel-3	< 0
Microturbines	Utilities-4	< 0
Advanced compressor controls	Motorsys-2	0.000
Sensors and controls	Other-5	0.001
Heat recovery technologies – chemicals	Chem-3	0.006
Advanced reciprocating engines	Utilities-2	0.007
Direct electrolytic causticizing	Paper-3	0.008
Black liquor gasification	Paper-1	0.008
Efficient cell retrofit designs	Alum-2	0.008
Advanced CHP turbine systems	Utilities-1	0.010
Pump efficiency improvement	Motorsys-6	0.010
Motor system optimization	Motorsys-5	0.012
Compressed air system management	Motorsys-3	0.015
Hi-tech facilities HVAC	HVAC-1	0.022
Inert anodes/wetted cathodes	Alum-4	0.029
Advanced lighting technologies	Lighting-1	0.034
Oxy-fuel combustion in reheat furnace	Steel-4	0.035
Variable wall mining machine	Mining-1	0.041
Advanced lighting design	Lighting-2	0.046

**Table 15. Technologies with the Lowest Cost of Saved Fuel**

<b>Technology</b>	<b>Code</b>	<b>Cost of Saved Fuel \$/mbtu</b>
Advanced forming/near net shape technology	Alum-1	< 0
Clean fractionation—cellulose pulp	Chem-1	< 0
Levulinic acid from biomass (biofine)	Chem-4	< 0
Cooling and storage	Food-4	< 0
100% recycled glass cullet for container glass	Glass-1	< 0
Anaerobic waste water treatment	Other-1	< 0
Membrane technology wastewater	Other-3	< 0
Black liquor gasification	Paper-1	< 0
Direct electrolytic causticizing	Paper-3	< 0
Near net shape casting/strip casting	Steel-2	< 0
Oxy-fuel combustion in reheat furnace	Steel-4	< 0
Smelting reduction processes	Steel-5	< 0
Ultrasonic dyeing	Textile-1	< 0
Advanced CHP turbine systems	Utilities-1	< 0
Advanced reciprocating engines	Utilities-2	< 0
Fuel cells	Utilities-3	< 0
Continuous melt silicon crystal growth	Electron-1	0.0
High Consistency forming	Paper-6	0.0
Biodesulfurization	Refin-1	0.0
Sensors and controls	Other-5	0.20
Roller kiln	Ceramics-1	0.57
Membrane technology—food	Food-3	0.59
Process Integration (pinch analysis)	Other-4	0.86
Plastics recovery	Chem-8	0.86
High efficiency/low NO <sub>x</sub> burners	Other-2	0.94
Autothermal reforming-Ammonia	Chem-7	1.13
Heat recovery technologies—chemicals	Chem-3	1.63
Heat recovery —paper	Paper-5	2.09
Heat recovery food industry—low temperature	Food-2	2.48

## Environmental Benefits

For some industries, the cost of complying with environmental regulation can be an important driver in the decision to invest in particular energy-efficient technologies, especially in the non-attainment areas. Of the 54 technologies profiled, 20 had environmental benefits that were either compelling or significant. These technologies are presented in Table 21. The benefits mainly fall in the areas of “reduction of wastes” and “emissions of criteria air pollutants.” The use of environmentally friendly emerging technologies is often most compelling when it enables the expansion of incremental production capacity without requiring additional environmental permitting. In selected cases, the decision to invest in these technologies based on their environmental criteria is part of a larger, long-term business strategy towards sustainable development and staying ahead of the regulatory curve.

**Table 16. Environmental Benefits**

Technology	Code		Environmental Benefits
Improved recycling technologies	Alum-3	Significant	Reduced emissions and reduced scrap metal waste - eases compliance for environmental regulation
Inert anodes/wetted cathodes	Alum-4	Significant	No CO <sub>2</sub> emissions and reduction of perfluorocarbon emissions
Roller kiln	Ceramics-1	Significant	Reduced NO <sub>x</sub> emissions, a major concern of ceramics and glass manufacturers
Clean fractionation - cellulose pulp	Chem-1	Significant	Uses a renewable feedstock, reduces 1.8 million tons of waste by 2010
Gas membrane technologies-chemicals	Chem-2	Significant	Decreases CO <sub>2</sub> emissions by 0.1325 tons/ton product per year
Levulinic acid from biomass (biofine)	Chem-4	Significant	Reduces landfill waste and uses a renewable feedstock
Liquid membrane technologies—chemicals	Chem-5	Significant	Decreases CO <sub>2</sub> emissions and other combustion related emissions
Autothermal reforming-Ammonia	Chem-7	Significant	50% reduction in NO <sub>x</sub> emissions
Plastics recovery	Chem-8	Compelling	Reduced land filling of plastics from automobile shredder residue
100% recycled glass cullet for container glass	Glass-1	Significant	Reduces NO <sub>x</sub> and SO <sub>x</sub> emissions – the primary sources of air pollutants from the glass industry
Advanced lubricants	Motorsys-8	Significant	Reduced volume of spent lubricant for disposal
Anaerobic waste water treatment	Other-1	Significant	Reduced sludge production; in other applications, the biochemical oxygen demand (BOD) level can be significantly reduced (CADDET, 1996)
High efficiency/low NO <sub>x</sub> burners	Other-2	Significant	Reduction of NO <sub>x</sub> emissions by 30-70%
BOF gas and sensible heat recovery	Steel-1	Significant	Reduced CO and PM emissions
Oxy-fuel combustion in reheat furnace	Steel-4	Significant	NO <sub>x</sub> emission reduction of up to 70-90%
Smelting reduction processes	Steel-5	Significant	Lower air and water emissions of sulfur and poly-aromatic hydrocarbons
Ultrasonic dyeing	Textile-1	Compelling	Reduces volume of waste water, while reducing salt and urea
Advanced CHP turbine systems	Utilities-1	Significant	Reduces combustion related emissions per unit of fuel input
Fuel cells	Utilities-3	Significant	Little to no NO <sub>x</sub> emissions

## Non-Energy Benefits

While energy and environmental concerns factor into technology investment decisions at many industrial facilities, it is frequently the productivity and product quality benefits that most frequently ensure the adoption of a technology. Improvements in productivity and quality contribute significantly to the economic attractiveness of a given technology and may indeed be the largest deciding factor in technology investments. Thirty-five technologies in this study had “significant” or “compelling” productivity, quality, or other non-energy benefits.

**Table 17. Non-Energy Benefits**

Technology	Code	Productivity Benefits	Product Quality Benefits	Other Non-energy Benefits	
Ultrasonic dyeing	Textile-1	Compelling	Compelling	None	
Advanced forming	Alum-1	Compelling	None	None	
Direct electrolytic causticizing	Paper-3	Compelling	Somewhat	None	
Motor diagnostics	Motorsys-4	Compelling	Somewhat	Somewhat	May be able to avoid plant capital expansions due to increased production
Liquid membrane technologies—chemicals	Chem-5	None	None	Significant	Investment 10% less than conventional installation
Biodesulfurization	Refin-1	None	Significant	None	
Dry sheet forming	Paper-4	None	Significant	None	
Gas membrane technologies—chemicals	Chem-2	None	Somewhat	Significant	Investment 10% less below conventional installation
Oxy-fuel combustion in rehear furnace	Steel-4	Significant	None	None	
New EAF furnace processes	Steel-3	Significant	None	None	
Efficient cell retrofit designs	Alum-2	Significant	None	None	
Fouling minimization	Refin-2	Significant	None	None	
Levulinic acid from biomass (biofine)	Chem-4	Significant	None	Significant	Makes the production of levulinic acid economical
Advanced CHP turbine systems	Utilities-1	Significant	Significant	None	
High Consistency forming	Paper-6	Significant	Significant	None	
Sensors and controls	Other-5	Significant	Significant	None	
Electron beam sterilization	Food-1	Significant	Significant	None	
Motor system optimization	Motorsys-5	Significant	Significant	Significant	Reduced fan speed can reduce worker noise exposure
Advanced reciprocating engines	Utilities-2	Significant	Significant	Somewhat	Can allow expansions without needing to upgrade utility service, and can allow for peak load shaving
Microturbines	Utilities-4	Significant	Significant	Somewhat	Can allow expansions without needing to upgrade utility service, and can allow for peak load shaving
Pump efficiency improvement	Motorsys-6	Significant	Significant	Somewhat	Ability to downsize equipment and free up space
Near net shape casting/strip casting	Steel-2	Significant	Somewhat	None	
Continuous melt silicon crystal growth	Electron-1	Significant	Somewhat	None	
Impulse drying	Paper-7	Significant	Somewhat	None	
Condebelt drying	Paper-2	Significant	Somewhat	None	
Advance ASD designs	Motorsys-1	Significant	Somewhat	None	
Advanced lubricants	Motorsys-8	Significant	Somewhat	None	
Advanced compressor controls	Motorsys-2	Significant	Somewhat	Significant	May avoid need for addition compressor purchase or allow retirement of existing compressor with resulting reduced O&M and salvage value
Compressed air system management	Motorsys-3	Significant	Somewhat	Significant	May avoid need for addition compressor purchase or allow retirement of existing compressor with resulting reduced O&M and salvage value
Inert anodes/wetted cathodes	Alum-4	Significant	Somewhat	Somewhat	Safety
Clean fractionation—cellulose pulp	Chem-1	Somewhat	None	Significant	Lower production costs
Variable wall mining machine	Mining-1	Somewhat	None	Significant	Improved working conditions and safety
Switched reluctance motor	Motorsys-7	Somewhat	Significant	None	
Advanced lighting technologies	Lighting-1	Somewhat	Somewhat	Significant	Added energy savings with use of controls and sensors; faster start-up
Advanced lighting design	Lighting-2	Somewhat	Somewhat	Significant	Added energy savings w/ task lighting; reduced HVAC load; faster start-up

## Likelihood of Success

It is difficult to predict how likely a technology is to be successful in the marketplace. Many factors will contribute to the outcome, including: changes in market conditions; the value of the energy and non-energy benefits; strategic considerations; and competition from other technologies. Based on all these factors, we made a qualitative assessment of the likelihood that a technology would succeed in the marketplace. Table 22 presents the twenty-one technologies rated with a high likelihood of success. They span the range of industrial sectors, but in general tend to have among the shortest paybacks. In addition, all have energy and/or non-energy benefits, which help account for the high likelihood of success.

**Table 18. Factors Contributing to a High Likelihood of Success**

Technology	Code	Est. Life (yr)	Simple Payback	Environ. Benefits	Other Benefits
Advanced forming	Alum-1	15	Immediate	None	P
Efficient cell retrofit designs	Alum-2	15	2.7	Somewhat	P
Gas membrane technologies—chemicals	Chem-2	15	10.2	Significant	Q, O
Levulinic acid from biomass (biofine)	Chem-4	20	1.5	Significant	P, O
Plastics recovery	Chem-8	20	2.8	Compelling	P
Continuous melt silicon crystal growth	Electron-1	7	Immediate	Somewhat	Q, P
100% recycled glass cullet	Glass-1	25	2.0	Significant	
Advanced lighting technologies	Lighting-1	4.0	1.3	None	Q, P, O
Advance ASD designs	Motorsys-1	15	1.1	None	P, Q
Motor diagnostics	Motorsys-4	15	Immediate	None	P, Q
Anaerobic waste water treatment	Other-1	20	0.8	Significant	O
Membrane technology wastewater	Other-3	10	4.7	Somewhat	P
Sensors and controls	Other-5	10	2.0	Somewhat	P, Q
Black liquor gasification	Paper-1	30	1.5	Somewhat	P, S
Dry sheet forming	Paper-4	20	48.3	Somewhat	Q
Heat recovery—paper	Paper-5	20	3.9	Somewhat	P, S
Biodesulfurization	Refin-1	15	1.8	None	Q
Near net shape casting/strip casting	Steel-2	20	Immediate	Somewhat	P, Q
New EAF furnace processes	Steel-3	40	0.3	Somewhat	P
Oxy-fuel combustion in rehear furnace	Steel-4	10	1.2	Significant	P
Advanced CHP turbine systems	Utilities-1	10	6.9	Significant	P, Q

## Suggested Actions to Support Technology Development

Each technology is at a different point in its development or commercialization process. Some technologies still need further R&D to address cost or performance issues. Other technologies are ready for demonstration. Some technologies have already proven themselves in the field, and only need the market to become informed about the technology's benefits and market channels to develop skills to deliver the technology.

Table 18 outlined the recommendations to support future development of the technologies. Note that these recommendations are not an endorsement of any particular technology. Future development will ultimately be decided by the technology purchasers and users. However, the recommended actions are intended to help clarify whether a technology is both technically and economically viable, and to help eliminate market barriers that would otherwise slow or inhibit the technologies' deployment.

Seventeen emerging energy-efficient industrial technologies can benefit from additional R&D. As Table 19 indicates, we suggest further R&D for several primary metal technologies (e.g., advanced forming, inert anodes/wetted cathodes in aluminum and near net shape casting in steel) and several Crosscutting motor and utility technologies (e.g., advanced ASD designs, switched reluctance motor, advanced reciprocating engines, micro-turbines, sensors, and controls). In addition to private research funds, several of the identified technologies have received some R&D support from the DOE or other public entities, including federal and state agencies.



**Table 19. Technologies Requiring Additional R&D**

Technology	Code
Advanced forming	Alum-1
Inert anodes/wetted cathodes	Alum-4
Continuous melt silicon crystal growth	Electron-1
Electron beam sterilization	Food-1
Membrane technology—food	Food-3
Advance ASD designs	Motorsys-1
Switched reluctance motor	Motorsys-7
Direct electrolytic causticizing	Paper-3
Dry sheet forming	Paper-4
Fouling minimization	Refin-2
Near net shape casting/strip casting	Steel-2
New catalysts	Chem-6
Biodesulfurization	Refin-1
Advanced reciprocating engines	Utilities-2
Microturbines	Utilities-4
Membrane technology wastewater	Other-3
Sensors and controls	Other-5

There are, however, a large number of technologies that already have made some headway into the marketplace or are at the prototype testing stage. The technologies presented in Table 22 represent excellent candidates for demonstrations. For some, field trials are needed to gain operating experience, but with others, demonstration is required for potential customers to gain comfort with the technology.

**Table 20. Candidate Technologies for Field Trials and Demonstration**

Technology	Code	Technology	Code
Advanced forming	Alum-1	Impulse drying	Paper-7
Efficient cell retrofit designs	Alum-2	Biodesulfurization	Refin-1
Improved recycling technologies	Alum-3	New EAF furnace processes	Steel-3
Roller kiln	Ceramics-1	Oxy-fuel combustion in rehear furnace	Steel-4
Clean fractionation—cellulose pulp	Chem-1	Smelting reduction processes	Steel-5
Heat recovery technologies—chemicals	Chem-3	Ultrasonic dyeing	Textile-1
Levulinic acid from biomass (biofine)	Chem-4	Advanced lighting technologies	Lighting-1
Plastics recovery	Chem-8	Advanced lighting design	Lighting-2
Membrane technology—food	Food-3	Motor diagnostics	Motorsys-4
Cooling and storage	Food-4	Anaerobic waste water treatment	Other-1
100% recycled glass cullet for container glass	Glass-1	High efficiency/low NO <sub>x</sub> burners	Other-2
Variable wall mining machine	Mining-1	Membrane technology wastewater	Other-3
Black liquor gasification	Paper-1	Sensors and controls	Other-5
Condebelt drying	Paper-2	Advanced CHP turbine systems	Utilities-1
Dry sheet forming	Paper-4	Advanced reciprocating engines	Utilities-2
Heat recovery—paper	Paper-5	Fuel cells	Utilities-3
High Consistency forming	Paper-6	Microturbines	Utilities-4

While we recommend further demonstration and dissemination of a given technology, it is often difficult to understand what is limiting a technology's uptake without a more comprehensive investigation of market issues. Some of the technologies in this category are common in European countries or Japan but have not yet penetrated the U.S. market. Others are being newly developed in the U.S. and face challenges in reducing the perceived risks by investors. Two technologies, *motor system optimization* (motorsys-5) and *pump efficiency improvement* (motorsys-6), are opportunities for training programs similar to those developed by the DOE for the *compressed air system management* (motorsys-3). For *advanced industrial CHP turbine systems* (utilities-1), the major recommended activity is removal of policy barriers. For others, their unique markets will dictate the form of the educational and promotional activities. We urge the reader to follow up on details in the specific technology profiles.

## V. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

While many profiles of individual emerging technologies are available, few reports have attempted to impose a standardized approach to the evaluation of these technologies. This report provides a way to review technologies in an independent manner, based on information on energy savings, economics, non-energy benefits, major market barriers, likelihood of success, and suggested next steps to accelerate deployment of each of the analyzed technologies.

This report serves much the same purpose for the industrial sector that *Emerging Energy-Savings Technologies and Practices for the Building Sector* (Nadel et al. 1998) did for the buildings sector. In fact, several of the technologies covered in the buildings study were chosen again here. These technologies are Crosscutting technologies, which not only span across industries but also across economic sectors.

However, important differences exist between these two reports due to the unique characteristics of the buildings and industrial sectors. In buildings, much of the energy use is related to the building itself (e.g., heating, cooling and lighting), while in industry most of the energy is associated with the process of turning raw materials into useable products. With so much energy focused on specific processes, many process-related technologies have narrow markets of applicability. By contrast, the buildings sector can be divided into fewer, larger groups (e.g., office buildings, warehouses, apartments, hospitality, and single-family homes) which share many common applications. Most of the industrial sector technologies are less broadly applicable.

There is also significant variation in energy use within industry group, and non-uniform geographic distribution of industry groups. Thus a specific process technology may have limited national impact, while being of critical importance to a region in which the affected industry is concentrated. State- or region-specific analysis of technologies could provide further insights into unique regional opportunities. Combining the region-specific circumstances with the technology evaluations offered in this report may lead to varying policy choices for regional entities such as state governments, state or regional agencies, or utilities. A regional focus could also identify different technologies that need to be assessed, specific to particular regions.

Our selection of a limited set of 54 technologies was an arbitrary constraint based on the funding available for this study. A number of the initial technologies screened appeared very interesting and would deserve further study, but were eliminated due to our resource limitations. In addition, the initial list of candidate technologies should not be viewed as all encompassing. The authors are aware that many other promising technologies exist, and by their nature new technologies will be continually emerging. Ideally, the effort reflected in this report would become the beginning of a continuing process that identifies and profiles the most promising emerging energy-efficient industrial technologies, and tracks the market success for those technologies previously profiled. An interactive database would allow the continual updating of information, rather than providing a static snapshot of the industrial technology universe.

The quality of data on emerging technologies is varied, especially for less fully developed technologies. For technologies yet to enter the commercial market, costs remain an issue of speculation, frequently tinted by optimism. In addition, further quantification of the other benefits based on the experience from technology users in the field is an important area for future analysis. It would be useful to revisit many of these technologies in a few years to update the information, as well as to see what lessons can be learned from experience in the marketplace.

Non-energy benefits are as important, if not more important, than energy savings in determining the market potential of energy-efficient technologies. In our analyses, we have indicated the importance of these benefits by rating them as driving the adoption decision (“compelling”), of equal importance to other factors (“significant”), or supporting a decision to adopt (“somewhat”). Almost all technologies chosen have some non-energy benefits. A more detailed assessment of these benefits may help to better evaluate future market potential for these technologies.

While our study evaluates each technology in relation to a given reference technology, the reality of the market is that technologies compete for market share. Interactive effects and inter-technology competition (e.g., paper drying technologies) have not been accounted for, but ideally should be in any type of integrated technology scenario. We expect that the data collected in this study will prove valuable to modelers who evaluate technology choices in the market. The authors will explore this issue further in a forthcoming companion report.

These observations lead us to suggest that an appropriate follow-on activity would be to establish an ongoing emerging industrial technology characterization effort. This effort would involve setting up a database to catalog emerging energy-efficient industrial technologies as they are identified. Our preliminary screening list of 174 technologies could form the initial basis for this database. Each year, a number of technologies would be selected for a more detailed assessment, as has been done for this study. In addition, every few years some of the detailed technology profiles would be revisited to update the information and track the technologies success in the marketplace. This database, along with the associated detailed technology assessments, would be a valuable resource to researchers, modelers, product developers, and policy-makers, all of whom need standardized information regarding these important emerging energy-efficient industrial technologies.

## VI. TECHNOLOGY PROFILES

The technology profiles for our study are presented in the following section. Table 21 identifies the final technologies profiled. Details regarding the methodology and assumptions used in the analysis are discussed in Section 3: Methodology and Approach.

**Table 21. Profiled Emerging Energy-Efficient Industrial Technologies and their Technology Code**

Technology	Code
Electron Beam Sterilization	Food-1
Heat Recovery Food Industry - Low Temperature	Food-2
Membrane Technology - Food	Food-3
Cooling and Storage	Food-4
Ultrasonic Dyeing	Textile-1
Black Liquor Gasification	Paper-1
Condebelt Drying	Paper-2
Direct Electrolytic Causticizing	Paper-3
Dry Sheet Forming	Paper-4
Heat Recovery - Paper	Paper-5
High Consistency Forming	Paper-6
Impulse Drying	Paper-7
Clean Fractionation - Cellulose Pulp	Chem-1
Gas Membrane Technologies-Chemicals	Chem-2
Heat Recovery Technologies - Chemicals	Chem-3
Levulinic Acid From Biomass (Biofine)	Chem-4
Liquid Membrane Technologies-Chemicals	Chem-5
New Catalysts	Chem-6
Autothermal Reforming-Ammonia	Chem-7
Plastics Recovery	Chem-8
Biodesulfurization	Refin-1
Fouling Minimization	Refin-2
Roller Kiln	Ceramics-1
100% Recycled Glass Cullet For Container Glass	Glass-1
BOF Gas and Sensible Heat Recovery	Steel-1
Near Net Shape Casting/Strip Casting	Steel-2
New EAF Furnace Processes	Steel-3
Oxy-Fuel Combustion In Reheat Furnace	Steel-4
Smelting Reduction Processes	Steel-5
Advanced Forming/Near Net Shape Technology	Alum-1
Efficient Cell Retrofit Designs	Alum-2
Improved Recycling Technologies	Alum-3
Inert Anodes/Wetted Cathodes	Alum-4
Continuous Melt Silicon Crystal Growth	Electron-1
Advance ASD Designs	Motorsys-1
Advanced Compressor Controls	Motorsys-2
Compressed Air System Management	Motorsys-3
Motor Diagnostics	Motorsys-4
Motor System Optimization	Motorsys-5
Pump Efficiency Improvement	Motorsys-6
Switched Reluctance Motor	Motorsys-7
Advanced Lubricants	Motorsys-8
Advanced CHP Turbine Systems	Utilities-1
Advanced Reciprocating Engines	Utilities-2
Fuel Cells	Utilities-3
Microturbines	Utilities-4
Advanced Lighting Design	Lighting-1
Advanced Lighting Technologies	Lighting-2
Hi-Tech Facilities HVAC	HVAC-1
Anaerobic Waste Water Treatment	Other-1
High Efficiency/Low NO <sub>x</sub> Burners	Other-2
Membrane Technology Wastewater	Other-3
Process Integration (Pinch Analysis)	Other-4
Sensors and Controls	Other-5
Variable Wall Mining Machine	Mining-1

## Condensed Methodology and Summary of Assumptions

This page briefly describes the information contained in each major segment of the technology profile tables and any major assumptions that entered the analysis. For a more detailed discussion of the project approach and methodology, please turn to Section 3: Methodology and Approach.

*Market Information* includes a description of the industries to which the technology/measure is applicable. We also provide information on the end-uses for the technology, the principal energy types used by the technology, and the primary market segment. There may be more than one market segment for which the technology is applicable; we used our judgement to identify the most predominant segment. Finally, we also included a key output driver or the energy consumption for our 2015 base-case related to that sector.

*Reference Technology* includes a description of the current technology or practice, the volume of production or annual operating hours associated used in the baseline and savings analysis, and baseline energy consumption for the existing process.

*New Measure Information* includes a description of the new technology, energy consumption information, information on the current status of the technology, the expected date of commercialization (if known), and the lifetime of the technology.

*Savings information* identifies electricity, fuel, and primary energy savings for a typical application of the new technology relative to the reference technology. The analyst made an assessment of the rate at which the technology is expected to penetrate the market. The penetration rates assume that the technologies compete against the reference technology but not against each other for the market share. We assumed a linear penetration curve. The penetration rates begin in the first year after commercialization, or 2001 for those technologies that are already commercialized. For measures with retrofit as the predominate mode of market deployment, the portion of the market that can be impacted by a technology is assumed to be 100 percent. For replacement (i.e., replace on failure), the portion is assumed to be the period of the study (15 years) divided by the measure life. For new construction, it is the growth in capital investment for the target industry divided by the anticipated total installed capital value in 2015. Feasible applications refers to the percentage of the total market that the technology is estimated to capture by 2015.

*Cost-Effectiveness* provides an estimate of the technology or measure's investment cost (\$/unit output), whether that investment is incremental or full cost, and any change in operations and maintenance cost (\$/unit output) for adopting the technology. We propose to include three measures of cost-effectiveness: cost of conserved energy for electricity, fuels, and primary energy, simple payback for the investment relative to the reference technology (years), and internal rate of return (IRR percent). Simple payback and internal rate of return are metrics that are often used by industries and financial analysts, while cost of conserved energy has been useful as a cost-effectiveness indicator for the policy community.

*Key Non-Energy Factors* are those factors that can significantly affect the decision to purchase a technology. These include the presence of other benefits (productivity, quality, environmental, other [i.e. safety]), and to what extent the technology is currently being promoted.

In the *Evaluation* section of this table, researchers identify the major market barriers that could impede the successful implementation of this technology. The technology's likelihood of success (high, medium, and low) is rated based on its cost-effectiveness, key non-energy factors, and major market barriers. We suggest what next steps are appropriate to accelerate the deployment of the technology. Finally, the analyst provides an assessment of the overall quality of the data used in the analysis using a rating of excellent, good, fair or poor.

## Electron Beam Pasteurization (Food-1)

Radiation pasteurization entails subjecting food to controlled amounts of ionizing radiation that has sufficient energy to knock electrons from the outer rings of atoms of the foods to create free radicals and ions, resulting in the destruction of bacteria and pathogens. The radiation used does not have sufficient energy to split atoms that would cause the exposed objects to become radioactive. The U.S. Food and Drug Administration has approved the following sources of ionizing radiation for the treatment of foods:

- Gamma rays produced by the natural decay of radioactive cobalt-60 or cesium-137 isotopes
- X-rays with a maximum energy of five million electron volts (MeV)
- Electrons with a maximum energy of 10 MeV

Electron beam technology has perhaps the greatest potential for the safe, effective, and cost-efficient radiation pasteurization of meat, dairy, and canned goods. In electron beam systems, a multi-stage electron accelerator generates a dense beam of high-energy electrons. This beam is magnetically focused and scanned across the target, providing saturation of the food product with electrons that deposit their energy and break the chemical bonds of its atoms. Electron beam sterilization has been used in medical devices for more than 40 years, but only in recent years have the problems of relatively low penetration ability and device complexity been solved.

Electron beam pasteurization competes with the other radiation treatments as an alternative to thermal pasteurization. Thermal pasteurization is the primary technology employed in the dairy and canning industries. In the traditional pasteurization process for milk, the liquid is raised to a temperature of 162 degrees Fahrenheit (72° C) for 15 seconds followed by rapid cooling to 44 degrees (7° C). Liquid foods such as milk, fruit juices, beer, and wine are pasteurized using plate-type heat exchangers consisting of a large number of thin, vertical steel plates that are clamped together in a frame. The plates are separated by small gaskets that allow the liquid to flow between each successive plate. After the process is completed, the product is packaged under aseptic conditions to prevent recontamination of the product. The technology uses over 90 percent less energy than conventional pasteurization techniques.

During the 1970's, several companies, including Varian Associates, Proctor and Gamble, and Siemens began renewed research in the application of x-ray technology for medical equipment and their involvement in the improvement of accelerated electron technology raised performance parameters to a new level. The major disadvantage of electron beams has been that the electrons don't penetrate more than an inch and a half into an organic object. Improvements in the equipment design have overcome this problem to a certain degree.

The greatest advantage of electron beam pasteurization is that it is quite versatile. The technology can be utilized to treat products that would normally undergo thermal treatment as well as products that cannot withstand the high temperatures of traditional pasteurization. Meat products and fresh fruits and vegetables can be irradiated to kill bacteria and molds. One of the largest market barriers that face this technology is the stigma that is associated with irradiated foods. None of the country's major food companies will publicly acknowledge interest in food irradiation (Skerret, 1997), but developments such as the Clinton Administration's food-safety initiative may renew interest in this area. Economics will play a large role in determining which of the alternative approaches to thermal pasteurization will ever become widely used in food processing. Food is a relatively inexpensive commodity, therefore even slight decreases in processing costs can have a big impact on consumer prices. Electron beam processing currently adds an additional ten cents or so per pound of product ([www.techreview.com/articles/nd97/skerrett.html](http://www.techreview.com/articles/nd97/skerrett.html)), but demonstration facilities such as SureBeam Corporation's electronic pasteurization system in Sioux City, Iowa ([www.surebeamcorp.com/food/systems.php](http://www.surebeamcorp.com/food/systems.php)), could soon bring about lower costs.

Electron beam pasteurization techniques can be a viable option for foods that cannot withstand high temperatures, such as meats, cheeses, fruits, and vegetables. In order for this technology to truly enter the marketplace, the initial capital and installation costs will need to come down, in all but the more expensive specialty food markets.

## Electron Beam Pasteurization Data Table

	Units	Notes	
<b>Electron Beam Pasteurization</b>			
<b>Food-1</b>			
<b>Replace thermal pasteurization</b>			
<i>Market Information:</i>			
Industries		Food	SIC 20
End-use(s)		Process heating, other	Okos, et al. 1998
Energy types		Natural gas, electricity, coal	
Market segment		New, replace on failure	
2015 basecase	tons	93150000	Assume 15% increase over USDA 1999 figures <a href="http://www.usda.gov/nass/aggraphs/milkprod.htm">http://www.usda.gov/nass/aggraphs/milkprod.htm</a>
<i>Reference technology</i>			
Description	heat pasteurization of milk (raise from ambient to 162 F for 15 sec, then cool to 44 F)		
Throughput or annual operating hours	tons	1.00	
Electricity use	kWh	4.40E+02	Okos, et al. 1998
Fuel use	MBtu	1.25	Okos, et al. 1998
Primary Energy use	MBtu	4.99	Okos, et al. 1998, assume 42.5% heating efficiency, 19.5% cooling efficiency
<i>New Measure Information:</i>			
Description	electron beam pasteurization of milk		
Electricity use	kWh	50.00	<a href="http://www.surebeamcorp.com/food/ebamtech.php">http://www.surebeamcorp.com/food/ebamtech.php</a> , 50kwh/ton
Fuel use	MBtu	0.00	
Primary Energy use	MBtu	0.43	<a href="http://www.biosterile.com/foodpast.htm">http://www.biosterile.com/foodpast.htm</a>
Current status		Commercialized	
Date of commercialization		1995	
Estimated average measure lifetime	Years	10	
<i>Savings Information:</i>			
Electricity savings	kWh/%	389.62	89%
Fuel savings	MBtu/%	1.25	100%
Primary energy savings	MBtu/%	4.57	91%
Penetration rate		low	Industry must overcome negative stigma of irradiated foods
Feasible applications	%	8%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	2903.45	
Fuel savings potential in 2015	Tbtu	9.28	
Primary energy savings potential in 2015	Tbtu	34.04	
<i>Cost Effectiveness</i>			
Investment cost	\$	100	Implementing electron beam is capital intensive
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	10	
Cost of conserved energy (electricity)	\$/kWh	0.08	
Cost of conserved energy (fuel)	\$/Mbtu	24.04	
Cost of conserved energy (primary energy)	\$/Mbtu	6.55	
Simple payback period	Years	19.2	
Internal rate of return	%	0.37%	
<i>Key non energy factors</i>			
Productivity benefits		Significant	Electron beam pasteurizes in a few seconds and does not require heating
Product quality benefits		Significant	Does not alter the taste or quality of the food
Environmental benefits		None	
Other benefits			
Current promotional activity	H,M,L	Medium	Several companies are involved in promoting the technology
<i>Evaluation</i>			
Major market barriers		Public perception	Negative publicity involving irradiated food. Banned in EU
Likelihood of success	H,M,L	Low	
Recommended next steps		Testing on safety	Testing for safety must be done to allay fears of public
Data quality assessment	E,G,F,P	Fair	
<i>Sources:</i>			
2015 basecase			<a href="http://www.usda.gov/nass/aggraphs/milkprod.htm">http://www.usda.gov/nass/aggraphs/milkprod.htm</a>
Basecase energy use			Okos, et al. 1998
New Measure energy savings			<a href="http://www.oit.doe.gov/factsheets/petroleum/pdf/gasbiopet.pdf">http://www.oit.doe.gov/factsheets/petroleum/pdf/gasbiopet.pdf</a>
Lifetime			Thayer, et al. 1996
Feasible applications			
Costs			
Key non energy factors			
Principal contacts			
Additional notes and sources			

## Low Temperature Heat Recovery in the Food Processing Industries (Food-2)

Food processing industries play a vital role in the U.S. economy and in foreign trade. Classified under Standard Industry Code (SIC) 20, together these industries account for a large portion of U.S. industrial energy use, ranking as the fifth largest energy-using industry after petroleum refining, chemicals, primary metals, and paper manufacturing. Unlike other energy-intensive industries, the food industry does not produce a homogenous output and operates at significantly lower temperatures. Therefore, energy consumption in food industries comes from a wide range of production activities. Some of the energy-consuming activities of the sector include roasting, baking, cooking, frying, drying, freezing, refrigeration, pasteurization, evaporation and distillation. There are also energy demands for supplying buildings with heat, light, and air conditioning. In 1994, roughly two-thirds of final energy demand for the food industries was fuel for boilers to provide steam and heat to the various processes (EIA 1997).

There are many opportunities to take advantage of heat recovery in food processing. Heat recovery describes a situation where “excess” heat from some production process is utilized in another process step. Heat recovery can be accomplished by using all or part of the exhaust gas from one process as the inlet gas to another process. Alternatively, a piece of equipment called a *heat exchanger* can capture the heat in the exhaust and transfer it to another flow of gas or liquid. Heat exchangers are commonly used throughout industrial processes, and there are numerous manufacturers producing many varieties of heat exchangers, including heat pumps, plate recuperators, tube recuperators, heat tubes, run-around coils, and economizers. Energy savings from heat recovery in the food industry depend upon finding applications where heat recovery is economical and improves the process.

Case studies illustrate that there are many potential applications for cost-effective heat recovery applications in the food industry. In some of these projects, excess heat from one energy-intensive process step was used in another process step. At bakeries, heat exchangers were installed in the exhaust stacks of the ovens where bread was baked. The heat recovered was used during the dough-rising stage (CADET 1994a, CADET 1997c) or provided hot water for other processes. At vegetable processing plants, excess heat from frying (CADET 1995a) or steam peeling (CADET 1999a) was used to provide hot water to the facility for use at other process steps. Two other projects at beverage facilities used heat exchangers to improve process integration; one was at a brewery (CADET 1999b) and one was at a whisky distillery (CADET 1994b).

Heat recovery also has important applications for drying processes. Important drying processes in the food industry include the drying of grains and beans for storage or fodder (CADET 1994c), drying malt for breweries (CADET 1997b), and pulp drying in the sugar processing industry. For drying, the material is typically treated with heated dry air. The gases leaving a dryer will have high moisture content and still contain residual heat. Heat exchanger systems capture both the heat remaining in the gases as well as the latent heat in the water vapor of these exhaust gases, and transfers this heat to the inlet gases for the dryer.

Most heat exchangers used in food processing are constructed of stainless steel, and this meets the requirements of most applications. In applications where significant amounts of dissolved chloride exists in the material being passed through the heat exchanger, which is common for preserved or prepared foods, the potential for corroding stainless steel is high. In these cases, the common choice is to use heat exchangers made of nickel, nickel-steel alloy, or titanium. Plastic heat exchangers may one day be used in these corrosive applications, but for now they are too costly and do not meet the design specifications for the food industry.

The eight projects cited above occurred around the world – Netherlands, UK, Australia, and Canada – and ranged in total project costs from \$13,000 to over \$1 million. These projects totaled annual energy savings of 290,000 MMBtu (306,000 GJ), with an average capital cost of roughly \$16 per MMBtu (\$15/GJ) saved annually. With the average price of primary energy around \$4 per MMBtu (\$3.8/GJ), the payback period for these projects averages around 4 years.

We estimate that food industry energy consumption in 2015 will be approximately 1700 TBtu (1790 PJ) of primary energy (AEO 1999). Roughly 50 percent of this will be fossil fuel for boilers meeting steam demand for food processing. Another 15 percent will be fossil fuel used directly in processes, and 35



## Heat Recovery Applications in the Food Industry Data Table

	Units	Notes	
Heat Recovery Applications in the Food Industry			
food-2			
Use of heat exchangers at various applications in the food industry.			
Market Information:			
Industries		Food Industry	
End-use(s)		Process heat	
Energy types		Fuels, Electricity	
Market segment		Retrofit	
2015 basecase use	TBtu	1710.5	EIA99
Reference technology			
Description	Minimal use of heat recovery in drying systems and to preheat boiler feed water		
Throughput or annual op. hrs.			
Electricity use	TWh	58	EIA, 1997
Fuel use	TBtu	985	EIA, 1997
Primary energy use	TBtu	1478.3	
New Measure Information:			
Description	Use of heat recovery technologies to lower energy consumption in drying and to reduce losses from boilers		
Electricity use	TWh	58	
Fuel use	TBtu	958	
Primary Energy use	TBtu	1451	
Current status		Commercialized, Research	Depends on specific application
Date of commercialization		1995	
Est. avg. measure life	Years	25	Distributor claims heat exchanger in non-corrosive environment has indefinitely lifetime if properly maintained
Savings Information:			
Electricity savings	TWh/%	0	0%
Fuel savings	TBtu/%	27.0	3%
Primary energy savings	TBtu/%	27.0	2%
Penetration rate		Low/Medium	
Feasible applications	%	30%	
Other key assumptions			
Elec svgs potential in 2015	TWh	0	
Fuel svgs potential in 2015	TBtu	9.4	
Primary energy svgs potential in 2015	TBtu	9.4	
Cost Effectiveness			
Investment cost	\$/Mbtu-s	16	Estimate of capital investment based on sample projects
Type of cost		Full cost	
Change in other costs	\$	0	Rough estimate value of average productivity benefits
Cost of saved energy (elec)	\$/kWh	2.48	
Cost of saved energy (fuel)	\$/Mbtu	2.48	
Cost of saved energy (primary)	\$/Mbtu	2.48	Discount rate for all CCE calculations is 15%
Simple payback period	Years	4.8	
Internal rate of return	%	20%	
Key non energy factors			
Productivity benefits		Somewhat	Increased throughput, less heat and vapor discharged to facility and atmosphere
Product quality benefits		Somewhat	
Environmental benefits		None	
Other benefits			
Current promotional activity	H,M,L	Low	
Evaluation			
Major market barriers		Awareness	Fears of fouling and corrosion
Likelihood of success	H,M,L	Low	
Recommended next steps		Promote pinch analysis	
Data quality assessment	E,G,F,P	Fair	Own estimates based on literature survey
Sources:			
2015 basecase			EIA, 1999
Basecase energy use			EIA, 1999
New measure energy savings			Numerous CADDET reports
Lifetime			Conversation with distributor (West Chem Equipment), author judgement
Feasible applications			Author judgement
Costs			Numerous CADDET reports
Key non energy factors			
Principal contacts			George Fisher Co.(Sam Wharry), West Chem Equipment
Additional notes and sources			

percent will be fuels consumed to meet the food industry's electricity demand (AEO 1999). Of the total energy consumed for steam demand, 20 to 25 percent is lost due to boiler inefficiencies (AEO 1999, Drescher et al. 1997). The use of heat recovery systems can lower the boiler losses to 12 to 16 percent in industries where there are opportunities for heat recovery (Drescher et al. 1997). Assuming that 20 percent of energy use falls into this category and is retrofit for heat recovery by 2015, 14 TBtu (15 PJ) of energy savings can be attained. For drying systems, we assume that 16 percent of food industry energy use is used for drying (CADDET Newsletter 1997). Estimates of the potential savings from heat recovery systems for drying range from 10 to 50 percent for various projects (Drescher et al. 1997, Mercer 1994). We assume that 20 percent of the drying energy demand is appropriate for heat recovery and retrofit by 2015, and that these projects on average reduce dryer energy demand by 25 percent. Under these conditions, energy consumption is lowered by 9.5 TBtu (10 PJ).

## Membrane Technology—Food (Food-3)

The food and kindred products industry (SIC 20) comprises a wide variety of activities. The sector is large and growing. The value of shipments exceeds \$400 Billion (Drescher et al. 1997), and is also a large energy consumer. Primary energy use in 1994 was 1480 TBtu (1560 PJ), equivalent to 5 percent of total industrial energy use in the U.S. Primary energy consumption in 2015 is estimated to be 1700 TBtu (1790 PJ) (AEO 1999). The main energy consuming sub-sectors are corn milling, sugar, meat packing, soybean oils, beverages, and dairy.

In the food industries, membranes are used to concentrate, fractionate and purify liquid products. In the food and beverage industry, four types of membrane processes are important: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Gas separation is only used in the fruit and vegetable sector for packaging in a nitrogen atmosphere. The differences between the membrane methods are the separation capabilities due to size and molecular weight, although the separation capabilities do overlap. Table 11 provides an overview of potential membrane applications in different food industries. Due to the diverse activities in the food industry, quantitative estimates of the potential capacities for membrane applications are difficult to make. Below we discuss some of the major potential applications in more detail.

### Overview Of Potential Membrane Applications In The Food Industry.

Sector	Applications	Membrane type
Dairy	Whey concentration	RO
	Milk concentration	RO
	Desalting of salt whey	ED*
	Fractionation of proteins	UF
	Concentration of egg and egg white	UF
Grain milling	Recovery of by-products from waste water	UF
Beverage	Cold stabilization of beer	MF
	Clarification of wine	UF
	Removal of alcohol from beer and wine	RO
	Pretreatment of water	RO
	Upgrading of citrus juices	RO
Sugar	Preconcentration of dilute sugar solutions	UF
	Syrup concentration	UF
	Recovery of sugar from rinse water	UF/RO
Fruits and vegetables	Concentration of tomato juice	RO/UF
	Concentrating juices	RO/UF
	Juice flavor and aroma concentration	UF/RO

\*Electrodialysis

Source: Köseoglu et al. 1993, Maaskant et al. 1995, KMS 2000.

We focus on the dairy, beverages, fruit and vegetables industry. Almost 40 percent of the total membrane market of over \$1 Billion in the U.S. is found in the food industries (Wiesner and Chellam 1999). The dairy industry is the most important sector using membranes in the U.S. (Dziezak 1990). The fruit and vegetable industry has a large potential for improved energy efficiency using membranes. The beverage sector is also an important sector for applying membranes. For example, membranes can be used for the removal of alcohol from beer and the treatment of water, but this application may decrease rapidly because of the possibility of producing beer without alcohol. In the sugar sector, membranes are used in almost 20 percent of the potential applications in countries like The Netherlands. In the dairy and fruits and vegetable industries, membrane technology is considered proven in many applications.

Barriers to implementation include the lack of information, as well as the need for specific membranes in specific applications. Major suppliers are APV (Denmark), Koch Membrane Systems (U.S.), Osmonics (U.S.), U.S. Filter (U.S.). Research is directed at new applications, more efficient and longer lasting

## Membrane Technology in the Food Industry Data Table

	Units		Notes	
Membranes				
Food-3				
Process Applications of Membranes in the Food Industry				
Market Information:				
Industries		Food	SIC 20	
End-use(s)		Separation		
Energy types		Fuel		
Market segment		New		
2015 basecase use	Tbtu	1712.0	EIA 1999 forecast of Food primary energy use	
Reference technology				
Description	Evaporation, Clarification			
Throughput or annual op. hrs.	N/A.			
Electricity use	GWh	930	Estimated energy use in 'membrane-eligible' process uses, 15% of 1994 pump use	
Fuel use	TBtu	147.8	Estimated energy use in 'membrane-eligible' process uses, 15% of 1994 fuel use	
Primary energy use	TBtu	155.7		
New Measure Information:				
Description	Membrane technology replaces existing separation processes			
Electricity use	GWh	2662		
Fuel use	TBtu	88.7		
Primary Energy use	TBtu	111.3		
Current status		Commercial, Research	Many applications commercial; new membranes under development	
Date of commercialization		1990		
Est. avg. measure life	Years	10		
Savings Information:				
Electricity savings	GWh/%	-1732	-186%	Actual savings depend on application
Fuel savings	TBtu/%	59.1	40%	Actual savings depend on application
Primary energy savings	TBtu/%	44.4	29%	Actual savings depend on application
Penetration rate		Medium		
Feasible applications	%	60%	Rough estimate, based on current uses	
Other key assumptions				
Elec svgs potential in 2015	GWh	-1039		
Fuel svgs potential in 2015	Tbtu	35		
Primary energy svgs potential in 2015	Tbtu	26.6		
Cost Effectiveness				
Investment cost	\$/Mbtu-s	450	Actual costs vary heavily depending on application	
Type of cost		Full cost		
Change in other costs	\$/Mbtu-s	-55	Actual costs vary heavily depending on application	
Cost of saved energy (elec)	\$/kWh	N/A		
Cost of saved energy (fuel)	\$/Mbtu	0.59		
Cost of saved energy (primary)	\$/Mbtu	0.78	Discount rate for all CCE calculations is 15%	
Simple payback period	Years	2.2		
Internal rate of return	%	45%		
Key non energy factors				
Productivity benefits		Somewhat	Reduced resource use	
Product quality benefits		Somewhat	Improved quality (drinks)	
Environmental benefits		Somewhat	Reduced water use	
Other benefits				
Current promotional activity	H,M,L	Medium		
Evaluation				
Major market barriers		Specificity, Unknown		
Likelihood of success	H,M,L	Medium		
Recommended next steps		Dissemination, R&D		
Data quality assessment	E,G,F,P	Fair, Poor		
Sources:				
2015 basecase			AEO 2000	
Basecase energy use			EIA, 1996 (MECS 1994)	
New measure energy savings			Estimate based on case-studies and Eichhammer, 1995	
Lifetime			Wiesner and Chellam, 1999	
Feasible applications			Author estimate	
Costs			Estimate based on payback period of case-studies (CADET)	
Key non energy factors			Case-studies (CADET)	
Principal contacts				
Additional notes and sources				

membranes. Federal research programs (e.g. ATP) support development of membrane technology, as well as development of specific applications (e.g. DOE, EPA).

**Dairy industry.** Worldwide, many thousands of m<sup>2</sup> membranes have been installed in the dairy industry. It also is the sector with the longest history of the use of membranes, which are used for the desalting of whey

(NF)<sup>15</sup>, the concentration of whey (RO), the conversion of milk into cheese and soft cheese and the preparation of egg white and egg yolk. For example, a nano-filtration unit was installed in 1996 for whey concentration at a dairy plant in The Netherlands, replacing a two-stage evaporation process (CADET 1998a). The system reduced steam use by almost 70 percent (from 13 MBtu/ton (15 GJ/t) dry solids to 3.6 MBtu/ton (4.2 GJ/t) dry solids), while power consumption increased from 89 kWh/ton (98 kWh/t) to 153 kWh/ton (168 kWh/t) dry solids. Net energy savings were 8.8 MBtu/ton (10.2 GJ/t) water removed. Additional savings were achieved in the use of sodium hydroxide and nitric acid, as well as reduced transport costs and emission charges, reducing the payback period to 1.3 years (CADET 1998a). The investment costs were \$9.3 ft<sup>2</sup> (\$100/m<sup>2</sup>) (CADET 1998a). Current developments in dairy industry are the reduction of bacteria in milk and the clearing of dairy fluids. The application of membranes in the dairy industry is considered to be in an important phase for implementation on a large scale.

**Beverages.** Water treatment is an important application of membranes in the beverages industry (Comb 1995). For example, membranes are used by Coca-Cola (in Salina, KS) and membranes are also used for juice concentration and for alcohol recovery in the production of non-alcoholic beers (Gach et al. 2000). A number of breweries (e.g. Miller Brewing Co.) already apply membranes for alcohol removal from beer. Nevertheless, potential exists for further application and development. Replacement of plate membranes by new spiral membranes at the Heineken brewery in Den Bosch, The Netherlands, reduced pumping energy and water demand, and resulted in savings of 0.17 kWh/gallon beer (4.6 kWh/100 liter beer). At investments of \$0.06/gallon (1.7\$/100 liter) production capacity, the simple payback period was just over 4 years (CADET 2000a).

**Fruits and Vegetables.** There have been several demonstration projects using membranes in the fruits and vegetables industry. At Golden Town Apple Products in Canada, a combination of ultra-filtration and reverse osmosis was used for apple juice concentration (CADET 1996a). In this process, the juice is heated to about 140°F (60°C) and afterwards passed through the reverse osmosis membrane and the ultra-filtration membrane. The system has a maximum capacity of 3,000 l/hr for feedstock, 1,500 l/hr for final concentrate and 1,500 l/hr for water removed by reverse osmosis. It is most economical for small systems that need to remove no more than 4,500 to 9,000 pounds (2040 to 4080 kg) of water an hour. The energy savings are estimated to be 66 percent compared to an evaporation process, while the volume of the equipment is reduced by 50 percent as are the transportation costs. The payback period of the combined system is about 2.5 years (CADET 1996a).

It is extremely difficult to estimate the potential energy savings from implementation of membranes in the food industry without a detailed study. For specific applications, energy savings may be up to 40-55 percent of the energy needs for distillation and evaporation. Research is aimed at increasing the number of applications, increasing product quality, lifetime, and increasing energy savings. A European study estimated that membranes could be used to replace 15 percent of fuel using applications in the food industries (Eichhammer 1995). Based on this estimate, we assume that fuel savings are on average 40 percent, while electricity use increases by 10 percent of the fuel savings (expressed as final or site energy). Additional production savings are achieved through product quality, reduced water use, and lower operation costs.

The investment and operating costs depend heavily on specific application, and may even be site-specific. However, for the purposes of this study we make a general estimate, noting that the costs may vary widely in practice. Generally, capital costs are expressed per unit of surface area, while about half of the capital costs are for the system components (e.g. pumps, piping) (Wiesner and Chellam 1999). System costs may vary between \$6/ft<sup>2</sup> and \$37/ft<sup>2</sup> (200\$/m<sup>2</sup> and 1300\$/m<sup>2</sup>). Based on the different case studies we estimate an average payback period of 3 years, including non-energy benefits.

Membrane life of a properly operated facility may easily exceed 10 years (Wiesner and Chellam 1999). We assume a lifetime of 10 years. The energy savings and cost estimates are rough. Given the large potential application area and potential energy savings, an in-depth study into membrane applications, energy savings, and capital and operational cost benefits is warranted.

<sup>15</sup> By the mid-1990s more than 10,000 m<sup>2</sup> for the desalting of whey had already been installed in the U.S. dairy industry (Maaskant et al. 1995).

## Cooling and Storage (Food-4)

Refrigeration in the food sector is a large energy consumer and is mainly used for freezing or cooling of meat, fruit, vegetables, as well as for frozen products (e.g. ice-cream, juice). Refrigeration in industry is mostly done by means of compression cooling and in some cases by absorption cooling (Mottal 1995). Electricity use for refrigeration in the food and beverages industry is estimated at 11.1 TWh (Xenergy 1998), mainly used by compressors.

Many options exist to improve the performance of industrial refrigeration systems. System optimization and control strategies combined show a large potential for energy efficiency improvement of up to 30 percent (Brownell 1998). Opportunities include system design, component design (e.g. adjustable speed drives), as well as improved operation and maintenance practices. We focus on new system designs. Adjustable speed drives and process control systems have been discussed elsewhere. New system designs include the use of adsorption heat pumps, gas engine driven adsorption cooling, new working fluids (e.g. ammonia, CO<sub>2</sub>) and alternative approaches (e.g. thermal storage). Due to the wide variety, we focus on selected technology developments in the areas of gas engines, thermal storage and new working fluids.

*Gas engines* can be applied to drive the compressor instead of an electric motor. A gas engine is used as the direct drive, and the system can follow refrigeration loads by using variable engine speed. The waste heat of the engine can be used to preheat water or for space heating at the plant. GRI has developed a system, marketed by Thermopower Corporation, which has been tested in ice production, food processing, and chemical industries (GRI 1997). Other suppliers market similar products. NYSERDA supported an innovative demonstration at a dairy plant with a gas engine with an absorption chiller. Without the absorption sub-cooling, the project would have saved 52 percent on a primary energy basis. With the absorption cooling the project decreased primary energy use by 77 percent (CADDET 1996b). The gas engine compressor system (without absorption cooling) has capital costs twice as high as a chiller system, and a payback period of about 2 years. A similar system installed at Pittsburgh (PA) cooling warehouse had a payback period of 1.9 years (CADDET 2000b). The gas engine-absorption cooling system has substantially higher capital costs compared to an electric chiller system (almost a factor 3 higher), but the large energy savings and reduced peak energy use result in a payback period of 4 years. The use of a gas engine may result in higher onsite NO<sub>x</sub> emissions, although offsetting high peaking power plant emissions. Hence, in non-attainment areas extra NO<sub>x</sub>-reduction measures need to be installed.

*Thermal storage* is an “old” technology in the sense that it has been used for several centuries for seasonal cooling. Thermal storage has been re-discovered for applications in the food industry to shave peak loads by using off-peak power to generate ice, which is stored in a so-called ice pond and used for cooling. Several plants operate thermal storage systems in the U.S., combined with innovative cooling concepts, e.g. a fermentation plant in Rochester (NY), a cheese factory in Corfu (NY), a food services company in Clark County (NV) and a vegetable and food processing plant in Placentia (CA). Energy savings vary depending on the plant. The fermentation plant in Rochester (NY) reduced cooling energy needs by 80 percent compared to the existing mechanical chiller system. This system had a payback period of up to 4 years (CADDET 1993a). In other applications the savings were not always fully documented or are much smaller. The load shift accounts for the productivity increase, as it allows the use of low-priced electricity at the off-peak hours. Given the current peaking power-supply problems in California, the Midwest and Texas, peak power is a highly valuable commodity, making this technology economically attractive.

Other major trends are a reduction of refrigerant charges and the development of *new working fluids*. Traditionally, the most common working fluids for compression heat pumps are ammonia and CFCs or HCFCs. R&D is directed toward alternative working fluids, especially for the CFCs and HCFCs due to the Montreal Protocol. These alternative working fluids can save energy. Savings of 2 to 20 percent have been reported (Trepp et al. 1992, Lorentzen 1993a, Lorentzen 1993b). Recent developments include the use of natural refrigerants such as CO<sub>2</sub> (Stene 1999). CO<sub>2</sub> is suitable for cooling of storage facilities. In Japan research has also looked at metal hydride systems for commercial cooling, as well as for small-scale systems. A first working prototype was demonstrated in 1995 at a very small scale (for a vending machine), and the technology has been demonstrated for a warehouse of 1100 ft<sup>2</sup> (100 m<sup>2</sup>) at storage temperatures of 40°F (-40°C). The system can be designed in a wide variety of scales (10 – 10,000 kW), and reduces power use by approximately 20 percent compared to traditional CFC-containing systems (JNT 1996).

# Cooling and Storage in the Food Industry Data Table

	Units	Notes
<b>Cooling and Storage Systems</b>		
<b>Food-4</b>		
<b>Innovative designs of cooling/refrigeration equipment in food preservation</b>		
<i>Market Information:</i>		
Industries	Food	SIC 20
End-use(s)	Motor and drives	Excluding motor systems, lighting, HVAC
Energy types	Electricity	
Market segment	New	
2015 basecase use	N/A.	Cooling demand in selected subsectors is unknown in 2015
<i>Reference technology</i>		
Description	Estimated energy consumption for cooling in the food industry	
Throughput or annual op. hrs.		
Electricity use	TWh	11 Xenergy, 1998
Fuel use	TBtu	0
Primary energy use	TBtu	94.4
<i>New Measure Information:</i>		
Description	Innovative designs of cooling/refrigeration equipment in food preservation	
Electricity use	TWh	9
Fuel use	TBtu	0
Primary Energy use	TBtu	75
Current status	Commercial	Thermal storage, other technologies being developed
Date of commercialization		1990
Est. avg. measure life	Years	15
<i>Savings Information:</i>		
Electricity savings	TWh/%	2 20% Estimates based on case studies
Fuel savings	TBtu/%	0.0 N/A.
Primary energy savings	TBtu/%	18.9 20%
Penetration rate		Low
Feasible applications	%	40%
Other key assumptions		
Elec svgs potential in 2015	TWh	1
Fuel svgs potential in 2015	TBtu	0.0
Primary energy svgs potential in 2015	TBtu	7.5
<i>Cost Effectiveness</i>		
Investment cost	\$/Mbtu-s	32 CAITAE,1998[2] (on primary energy basis)
Type of cost		Full cost
Change in other costs	\$/Mbtu	-6 Credit for shift of peak electricity use (on primary energy basis)
Cost of saved energy (elec)	\$/kWh	-0.53
Cost of saved energy (fuel)	\$/Mbtu	-0.53
Cost of saved energy (primary)	\$/Mbtu	-0.53
Simple payback period	Years	2.6
Internal rate of return	%	38%
<i>Key non energy factors</i>		
Productivity benefits		None
Product quality benefits		None
Environmental benefits		Somewhat
Other benefits		Somewhat
Current promotional activity	H,M,L	Low Off-peak electricity use
<i>Evaluation</i>		
Major market barriers		Unknown, New
Likelihood of success	H,M,L	Medium
Recommended next steps		Demonstration,Dissemination
Data quality assessment	E,G,F,P	Fair Estimates based on case studies
<i>Sources:</i>		
2015 basecase		
Basecase energy use		Xenergy, 1998
New measure energy savings		CAITAE,1998[2] and DOE [1997]
Lifetime		Author's estimate
Feasible applications		Author's estimate
Costs		CAITAE,1998[2]
Key non energy factors		CAITAE,1998[2]
Principal contacts		
Additional notes and sources		

For the technology characterization, we assume a potential for energy efficiency improvement of 20 percent on average, which can be achieved using different technologies, e.g. thermal storage, natural gas engine (not for non-attainment areas) and the use of new refrigerants in small-scale industrial applications. Higher energy savings are possible in specific cases, as outlined above.

Given the incentives for reduction of peak power use and expected peaking-power shortages in important food producing regions, we assume that there is a substantial interest in implementing new refrigeration equipment in the food industry. Hence, we estimate that between 2000 and 2015 40 percent of the potential may be realized.

Capital costs will depend heavily on the specific site and cooling conditions, as well as technology implemented. Hence, the costs and profitability of the investment will vary widely. We base the cost estimate on the thermal storage system installed at Kirk Produce, Placentia (CA) (CADET 1990). The cost savings because of switching to off-peak hours electricity use have been accounted as a productivity benefit. Other benefits may occur, such as increased product quality (CADET 1990), but have not been taken into account in the cost estimates.

Most technologies, except for the use of selected new refrigerants, have been demonstrated commercially. Hence, dissemination of the results among other potential users is needed, as is demonstration of new concepts or innovative combinations of efficient cooling systems.

## Ultrasound Enhanced Dying (Textile-1)

The textile industry in the United States is a mature industry that used 476.5 TBtus of Primary energy, or 2.3 percent of manufacturing energy in 1994 (EIA 1997). While some of the more labor intensive portions of the industry have moved overseas in the past two decades, the less labor intensive, more energy intensive portion of the industry have stayed in this country, largely through the application of technology to increase productivity. One of the most energy intensive sectors in textiles is dyeing and finishing. The dying of fabric in the textile industry involves two physical processes: the transport of the dyestuffs into the fibers, and the dyestuffs' uptake by or reaction with the fibers, resulting in a fast color. Traditionally these actions are accomplished by the application of time, temperature, and pressure. The addition of chemicals, such as salt and urea, to speed the process is usually needed. Conventional dying processes are capital and energy intensive, and the presence of salt and urea in the waste stream creates pollution abatement challenges (Mock 2000). In addition, ultrasound has been shown to enhance the washing phase in which unreacted dyestuffs are removed from the fabric. Both time required for washing and volume of water required are reduced.

The application of ultrasound in the dying process offers a number of advantages. Research has indicated that in the presence of ultrasound, the transport and uptake of dye by the fabric can be significantly accelerated. These results occur because the ultrasound energy causes the fiber to swell while reducing surface tension. In addition, the ultrasound allows for a more rapid reaction of the dye with the fabric, because the ultrasound energy preferentially heats the dyestuffs in the fabric. All these benefits of accelerated dyeing can be achieved at lower temperature and atmospheric pressure without the need to add chemicals to the dyestuffs. In addition, the use of ultrasound allows for precise control of the color shade, thus significantly reducing variations in shade commonly experienced with conventional dyeing processes (McCall, Cato and Grady 1992).

Because of the need to maintain a uniform ultrasound field, the technology is only applicable to web dyeing. In web dyeing, a single thickness of fabric is dyed continuously on machine referred to as a dye range. The fabric web is transported under tension through the various stages of the process on drums (dyeing, fixing, washing and drying) similar to a papermaking machine. Research has shown particular efficacy for the application of ultrasound in continuous dyeing of cotton fabric (McCall, Cato and Grady 1992, Grady 2000, Mock 2000). Web-dyed fabric represents about 0.13 percent of domestic value of textile shipments, with dyeing representing about 0.12 percent of the energy used in the textile industry (Census 1996, Census 2000).

The application of ultrasound reduces thermal energy used directly by the process by 10 percent. In addition, savings are realized in the reduced treatment of wastewater. The volume of spent dyestuffs and wash-water are reduced, and treatment is made easier because the concentration of salt and urea in the waste stream is reduced (Mock 2000). In addition, the lack of salt and urea in the dyestuff may also allow for recycling of the dyestuff (McCall, Cato and Grady 1992). Because of the lack of data and the variations in how wastewater is treated between different plants, we have been unable to estimate these additional energy savings.

Ultrasound can be retrofitted to existing, dye ranges or be engineered into new systems. Because ultrasound decreases dyeing, fixing and washing times, the through-put for the equipment can be increased significantly at the same operating cost, thus reducing the fixed cost associated with the operation of a range. In addition, because less dye stuffs and chemicals are required to dye a lot of fabric, variable costs are also reduced. ACEEE has assumed that production for a range could be increased by 50 percent, resulting in a corresponding annual unit fixed and variable O&M costs reduction of \$330,000 per million yards of fabric.

A number of barriers exist to the deployment of this technology. Because this sector of the industry is mature, operating profits are low, and significant international looms, companies are hesitant to make new capital outlays. In addition, most of the dyeing equipment manufacturers are not domestic and most of the ultrasound development has occurred in this country. The technology has been demonstrated at the bench scale, and while research into the science has continued, commercialization activities have been suspended due to a discontinuation of federal textile research funding. Foreign equipment manufacturers have not



stepped into the breach. One of the principal researchers in the area indicates that the primary activity need to move the technology into market is funding to demonstrate a commercial prototype (Grady 2000). The United States-Asian Environmental Partnership has also identified this technology as one of six key emerging textile technologies (USAEP 1999).

### Ultrasound Enhanced Dying Data Table

	Units	Notes	
Ultrasonic Dying			
Textile-1			
Replace existing continuous web drying with ultrasonic enhanced dying			
Market Information:			
Industries		Textile	SIC 226
End-use(s)		Other	
Energy types		Electricity, gas	
Market segment		New, retrofit	Both new dye ranges and as a retrofit to existing ranges
2015 basecase	million sq.yds.	4291	Based on 1999 Cotton Broadwovens production (Census 2000) , scaled using EIA 2000 growth projection (Honeycutt 2000).
Reference technology			
Description	Web dying of cotton broadwovens using a continuous dye range		
Throughput or annual operating hours	sq.yds	1,000,000	
Electricity use	kWh	92.2	1992 energy intensity is based on prorating MECS Energy use for textiles to cotton broadwovens as reported in Current Industrial Reports (Census 1998).
Fuel use	MBtu	53.0	
Primary Energy use	MBtu	53.8	
New Measure Information:			
Description	Apply ultrasound to web dying, reducing temperature, contact time, & eliminating salts & urea		
Electricity use	kWh	92.2	10% by reduced contact time and increased dye transfer rate at lower temperatures.
Fuel use	MBtu	47.7	
Primary Energy use	MBtu	48.5	
Current status	Bench-scale prototype		
Date of commercialization		2005	
Estimated average measure lifetime	Years	10	
Savings Information:			
Electricity savings	kWh/%	0	0%
Fuel savings	MBtu/%	5.3	10.0%
Primary energy savings	MBtu/%	5.3	9.9%
Penetration rate		Medium	45% penetration in 2010
Feasible applications	%	23%	Feasible 50% of cotton broadwovens
Other key assumptions for savings	Does not include savings in wash water treatment		
Electricity savings potential in 2015	GWh	0	
Fuel savings potential in 2015	TBtu	5.1	
Primary energy savings potential in 2015	TBtu	5.1	
Cost Effectiveness			
Investment cost	\$	100,000	Cost to add ultrasound generators (McCall et al, 1992)
Type of cost		Full cost	Cost of generators incremental to range cost
Change in annual costs (O&M/other benefits)	\$	-330,000	Increases throughput by 50% for same O&M
Cost of conserved energy (electricity)	\$/kWh	NA	
Cost of conserved energy (fuel)	\$/MBtu	-58,526	
Cost of conserved energy (primary energy)	\$/MBtu	-58,526	Discount rate for all CCE calculations is 15%
Simple payback period	Years	0.3	
Internal rate of return	%	330%	
Key non energy factors			
Productivity benefits		Compelling	Increases throughput, thus expanding capacity and reducing unit O&M cost for existing capacity
Product quality benefits		Compelling	More first quality fabric due to Reduced improved control.
Environmental benefits		Compelling	Reduces volume of waste water, while reducing salt and urea
Other benefits		None	
Current promotional activity	H,M,L	Low	Commercialization suspended due to funding cuts.
Evaluation			
Major market barriers		Lack of domestic manufacturers, commercial equipment, and increased first cost	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Funding of production prototype demonstration	
Data quality assessment	E,G,F,P	Fair	
Sources:			
2015 basecase		Census 2000 and Honeycutt 2000	
Basecase energy use		Derived from EIA 1997	
New Measure energy savings		McCall et al 1992, Grady 2000	
Lifetime		Grady 2000, Mock 2000	
Feasible applications		Mock 2000	
Costs		McCall et al 1992, Grady 2000 and Mock 2000	
Key non energy factors		McCall et al 1992, Grady 2000 and Mock 2000	
Principal contacts		Perry Grady, NCSU 919/515-3255	
Additional notes and sources			

## Black Liquor Gasification (Paper-1)

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994 (EIA 1997). Of this amount, we estimate that 1,348 TBtu (1422 PJ) of biomass is used in boiler plant facilities to produce steam for various paper manufacturing processes (EIA 1997). Boiler plants that burn biomass materials are primarily located at Kraft pulp mills, which currently account for nearly 80 percent of the pulp produced in the U.S. (Kincaid 1998). In standard integrated Kraft mills, the spent liquor produced from de-lignifying wood chips (called black liquor) is normally burned in a large recovery boiler, named that because the black liquor combustion is used to recover the chemicals used in the delignification process. Because of the relatively high water content of the black liquor fuel (the fuel is usually combusted at a solids content of 65-75 percent), the efficiency of existing recovery boilers is limited. Electricity production capacity is also reduced since recovery boilers produce steam at lower pressures for safety reasons.

One of the new technologies being developed as an alternative to direct combustion of the black liquor is the gasification of the liquor and its subsequent combustion in gas turbines designed to accommodate the lower energy content black liquor gas. The gasification of the liquor converts it into a more useable energy source (Worrell, Bode, and de Beer 1997). While there are also technologies directed solely on gasification, in this assessment we focus on the combined cycle turbine technology combined with gasification. This combination technology has potential to produce significantly more electricity than the current boiler/steam turbine systems, and even make the mill an electricity exporter.

The two main types of gasification are low temperature/solid phase and high temperature/smelt phase. The gasification produces a fuel gas that needs to be cleaned to remove undesired impurities for the power system and to recover pulping chemicals. Low temperature gasification is based on a fluidized bed at atmospheric pressure and a temperature 1290°F (700°C) or lower, below the melting point of inorganic salts that comprise most of the char from black liquor. Sodium carbonate is used as the bed material and is precipitated out and reused (Worrell, Bode, and de Beer 1997, Berglin et al. 1996). The key manufacturer of this process is Manufacturing and Technology Conversion International (MTCI), a U.S. firm (Larson and Raymond 1997, Larson et al. 2000).

High temperature gasification occurs at 360 lbs/in<sup>2</sup> (2.5 Mpa) and above the melting point of the inorganic salts 1740°F (950°C) or higher, and chemicals are recovered in a smelt. Higher temperatures lead to higher carbon conversion rates but also may lead to more corrosion in the reactor vessel (Worrell, Bode, and de Beer 1997). The synthesis gas is water quenched (producing low-pressure steam) and cleaned before being fired in the turbine. Kvaerner has done significant research and development of high-temperature systems and the first commercial demonstration of a pressurized, oxygen-blown gasifier will take place in Pieta, Sweden (Larson and Raymond 1997, Larson et al. 2000).

Energy savings estimates for this technology vary but are potentially significant. Existing recovery boilers consume roughly 27 Mbtu (28.5 PJ) of black liquor and other biomass per air dried ton of chemical pulp with power production efficiencies using steam turbine systems of 10 percent (Consonni et al. 1998, Larson et al. 1997). While increased fuel inputs are required for gasification systems, and increased electricity inputs are required (especially for gas compression in the combined cycle system), power efficiencies are much higher, thereby allowing for significant primary energy savings. Based on an electricity production capacity of 2,000 kWh/ton, which represents an average of the range of outputs from the various systems (output ranges from 1200-3000 kWh/ton), we assume a primary energy savings potential of 6 Mbtu/ton (7 GJ/t) pulp.

Currently, there are no full-scale gasifier/combined cycle plants operating. However, the first fully commercial high temperature air-blown black liquor gasifier plant was installed in 1997 at Weyerhaeuser in Bern, North Carolina (Erikson and Brown 1999). (A low-temperature demonstration gasifier was demonstrated at the same site in the early 1990s.) The current gasifier is a high-temperature unit developed by Kvaerner (Erikson and Brown 1999). This 734 klb/day unit provides incremental recovery capacity with the product gas being burned in a boiler.

## Black Liquor Gasification Data Table

	Units	Notes		
<b>Black liquor gasification</b>				
<b>Paper-1</b>				
<b>Black liquor gasification</b>				
<i>Market Information:</i>				
Industries		Pulp and Paper	SIC 26	
End-use(s)		Utilities		
Energy types		Biomass		
Market segment		New		
2015 basecase use	Mton	70.0	EIA 1999. Kraft pulp throughput estimate in 2015	
<i>Reference technology</i>				
Description	Tomlinson recovery boilers			
Throughput or annual op. hrs.	tons	1	Per air dry ton pulp. Recovery boiler sizes range from XX - YY	
Electricity use	kWh	28	Power output of 800-850 kWh/ton pulp	
Fuel use	MBtu	26.6	Range of 24-27. HP steam output of 11 to 14 Mbtu/ton pulp	
Primary energy use	MBtu	26.9		
<i>New Measure Information:</i>				
Description	Black liquor gasification with combined cycle gas turbine, BLGCC			
Electricity use	kWh	267	Power consumption ranges fm. 68-400 kWh/ton. Power production ranges fm. 1200-3000 kWh/ton pulp	
Fuel use	MBtu	28.7	Fuel consumption ranges 22-38 Mbtu/ton. Steam output of ranges from 7-14 Mbtu/ton pulp	
Primary Energy use	MBtu	31.0		
Current status		Research	Gasifier demo facilities operating, but not with CC turbines	
Date of commercialization				
Est. avg. measure life	Years	30		
<i>Savings Information:</i>				
Electricity savings	kWh/%	961	34%	Assume a power production of 2000 kWh/ton.
Fuel savings	MBtu/%	-2.1	-8%	Increased black liquor/biomass consumption
Primary energy savings	MBtu/%	6.1	23%	
Penetration rate		Medium		
Feasible applications	%	15%	Assume feasible for 15% of 2015 chemical pulp production	
Other key assumptions				
Elec svgs potential in 2015	GWh	10097	Savings applied to feasible applications for 2015 output	
Fuel svgs potential in 2015	Tbtu	-22	Savings applied to feasible applications for 2015 output	
Primary energy svgs potential in 2015	Tbtu	63.7	2% savings. Primary energy consumption of 3549 Tbtu in 2015	
<i>Cost Effectiveness</i>				
Investment cost	\$	20	Full investment cost range - \$300/t pulp. replacing at end of life.	
Type of cost		Incremental		
Change in other costs	\$	5	Operation and maintenance. Range from \$2-7 shown in literature.	
Cost of saved energy (elec)	\$/kWh	0.01		
Cost of saved energy (fuel)	\$/Mbtu	-3.82		
Cost of saved energy (primary)	\$/Mbtu	1.33	Discount rate for all CCE calculations is 15%	
Simple payback period	Years	1.5		
Internal rate of return	%	69%		
<i>Key non energy factors</i>				
Productivity benefits		Somewhat	Increased throughput, fuel flexibility, reduced capital costs	
Product quality benefits		None		
Environmental benefits		Somewhat	Reduced emissions	
Other benefits		Somewhat	Reduced explosion risk compared w/ conventional systems.	
Current promotional activity	H,M,L	Medium	Demonstration facilities already constructed	
<i>Evaluation</i>				
Major market barriers		Technical, marketing	Refractories, gas cleanup, chemical recovery systems. High cost of initial units	
Likelihood of success	H,M,L	High		
Recommended next steps		Demonstration	Encourage demonstration project of combined cycle facility	
Data quality assessment	E,G,F,P	Excellent		
<i>Sources:</i>				
2015 basecase			EIA, 1999	
Basecase energy use			Larson et al., 2000; Consoni et al.,1998	
New measure energy savings			Larson et al., 2000; Consoni et al.,1998; Lorson et al., 1997	
Lifetime			Worrell et al.,1997a	
Feasible applications			Larson et al., 2000, Robinson, 2000.	
Costs			Larson et al., 2000	
Key non energy factors			Lason et al. 2000; Sadowski et al.1999; OIT 1999a	
Principal contacts			Eric Larson, <a href="http://www.princeton.edu/~cees">http://www.princeton.edu/~cees</a>	
Additional notes and sources				

The U.S. Department of Energy is interested in promoting both black liquor and biomass gasification through its support of research and demonstration projects under the Office of Industrial Technology. The DOE recently issued two rounds of solicitations on biomass and black liquor gasification. Georgia Pacific will be demonstrating an MTCI low pressure atmospheric system in a soda chemical pulping mill, a process that produces a feed similar to black liquor (Robinson 2000). Plans to demonstrate a high-temperature

system, a joint Kvarener/Air systems project, were unsuccessful but other demonstration projects may emerge in the second round of DOE solicitations.

Recent research on capital cost estimates for gasification systems by a research team that consisted of staff from Princeton University and Weyerhaeuser found a range of costs for high-temperature and low-temperature combined cycle facilities. These costs ranged \$270-340 \$/ton (\$300-375/t) pulp for a commercially developed technology as a new installation (Larson et al. 2000), and depend in part on the additional complexity introduced into the mill related to gas cleanup and chemical recovery. In general, the gasification combined cycle system is expected to have equal or slightly higher costs when compared to conventional systems while at the same time allowing for increased throughput and most importantly, increased power generation (OIT 1999, Larson et al. 2000). Therefore, while annual operations costs were estimated to increase slightly to between \$2-7/ton (\$2-8/t) compared to existing systems, the credit a mill receives from reduced electricity purchases make the cost-effectiveness of such a system relatively attractive. The electricity buyback price therefore becomes an important driver in project economics (Larson et al. 1998, Sadowski, et al. 1999). The gasification systems also are expected to improve environmental performance, with fewer particulates and nitrogen oxides than in conventional systems (OIT 1999). Finally, gasifiers are less likely to explode; this provides additional safety benefits.

The opportunities for this technology are large. A majority of the recovery furnaces and conventional power boilers in existing pulp and paper plants are 20 to 30 years old and more than half of them will need to be replaced or upgraded in the near future (OIT 1999, Larson and Raymond 1997). Analysis from the industry/DOE teams gives the technology a high rating (Erikson and Brown 1999).

However, additional research and demonstration are needed before gaining market acceptance. Some key areas include: developing adequate clean up systems for the medium Btu gas, improving refractory reliability, demonstrating cost-effective chemical recovery (especially sulfur separation), and demonstrating overall system integration (Larson and Raymond 1997, Oscarsson 1999). It seems clear that a cost-shared, public-private partnership that involves several companies would be needed to help overcome the technological barriers and to reduce risks given the high capital cost of initial units. This is beginning, but more active involvement will be required.

For this technology to be successful in the marketplace, further development, testing, and demonstration will be necessary in the U.S. For the near term, given additional developmental barriers, we believe that there is a medium likelihood of achieving significant market penetration in the near term (by 2015) with increasing successes likely in the slightly longer term.

## Condensing Belt Drying (Paper-2)

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994 (EIA 1997). Papermaking (as opposed to pulp production) is usually divided into four basic steps: 1) stock formation and forming, 2) pressing (mechanical dewatering), 3) evaporative drying, and 4) finishing. Of these steps, the drying is the most energy-intensive since it requires evaporation of the water on the web. We estimate that of this amount, 27 percent (787 TBtu) (830 PJ) of primary energy was used for paper drying in 1994 (Martin et al. 2000).

In current drying practices, after the paper sheet is formed and pressed to remove excess water and promote bonding of fibers, and no more water can be removed mechanically, the sheet moves through a series of 40-50 steam heated cylinders, with the final consistency being about 90-95 percent solids content. With the Condensing Belt (or Condebelt) drying technology being developed by Valmet (a Finnish company), the paper is dried in a drying chamber by contact with a continuous hot steel band, heated either by steam or hot gas, rather than being run through the steam-heated cylinders. On the other side of the sheet are three layers: a fine wire gauze, a coarse wire gauze, and an externally cooled steel band. The evaporated water passes through the wire gauze and condenses on the steel band. The condensate is removed by pressure and suction (de Beer 1998). The benefit of the Condebelt technology is that it has the potential to completely replace the drying section of a conventional paper machine, and has a drying rate 5-15 times higher than conventional methods (Lehtinen 1995).

Based on results from pilot plant tests performed by Valmet, de Beer (1998) estimates that for larger drying machines where losses through the seals of the drying chamber can be better controlled, steam savings are 10 to 20 percent of existing processes, while electricity consumption is expected to remain equal.

The first commercial installations of the Condebelt technology were in Finland (1996) and South Korea (1999). These two plants produce industrial and packaging paper grades, and this technology may be applicable initially to continuous paperboard production (Huovila and Ojala 1999, Dimond 2000). Because the Condebelt has a higher drying rate than standard drying machines, the size of the Condebelt dryer can be reduced. The two plants have been constructed as add-on technologies to existing facilities, with minimal energy savings. However, larger savings are possible if the Condebelt were constructed as a full replacement.

This technology is still in the early commercialization stage. Total costs for the installation of a paper machine including the forming and pressing can range from \$850-1,300/ton (Hekkert and Worrell 1997). Initial cost for the demonstration facility were \$260/ton paper (de Beer 1998). One estimate suggests that the cost of installing Condebelt for a greenfield (or newly constructed) plant would run up to double the cost of an existing cylinder machine (Ojala 2000, Ronkainen 2000). Other estimates suggest that the cost would be roughly the same (Worrell, Bode, and de Beer 1997, Hekkert and Worrell 1997). We assume a 25 percent increase from existing costs. Operations and maintenance costs are not expected to change significantly from current practice.

Installation of Condebelt technology is expected to result in increased productivity (increased throughput, less capital expenditure) while also allowing for some improvement in product quality (Retulainen and Hämäläinen 1999, de Beer 1998). There do not appear to be any significant technical barriers although no full scale large commercial operations have been installed in the U.S. There are, however, other competing commercial and emerging drying technologies that may limit rapid uptake by the U.S. market.

While there appear to be limited technical barriers for this technology, it remains to be proven for a variety of paper grades (aside from linerboard) and has yet to make headway in the U.S. market. We believe that the market penetration for this technology by 2015 could be medium to low, and that several demonstration projects would probably be necessary to see how the technology fares under U.S. conditions.

# Condensing Belt Drying Data Table

	Units	Notes		
<b>Condebelt drying</b>				
<b>paper-2</b>				
<b>Condensing belt drying</b>				
<i>Market Information:</i>				
Industries		Pulp and Paper	SIC 26	
End-use(s)		Process heating		
Energy types		Fuels, electricity		
Market segment		New, retrofit		
2015 basecase use	Mton	132.5	EIA, 1999	paper throughput estimate in 2015
<i>Reference technology</i>				
Description	Drying section, paper production			
Throughput or annual op. hrs.	tons	1		
Electricity use	kWh	19	Motor drive for machine rollers	
Fuel use	MBtu	8.6	Steam use in drying cylinders	
Primary energy use	MBtu	8.7		
<i>New Measure Information:</i>				
Description	Condensing belt drying system			
Electricity use	kWh	19	De Beer, 1998b	
Fuel use	MBtu	7.3	De Beer, 1998b	
Primary Energy use	MBtu	7.5		
Current status		Commercial		
Date of commercialization		1996		
Est. avg. measure life	Years	20	Worrell et al., 1997a	
<i>Savings Information:</i>				
Electricity savings	kWh/%	0	0%	De Beer, 1998b
Fuel savings	MBtu/%	1.3	15%	De Beer, 1998b
Primary energy savings	MBtu/%	1.3	15%	
Penetration rate		Medium		
Feasible applications	%	20%	Applicable to most paper grades. Demo currently w/ linerboard	
Other key assumptions				
Elec svgs potential in 2015	GWh	0		
Fuel svgs potential in 2015	Tbtu	34		
Primary energy svgs potential in 2015	Tbtu	34.1	Primary energy consumption of 3549 Tbtu in 2015	
<i>Cost Effectiveness</i>				
Investment cost	\$	260	Assume full paper machine costs of \$1000/ton. Assume 50% drying end.	
Type of cost		Incremental	\$600/ton full investment cost. (De Beer, 1998; Worrell et al. 1997)	
Change in other costs	\$	0		
Cost of saved energy (elec)	\$/kWh	N/A		
Cost of saved energy (fuel)	\$/Mbtu	32.24		
Cost of saved energy (primary)	\$/Mbtu	32.24	Discount rate for all CCE calculations is 15%	
Simple payback period	Years	65.2		
Internal rate of return	%	-9%		
<i>Key non energy factors</i>				
Productivity benefits		Significant	Reduced capital expenditure (small machines), higher production rate	
Product quality benefits		Somewhat	Improvement in strength properties	
Environmental benefits		None		
Other benefits				
Current promotional activity	H,M,L	Low	One major supplier, non-US	
<i>Evaluation</i>				
Major market barriers		Marketing		
Likelihood of success	H,M,L	Low		
Recommended next steps			US demonstration at commercial scale	
Data quality assessment	E,G,F,P	Good		
<i>Sources:</i>				
2015 basecase			EIA, 1999	
Basecase energy use			Elaahi & Lowitt, 1988; Nilsson et al, 1995; Giraldo & Hyman, 1994; Jaccard & Willis, 1996	
New measure energy savings			De Beer, 1998b	
Lifetime			Worrell et al., 1997a	
Feasible applications			Retulainen, E., Hämäläinen, A. 1999	
Costs			De Beer, 1998b	
Key non energy factors			Retulainen, E., Hämäläinen, A. 1999	
Principal contacts			Timo Ojala (Timo.Ojala@valmet.com)	
Additional notes and sources				

### Direct Electrolytic Causticizing (Paper-3)

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994, or 13 percent of manufacturing energy use (EIA 1997). Kraft pulp production is the predominant process, accounting for nearly 80 percent of the pulp produced in the U.S. and more than 700 TBtu (738 PJ) of primary energy (Kincaid 1998, Martin et al. 2000).

In a typical Kraft mill, the extraction and reuse of the pulping chemicals following chemical or Kraft pulping consists of three stages: black liquor concentration, energy recovery, and recaustization of the remaining liquor. The concentration usually takes place in Multiple Effect Evaporators (MEEs) and Direct Contact Evaporators (DCEs) to drive up the final solids concentration to 70-80 percent. The black liquor is sprayed into the recovery boiler where the remaining water evaporates. The organic components of the solids burn, thereby releasing the heat that dries the liquor transferring heat to boiler tubes for heat generation. The heat of this combustion smelts the remaining inorganic chemicals, which flow from the furnace and are ready for recaustization. The smelt from the recovery boiler is mixed with some weak white liquor to form green liquor. This green liquor consists mostly of sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium sulfide ( $\text{Na}_2\text{S}$ ). The green liquor is recausticized by the addition of calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) under controlled temperature and agitation. This recaustization converts the sodium carbonate back to sodium hydroxide ( $\text{NaOH}$ ) and leaves a precipitate of calcium carbonate ( $\text{CaCO}_3$ ). The precipitate is removed, leaving white liquor that can be reused to pulp more wood. The calcium carbonate precipitate also feeds back into the process in the lime kiln, where it is heated to produce lime ( $\text{CaO}$ ) which is then dissolved in water to produce the calcium hydroxide used in recaustization. The lime kiln is usually fueled by oil or gas, and requires on average 1.9 Mbtu/ton (2.3 GJ/t) pulp fuel and 14 kWh/ton (15 kWh/t) pulp electricity (Elaahi and Lowitt 1988, Jaccard and Willis 1996, Nilsson et al. 1995).

Direct electrolytic causticizing is a process where, rather than using the traditional causticizing process and equipment, an electrolysis cell is used to remove carbonate from a molten smelt solution of sodium carbonate, sodium sulfide and sodium sulfate. Carbon (from carbonate) is removed from the system in the form of carbon monoxide and carbon dioxide. Sodium oxide ( $\text{Na}_2\text{O}$ ), the desired electrolytic product, is contacted with water to produce sodium hydroxide ( $\text{NaOH}$ ). This product is then used for white liquor production early in the Kraft cycle (Wartena 2000).

This technology is pre-commercial and is being developed by the Institute of Paper Science and Technology in Atlanta, Georgia. Initial funding was cost shared by the U.S. Department of Energy (DOE 1998) and the research is now being directly funded by industry. An electrolysis cell was designed and assembled in the laboratory. The next steps include running tests on the laboratory scale cell with mill smelt, improving the understanding of electrolytic fundamentals, and constructing a pilot scale plant (Pfromm 2000). The pilot scale plant will require commercial investment but interest has already been expressed. Initially, the technology will probably be used as an add-on for causticizing a partial stream of Kraft smelt, especially for mills facing capacity bottlenecks. The technology is compatible with smelt produced from combined cycle black liquor gasification and could be a component of more advanced mill designs (Pfromm 2000).

On a final energy basis the recausticizing using electrolytic cells is expected to consume up to 50 percent less than the existing lime kiln configurations in plants, with a cell consumption estimated at 272 kWh/ton pulp (247 kWh/t) (Pfromm 2000). However, since the production of electricity is currently associated with losses of nearly two-thirds of the initial heating value of the fuels at the power plant, on a primary energy basis the consumption of the cells is expected to be on par or slightly below existing systems. The compelling driver, therefore, of this technology, is the capital cost savings. All recausticizing equipment of a 1,000 ton-per-day mill would be replaced by one electrolytic cell ( $5\text{m}^2$ ) (DOE 1998). Recent estimates for capital expenditures are \$22 million for a 1,000 ton pulp/day mill, or roughly \$60/ton pulp<sup>16</sup>. The electrochemical approach also promises to simplify the control of the process and improve product quality.

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<sup>16</sup> These costs are lower than the costs for rebuilding existing facilities. These are rough estimates based on similar costs to operate electrolytic reduction cells in aluminum facilities, and include costs for inert anode cells, cell controls, and the potline.

# Direct Electrolytic Causticizing Data Table

	Units	Notes	
Direct electrolytic causticizing paper-3			
One step causticizing process in Kraft mills			
Market Information:			
Industries	Pulp and Paper	SIC 26	
End-use(s)	Process heating		
Energy types	Fuels, electricity		
Market segment	New		
2015 basecase use	70.0	Kraft pulp production estimate, Annual Energy Outlook, 2000	
Reference technology			
Description	Existing recausticizing process (including lime kiln)		
Throughput or annual op. hrs.	ton	1	Based on energy use per ton pulp
Electricity use	kWh	14	Martin et al., 2000
Fuel use	MBtu	2.1	Jaccard and Willis, 1996; Nilsson et al., 1995
Primary energy use	MBtu	2.3	
New Measure Information:			
Description	Direct causticizing using electrolytic reduction		
Electricity use	kWh	272	Pfromm, 2000
Fuel use	MBtu	0.0	
Primary Energy use	MBtu	2.3	
Current status	Pre-commercial		
Date of commercialization	2005-2010		
Est. avg. measure life	Years	10	
Savings Information:			
Electricity savings	kWh/%	-258	-1912% Pfromm, 2000
Fuel savings	MBtu/%	2.1	100%
Primary energy savings	MBtu/%	0.0	0%
Penetration rate		low	
Feasible applications	%	10%	Initially mills with capacity bottlenecks
Other key assumptions			
Elec svgs potential in 2015	GWh	-1811	
Fuel svgs potential in 2015	Tbtu	15	
Primary energy svgs potential in 2015	Tbtu	-0.3	
Cost Effectiveness			
Investment cost	\$	-10	Assume that cell costs will be lower than existing costs
Type of cost		Incremental	
Change in other costs	\$	0	
Cost of saved energy (elec)	\$/kWh	0.01	
Cost of saved energy (fuel)	\$/Mbtu	-0.93	
Cost of saved energy (primary)	\$/Mbtu	40.17	Discount rate for all CCE calculations is 15%
Simple payback period	Years	N/A	No payback: net energy savings too low
Internal rate of return	%	N/A	
Key non energy factors			
Productivity benefits		Compelling	Reduction of capital investment requirements Better control of causticizing process may lead to better product quality
Product quality benefits		Somewhat	
Environmental benefits		Somewhat	Reduction of dust and other emissions from lime kilns on site
Other benefits			
Current promotional activity	H,M,L	Somewhat	Pre-commercial but technology has support
Evaluation			
Major market barriers		Technical	Still need technology to be tested
Likelihood of success	H,M,L	Medium	
Recommended next steps			Continued R&D
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			EIA, 2000
Basecase energy use			Martin et al. 2000
New measure energy savings			Pfromm, 2000
Lifetime			ASME, 1999
Feasible applications			Author estimate
Costs			Pfromm, 2000
Key non energy factors			Pfromm, 2000
Principal contacts			Peter Pfromm, IPST (peter.pfromm@ipst.edu)
Additional notes and sources			

While the promise of this technology is strong, and there is industry support, it is still in its early stages of development. It is unlikely that a full-scale working cell will likely be deployed until 2005, but given success, we could expect to see the technology begin to make headway initially for cases of incremental capacity expansion at particular mills, and later with replacement of existing technology.



### **Dry Sheet Forming (Paper-4)**

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994 (EIA 1997). Papermaking (as opposed to pulp production) is usually divided into four basic steps: 1) stock formation and forming, 2) pressing (mechanical dewatering), 3) evaporative drying, and 4) finishing. Of these steps, the drying is the most energy-intensive since it requires evaporation of the water on the web. We estimate that of this amount, 27 percent (787 TBtu) (830 PJ) of primary energy was used for paper drying in 1994 (Martin et al. 2000). In the forming step, the continuous slurry that has been prepared is formed into a uniform web. The most common forming machines are twin wire formers (for thin and multi-layered sheets). Both machines deposit low consistency wood-pulp (less than 1 percent wood-pulp) onto a moving wire mesh which allows water to drain away.

While originally conceived as a paper technology, dry web forming has developed into its own industry niche of non-wovens, which involves the production of light absorbent paper-like materials used in personal hygiene products. In dry web forming, the non-woven is produced without the addition of water. The fibers can be disbursed either through a carding technique or through an air layering technique. In the former, the fibers are disbursed mechanically while in the latter, fibers are suspended in air and paper is formed from this suspension. Fiber-to-fiber bonding is obtained by adding resins to the fibers or by spraying a polymer-latex onto the web formed. The air laying technique allows for a higher production rate and better control and most dry forming is done through this technique (de Beer et al. 1998b, Pivko 1999b).

The advantage of dry sheet forming is the significant savings in energy requirements for evaporating water from the sheet in the later drying stage. De Beer (1998b) estimates a savings of 50 percent in drying fuel requirements and an increase in electricity consumption in an air layering plant of 150-250 kWh/ton paper to maintain the air stream and motor drive for the equipment.

Airlaid drying/dry sheet forming technology was invented simultaneously by a Danish inventor named Karl Kroyer and by the Japanese at Honshu paper company (Pivko 1999b). Early conception of the technology occurred in the 1940s, but commercialization of today's processes took place in the early 1980s through Moeller and Jochumsen (M&J), a Danish firm (Pivko 1999b). Today, other producers of dry formed technology include Dan Web (Denmark) and Honshu Paper Co. (Japan) (de Beer 1998, Pivko 1999b). United Paper Mills-kymmene had originally licensed the Dan-Web technology (used at Walkisoft, Finland) but is now not a manufacturer of this technology (Pivko 1999b). Worldwide, installed capacity with this technology is about 350 ktons, and is growing rapidly. New capacity additions expected over the next couple of years are 120 ktons, mostly in North America (Pivko 2000). Current installed capacity in North America is estimated to be only 0.1 percent of total paper production in this region (Pivko 1999a, FAO 2000). The largest capacity plant is being constructed in North Carolina (Ward 2000).

The primary products currently being produced with this technology are personal hygiene products (diapers, feminine hygiene, adult incontinence, training pants for babies, baby wipes), and some specialty areas (tableware, medical products, hot towels in restaurants). This is a small percentage of the overall paper tissue market as production has already shifted into the non-wovens. We estimate that the market replacement potential is 5 percent of U.S. paper production (Kincaid 1998).

If this technology becomes applicable to the paper industry, direct investment costs could be one-third to one-half a conventional non-integrated paper mill (de Beer 1998). Operation and maintenance costs are also expected to be lower (de Beer 1998). However, the technology does not have the same type of machine speed as paper producers (1,500 m/min as compared to up to 6000 m/min on conventional paper machines) (Pivko 2000). Total costs for the installation of a paper machine (including the forming and pressing) can range from \$850-1,300/ton (Hekkert and Worrell 1997). Air-laid technologies are slightly more expensive. A 55,115 ton (50,000 tonne) state-of-the-art plant in North Carolina under construction is being built at an estimated cost of \$1,500/ton, the first project where costs have dropped below \$2,000/ton (Pivko 2000). These lower costs may expand the potential market opportunities for this type of material. Aside from potential cost efficiencies that are associated with this technology, wastewater pollution is eliminated thereby allowing a more flexible location of paper mills closer to demand centers.

# Dry Sheet Forming Data Table

	Units		Notes
<b>Dry sheet forming paper-4</b>			
<b>Dry sheet forming</b>			
<i>Market Information:</i>			
Industries		Pulp and Paper	SIC 26
End-use(s)		Process heating	
Energy types		Fuels, electricity	
Market segment		New, retrofit	
2015 basecase use	Mton	132.5	EIA, 1999,paper throughput estimate in 2015
<i>Reference technology</i>			
Description	Paper drying		
Throughput or annual op. hrs.	tons	1	
Electricity use	kWh	480	Martin et al., 2000
Fuel use	MBtu	9.2	Fuel use primarily in drying, not forming stage; Martin et al.,2000
Primary energy use	MBtu	13.3	
<i>New Measure Information:</i>			
Description	Dry sheet forming		
Electricity use	kWh	710	De Beer, 1998b
Fuel use	MBtu	4.6	De Beer, 1998b
Primary Energy use	MBtu	10.6	
Current status		Commercial	
Date of commercialization		1985	
Est. avg. measure life	Years	20	Worrell et al., 1997
<i>Savings Information:</i>			
Electricity savings	kWh/%	-230	-48%
Fuel savings	MBtu/%	4.3	47%
Primary energy savings	MBtu/%	2.3	18%
Penetration rate		Medium	
Feasible applications	%	5%	Currently applied only to specialty products; Pivko, 1999
Other key assumptions			
Elec svgs potential in 2015	GWh	-1521	
Fuel svgs potential in 2015	Tbtu	28	
Primary energy svgs potential in 2015	Tbtu	15.5	
<i>Cost Effectiveness</i>			
Investment cost	\$	350	Cost ranges from \$1,500 to \$2000/tonne (Pivko, 1999)
Type of cost		Incremental	
Change in other costs	\$	0	
Cost of saved energy (elec)	\$/kWh	-0.24	
Cost of saved energy (fuel)	\$/Mbtu	13.02	
Cost of saved energy (primary)	\$/Mbtu	23.87	Discount rate for all CCE calculations is 15%
Simple payback period	Years	48.3	
Internal rate of return	%	N/A.	
<i>Key non energy factors</i>			
Productivity benefits		None	
Product quality benefits		Significant	Improved product quality for personal hygiene products
Environmental benefits		Somewhat	Reduction in water waste
Other benefits			
Current promotional activity	H,M,L		Technology already in the marketplace
<i>Evaluation</i>			
Major market barriers		Technical	In niche market. Technology not likely applicable for broader application
Likelihood of success	H,M,L	High	For the niche market
Recommended next steps			Research/demonstration on applicability to other grades
Data quality assessment	E,G,F,P	Good	
<i>Sources:</i>			
2015 basecase			EIA, 1999
Basecase energy use			Elahi & Lowitt, 1998; Nillson et al., 1995; Jaccard & Willis, 1996
New measure energy savings			De Beer, 1998
Lifetime			Worrell et al., 1997a
Feasible applications			Pivko, 1999
Costs			Pivko, 1999
Key non energy factors			De Beer, 1998; Pivko, 1999
Principal contacts			Ivan Pivko, Notabene Associates Inc. ibpivko@aol.com; 941-383-8404
Additional notes and sources			

It appears that dry sheet forming technology will continue to be developed for specialty applications and in the near future will not be adapted for production of standard paper grades. Rather, the higher quality product has caused a restructuring of tissue production for personal hygiene products in standard paper mills to non-wovens dry forming technology.

## Heat Recover Paper—Enclosing Hoods (Paper-5)

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994 (EIA 1997). Papermaking (as opposed to pulp production) is usually divided into four basic steps: 1) stock formation and forming, 2) pressing (mechanical dewatering), 3) evaporative drying, and 4) finishing. Of these steps, the drying is the most energy-intensive since it requires evaporation of the water on the web. We estimate that of this amount, 27 percent (787 TBtu) (830 PJ) of primary energy was used for paper drying in 1994 (Martin et al. 2000).

In the drying section, steam filled rollers dry paper through the evaporation of water in the web. A typical drying machine may have up to 40-50 steam heated drying cylinders (de Beer 1998, Elaahi and Lowitt 1988). Heat recovery technologies are primarily directed at this initial stage of the drying section. In the middle of this section is the size press which can apply coating to the paper. The size press must be placed so that the paper can continue drying after coating because the coating itself must also dry. The last stage in the papermaking process is the Calendar stack, which is a series of carefully spaced rollers that control the thickness and smoothness of the final paper.

There is a strong link between pulp consistency and steam demand on the drying section. Here, pulp enters with a consistency of 40-45 percent and paper exits the machine with a consistency of 90-95 percent (de Beer 1998, Abrahamsson et al. 1997). Typically 2 kg water are evaporated per kg of paper and 6.7 kg of air is required to remove 1 kg of water vapor (de Beer 1998). In the paper making process, the heat, which is mainly required in form of low-pressure steam, is transferred to the web via the steam-injected cylinders. As the water vapor exits the web, carried away by pre-heated air, and the web is dried, saturated low-pressure steam is released. The goal of more advanced waste heat recovery systems is to convert this lower quality steam into more useful heat. Existing equipment based on canopy air-to-air heat recovery systems recover about 15 percent of the energy contained in the hood exhaust air.

There are several systems for heat recovery that can improve energy efficiency. One new system involves the installation of enclosed hoods and sensors on the drying section of the paper machine. Paper machines with enclosed hoods can require up to one-half the amount of air per ton of water evaporated than paper machines with canopy hoods. Thermal energy demands are reduced since a smaller volume of air is heated. Electricity requirements in the exhaust fan are also reduced optimizing drying efficiency (Elaahi and Lowitt 1988, CADDET 1994d). Another promising system further upgrades this waste heat by means of heat pumps and mechanical vapor recompression (MVR) (Van Deventer 1997, Abrahamsson et al. 1997). A different technology approach, which involves the heating provided to the cylinders, is to use stationary siphons to better extract the exhausted steam from the cylinders (Morris 1998). The heat can also be recuperated from the ventilation air of the drying section and used for heating of the facilities (de Beer et al. 1994).

In 1994, U.S. paper drying consumption averaged about 8.6 Mbtu/ton (10 GJ/t) (Martin et al. 2000). Roughly 20 percent of the heat is required for air heating. By enclosing hoods, air heating requirements are minimized because of higher rates of heat recovery from the captured steam. Optimizing ventilation and using sensors control on the machine allows steam savings of 0.65 Mbtu/ton (0.75 GJ/t) paper and electricity savings of 5.7 kWh/ton (6.3 kWh/t) paper (CADDET 1994d). Conchie (1993) claims further savings of 0.86 Mbtu/ton (1 GJ/t) in a UK tissue mill. The savings was achieved by replacing the worn out Yankee hood and adding two novel features to the machine: the counter current series air flow (mainly of interest to manufacturers of tissue and machine-glazed papers) and humidity sensors (of general relevance to all papermakers). By using MVR to produce superheated steam from the water vapor extracts from the web, Van Deventer (1997) estimated steam savings of 50 percent and an increase in electricity consumption of 145 kWh/ton (159 kWh/t). Improved siphon technology can achieve savings up to 0.76 mbtu/ton (0.88 GJ/t).

CADDET (1994d) notes a cost of \$9.5/ton paper and additional O&M costs of \$0.07/ton paper for the installation of a closed hood system that optimizes ventilation (CADDET 1994d, Conchie 1993). The addition of technologies to upgrade the heat (e.g. MVR and heat pumps) is estimated to be more expensive,

## Heat Recovery Paper Data Table

	Units	Notes	
Heat Recovery Paper (Enclosing hood)			
Paper-5			
Heat recovery in paper drying			
Market Information:			
Industries		Pulp and Paper	SIC 26
End-use(s)		Process heating	
Energy types		Fuels, electricity	
Market segment		New, retrofit	
2015 basecase use	Mton	132.5	EIA, 1999.paper throughput estimate in 2015
Reference technology			
Description	Drying section paper production		
Throughput	tons	1	
Electricity use	kWh	18	Martin et al., 2000 (electricity share for the whole drying section)
Fuel use	MBtu	1.8	20% of Fuel use in drying is for air heating; de Beer, 1998
Primary energy use	MBtu	2.0	
New Measure Information:			
Description	Enclosing hood in the drying section of papermaking allows to recover the heat necessary for air heating		
Electricity use	kWh	12	CADDET, 1994f; Van Deventer, 1997
Fuel use	MBtu	1.1	CADDET, 1994f; Van Deventer, 1998
Primary Energy use	MBtu	1.2	
Current status	Commercial		
Date of commercialization			
Est. avg. measure life	Years	20	Based on lifetime of other drying technologies
Savings Information:			
Electricity savings	kWh/%	6.30	35%
Fuel savings	MBtu/%	0.76	41%
Primary energy savings	MBtu/%	0.81	41%
Penetration rate	Medium		
Feasible applications	%	20%	Author estimate, based on stock turnover of larger machines
Other key assumptions			
Elec svgs potential in 2015	GWh	166.9	
Fuel svgs potential in 2015	Tbtu	20.1	
Primary energy svgs potential in 2015	Tbtu	21.6	
Cost Effectiveness			
Investment cost	\$	9.5	CADDET 1994f; Conchie, 1993
Type of cost	Full cost		
Change in other costs	\$	0.07	O&M costs CADDET (1994f)
Cost of saved energy (elec)	\$/kWh	0.25	
Cost of saved energy (fuel)	\$/Mbtu	2.09	
Cost of saved energy (primary)	\$/Mbtu	1.95	Discount rate for all CCE calculations is 15%
Simple payback period	Years	3.9	
Internal rate of return	%	25%	
Key non energy factors			
Productivity benefits		Somewhat	Increased throughput
Product quality benefits		None	
Environmental benefits		Somewhat	Reduced emissions
Other benefits		Somewhat	Safety. The steam is not discharged indoor
Current promotional activity	H,M,L	Medium	Installations do already exist in EU
Evaluation			
Major market barriers	Information		
Likelihood of success	H,M,L	Medium	
Recommended next steps	Continued demonstration		
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase	EIA, 1999		
Basecase energy use	Martin et al. 2000		
New measure energy savings	(CADDET 1994f) (Conchie 1993).		
Lifetime	De Beer 1998; Martin et al. 2000		
Feasible applications	Both paper mills and waste paper mills		
Costs	(CADDET 1994f) (Conchie 1993).		
Key non energy factors	(CADDET 1994f) (Conchie 1993).		
Principal contacts	CADDET 1994f; Willem van Zanten (w.van.zanten@novem.nl)		
Additional notes and sources			

\$17.6/ton paper (de Beer et al. 1994). Because the heat exchangers require frequent cleaning, the additional O&M costs will amount to \$1.6/ton paper. In addition to energy savings, enclosing hoods and optimizing ventilation can also increase productivity. In one installation, the payback from increased material throughput (an additional 5,500 tons) was less than 1.5 years (CADDET 1994d).

Enclosing hoods and optimizing ventilation can be a successful technology in the marketplace for all paper grades, and there might be a likelihood of achieving significant market penetration for the future. It is most likely that this technology would be installed for larger newer machines, so rapid market penetration is limited.

## High Consistency Forming (Paper-6)

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994 (EIA 1997). Papermaking (as opposed to pulp production) is usually divided into four basic steps: 1) stock formation and forming, 2) pressing (mechanical dewatering), 3) evaporative drying, and 4) finishing. Of these steps, the drying is the most energy-intensive since it requires evaporation of the water on the web. We estimate that of this amount, 27 percent (787 TBtu) (830 PJ) of primary energy was used for paper drying in 1994 (Martin et al. 2000).

In the forming step, the continuous slurry that has been prepared is formed into a uniform web. The most common forming machines are Fourdrinier machines (for thin sheets) and twin wire formers (for multi-layered sheets). Both machines spray low consistency pulp (less than 1 percent pulp) onto a moving wire mesh which allows water to drain away. In high consistency forming, the process pulp enters at the forming stage, and has more than double the consistency (3 percent) than normal furnish. This measure increases forming speed and leads to energy savings in the pressing section, due to reduced de-watering and vacuum power requirements (Dudley, 2000; Martin et al. 2000).

High consistency forming (HCF) was patented in the 1960s and developed by Ahlstrom Corporation in the 1970s (Dudley, 2000). Pilot plants using various technology configurations were tested in the mid-1980s, and the SymFlo HC design was commercialized in 1985. However, the technology has been slow to catch on, and currently there are only a few large scale operating installations worldwide (Dudley, 2000). The primary market currently for this technology is liquid packaging, although there is a possibility to expand it to the folding carton sector as well (Dudley, 2000).

The driving force for its adoption is the potential savings in material, as the forming can lead to a 5-8 percent savings in basis weight (Eklund 2000; Dudley, 2000). The reason for this savings is that the technology uses a multi-ply (more than one headbox) configuration. This allows for setting the fibers in a bulkier three-dimensional configuration than normal headbox configurations, or in industry terms there are more fibers in the Z-direction. This bulkier sheet allows the papermaker to achieve an equal caliper at less fiber weight (Dudley, 2000). The technology can be installed as an add-on technology to existing processes with some modifications. It is mainly geared toward paper grades where stiffness is highly valued. HCF forming is not viable for lightweight papers. It requires a minimum basis weight of 100 grams/square meter (due to fluid dynamics issues) and HCF formed in a single layer at such low basis weights is subject to tearing due to low machine direction tensile strength (Dudley, 2000, Elaahi and Lowitt 1988). Weyerhaeuser has been using a high consistency forming machine to produce liquid packaging board (e.g. cups, milk cartons) and this technology is also being deployed by International Paper for similar applications (Eklund 2000).

Initial expectations for this technology were that it would yield significant energy savings. Early tests of the technology found an energy savings in the drying section of 10-15 percent (Elaahi and Lowitt 1988, Nomura et al. 1989). In practice these drying energy savings have not materialized. Rather, energy requirements for stock preparation and for vacuum and dewatering requirements (i.e. less pumping power) are reduced. We estimate a 20 percent saving in stock preparation estimated at 50 kWh/ton (Dudley 2000, Martin et al. 2000).

Since this forming technology reduces the water content of the sheet entering the press section, less material (e.g. wire) is needed for dewatering. This can result in a 10-15 percent savings in capital costs for the wet end of the machine since it allows for reductions of the size of both the forming and drainage area (Dudley 2000, Eklund 2000). We estimate a capital cost savings of \$10/ton (\$11/t) paper and a slight increase in operation and maintenance costs of \$0.6/ton (\$0.7/t) paper (Dudley 2000, Jaccard and Willis 1996). Product quality is also expected to improve since the paper would have increased strength.

The driving force behind the adoption of this technology is the potential savings in fiber (5-8 percent) and improved product quality for selected markets. As of now, high consistency forming has not penetrated broadly into the U.S. market. However, given the potential savings in material costs, we expect that for

particular boxboard applications (e.g. liquid packaging), this technology has a large potential to gain a broader acceptance into the U.S. market in the near term.

### High Consistency Forming Data Table

	Units	Notes	
High Consistency forming paper-6			
High Consistency forming			
Market Information:			
Industries		Pulp and Paper	SIC 26
End-use(s)		Process heating	
Energy types		Electricity	
Market segment		New, retrofit	
2015 basecase use	Mton	132.5	EIA, 1999,paper throughput estimate in 2015
Reference technology			
Description	Paper production		
Throughput or annual op. hrs.	tons	1	
Electricity use	kWh	480	Martin et al., 2000
Fuel use	MBtu	9.2	Fuel use primarily in drying, not forming stage; Martin et al.,2000
Primary energy use	MBtu	13.3	
New Measure Information:			
Description	Install high consistency former		
Electricity use	kWh	430	No change in electricity consumption
Fuel use	MBtu	9.2	
Primary Energy use	MBtu	12.8	
Current status		Commercial	Demonstrated in Japan and Canada
Date of commercialization		1985	SymFlo HC model
Est. avg. measure life	Years	20	Worrell et al., 1997a
Savings Information:			
Electricity savings	kWh/%	50	10%
Fuel savings	MBtu/%	0.0	0%
Primary energy savings	MBtu/%	0.4	3%
Penetration rate		Medium	
Feasible applications	%	9%	Exclude light grades of paper
Other key assumptions			
Elec svgs potential in 2015	GWh	612	
Fuel svgs potential in 2015	Tbtu	0	
Primary energy svgs potential in 2015	Tbtu	5.2	
Cost Effectiveness			
Investment cost	\$	-10	\$70/tonne for new installation
Type of cost		Incremental	Assume no additional cost for installation of high consistency former
Change in other costs	\$	0.6	Operations and maintenance
Cost of saved energy (elec)	\$/kWh	-0.02	
Cost of saved energy (fuel)	\$/Mbtu		
Cost of saved energy (primary)	\$/Mbtu	-2.26	Discount rate for all CCE calculations is 15%
Simple payback period	Years	Immediate	
Internal rate of return	%	N/A	
Key non energy factors			
Productivity benefits		Significant	Potential of up to 8% reduction in raw materials requirements
Product quality benefits		Significant	
Environmental benefits		Somewhat	Less water use
Other benefits			
Current promotional activity	H,M,L	Low	
Evaluation			
Major market barriers		Technical, marketing	
Likelihood of success	H,M,L	Medium	
Recommended next steps			Demonstration
Data quality assessment	E,G,F,P	Fair	
Sources:			
2015 basecase			EIA, 1999
Basecase energy use			Jaccard and Willis, 1996, Giraldo & Hyman, 1994; Elaahi & Lowitt, 1988
New measure energy savings			Dudley 2000; de Beer 1998
Lifetime			Worrell et al., 1997a
Feasible applications			Dudley 2000; Eklund 2000
Costs			Dudley 2000; de Beer 1998
Key non energy factors			Eklund, 2000
Principal contacts			Weyerhaeuser, Longview mill
Additional notes and sources			

## Impulse Drying (Paper-7)

The pulp and paper industry is a large industrial energy user, with an estimated primary energy consumption of 2,970 TBtu (3133 PJ) in 1994 (EIA 1997). Papermaking (as opposed to pulp production) is usually divided into four basic steps: 1) stock formation and forming, 2) pressing (mechanical dewatering), 3) evaporative drying, and 4) finishing. Of these steps, the drying is the most energy-intensive since it requires evaporation of the water on the web. We estimate that of this amount, 27 percent (787 TBtu) (830 PJ) of primary energy was used for paper drying in 1994 (Martin et al. 2000).

In current drying practices, after the paper sheet is formed and pressed and no more water can be removed mechanically, the sheet moves through a series of 40-50 steam heated cylinders, with the final consistency being about 90-95 percent solids content. In conventional papermaking the web has a moisture content of 45-50 percent before entering the drying section. Impulse drying is a technology that improves the mechanical dewatering of paper and reduces the amount of water that needs to be removed in the drying section. In impulse drying the paper web is subjected to very high temperatures at the press nip in order to drive moisture out of the web so that the moisture content is significantly reduced (to 38 percent or less) before entering the drying phase (OIT 1999). The technology involves pressing the paper between one very hot rotating roll (300-900°F) and a static concave a conventional shoe press. The pressure is about ten times higher than that in press and Condebelt drying (de Beer et al. 1998b, Boerner and Orloff 1994). Ultimately, consistencies of the sheet can be increased to 55 percent for board and 78 percent for lightweight paper using impulse drying, but the paper still needs to be fed through a conventional drying system after this stage (de Beer 1998). The impulse dryer can be retrofitted into an existing machine or incorporated into new models. For new machines, the size and costs of the paper machine can be reduced compared to existing processes, thereby making it more cost-effective. Also the drying rate can be significantly increased (50-500 times).

This technology first began development in 1980 at the Institute of Paper Science and Technology in the U.S. with the collaboration of Beloit (de Beer 1998). The patents for this technology were originally licensed to Beloit and are now owned by Valmet, a Finnish company.

While impulse drying is applicable to many grades of paper, initial U.S. efforts were directed toward the drying of newsprint and linerboard (de Beer 1998, IPST 1998). Successful production of reeled impulse dried linerboard took place in September, 1998 when an impulse dryer was tested on a Beloit paper machine (Orloff et al. 1999). Beloit research facilities tested a variety of pilot scale configurations, including the addition of a short and regular shoe press and hover press, to eliminate delamination problems (Orloff and Crouse 1999). Most recent, test trials have documented an increase in speed and an increase in speed, press dryness, and strength characteristics compared to existing technology (Orloff et al. 2000, Larsson and Orloff 2000).

Given the higher consistencies of the paper or board entering the conventional drying section, drying energy consumption is significantly reduced. de Beer (1998) assumes potential steam consumption reductions of 40-50 percent with a small increase in electricity consumption of 5-10 percent (de Beer 1998). However, these estimates assume that the rotating roll is heated by fuel. Both the Canadian and U.S. pilot tests were based on electric induction heating of the rotating roll which reduces primary energy savings to closer to 15 percent (Orloff et al. 1999, CADDET 1995b).

Incremental installation costs range from \$70-100/ton paper although these cost data are not based on actual full-scale operating facilities (Jaccard and Willis 1996, Worrell, Bode, and de Beer 1997). Operation and maintenance costs are not expected to change since additional costs for the impulse dryer maintenance are reduced by the shorter machine (de Beer 1998).

Impulse drying has been shown to produce paper which is thinner, smoother and stronger than that yielded by the conventional drying process (CADDET 1995b, IPST 1998, Orloff and Crouse 1999, Orloff et al. 2000). Trials with a South African furnish demonstrated increased production speeds by 14 percent and



## Impulse Drying Data Table

	Units		Notes	
Impulse drying				
paper-7				
Impulse drying				
Market Information:				
Industries		Pulp and Paper	ST 26	
End-use (s)		Process heating		
Energy types		Fuels, electricity		
Market segment		New, retrofit		
2015 basecase use	M ton	132.5	EPA, 1999 paper throughput estimate in 2015	
Reference technology				
Description	Drying section, paper production			
Throughput or annual op. hrs.	tons	1		
Electricity use	kW h	19	Motor drive for machine rollers	
Fuel use	MBtu	8.6	Steam use in drying cylinders	
Primary energy use	MBtu	8.7		
New Measure Information:				
Description	Impulse drying system			
Electricity use	kW h	170	Orloff et al., 1999	
Fuel use	MBtu	6.2	Orloff et al., 1999	
Primary Energy use	MBtu	7.6		
Current status	Commercial			
Date of commercialization	1996			
Est. avg. measure life	Years	20	Wonnell et al., 1997a, Atlas project	
Savings Information:				
Electricity savings	kW h/%	-151	-810%	
Fuel savings	MBtu/%	2.4	28%	
Primary energy savings	MBtu/%	1.1	13%	
Penetration rate	Medium			
Feasible applications	%	20%	Initial penetration in newsprint and linerboard	
Other key assumptions				
Electric savings potential in 2015	GW h	-4009		
Fuel savings potential in 2015	Tbtu	64		
Primary energy savings potential in 2015	Tbtu	29.5	Primary energy consumption of 3549 Tbtu in 2015	
Cost Effectiveness				
Investment cost	\$	70	Full investment cost \$75-100	
Type of cost	Incremental			
Change in other costs	\$	0		
Cost of saved energy (elec)	\$/kW h	-0.07		
Cost of saved energy (fuel)	\$/MBtu	4.66		
Cost of saved energy (primary)	\$/MBtu	10.04	Discount rate for all CCE calculations is 15%	
Simple payback period	Years	20.3		
Internal rate of return	%	0%		
Key non energy factors				
Productivity benefits		Significant	Reduced capital expenditure (small machines), higher production rate	
Product quality benefits		Somewhat	Improvement in strength properties	
Environmental benefits		None		
Other benefits				
Current promotional activity	H/M/L	Low	One major supplier, non-US	
Evaluation				
Major market barriers		Marketing		
Likelihood of success	H/M/L	Medium		
Recommended next steps			US demonstration at commercial scale	
Data quality assessment	E/G/F/P	Good		
Sources:				
2015 basecase	EPA, 1999			
Basecase energy use	Elahi & Lowitt, 1988; Nilsson et al., 1995; Gallo & Hymann, 1994; Jaccard & Willis, 1996			
New measure energy savings	De Beer, 1998			
Lifetime	Wonnell et al., 1997a			
Feasible applications	Marin et al., 2000			
Costs	De Beer, 1998b; Wonnell et al., 1997a			
Key non energy factors	De Beer, 1998b; Orloff et al., 1999			
Principal contacts	D. Orloff, EPT-Georgia (david.orloff@epstedu)			
Additional notes and sources				

reduced basis weight (i.e. increased strength) by 2.5-5 percent, with an overall 20 percent improvement in productivity (Orloff et al. 2000). The drying section can also be reduced, resulting in lower capital costs. It allows an existing paper mill to operate at increased speeds (thus increasing production capacity), and allows for a new paper machine to significantly reduce the number of conventional drying rollers.

While the technology is promising, there were problems initially with the paper delaminating or sticking to the roll (Boerner and Orloff 1994, Orloff and Crouse 1999). Recent research has focused on inhibiting sheet delamination through impulse drying at elevated ambient nip-opening pressures or through controlled depressurization (Orloff and Crouse 1999, Orloff et al. 2000). These new methods may actually improve the operational flexibility of the technology. Still, there is concern that technical obstacles for commercialization might be insurmountable (Ronkainen 2000).

The creation of a commercial market for impulse drying has not yet become a reality and the development of full-scale commercial demonstration units will still be needed to help transition this technology to market. There does not yet appear to be significant backing for a large scale U.S. demonstration project and researchers at the Swedish pulp and paper research institute have recently stated that there is still a lot of work to be done before commercial application will be reality (Luiten 2000).

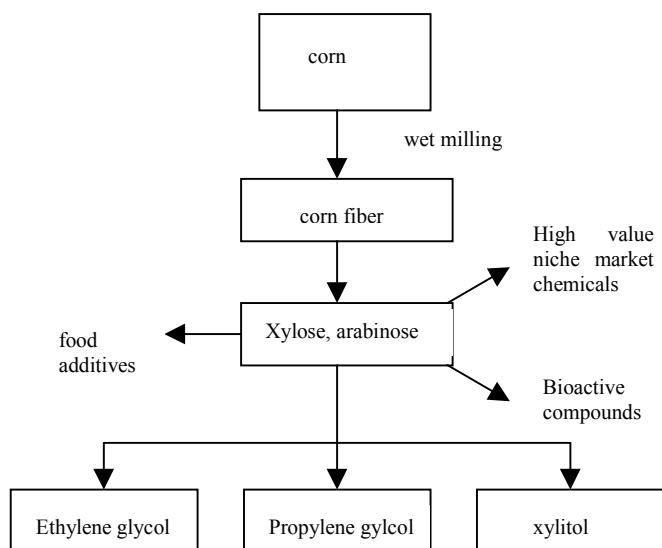
## Clean Fractionation (Chemicals-1)

Polyols are a major feedstock in the chemical industry. Polyols include ethylene and propylene glycol. The goal of the technology is to use a low-value feedstock in an innovative and economical manner. The majority of corn fiber in the United States (over 10 billion pounds) is sold as animal feed for approximately \$0.04 per pound. Corn fiber fractionation aims to create a high value product from this inexpensive feedstock. Ethylene glycol and propylene glycol are used to produce antifreeze, polyester, fiberglass reinforced plastics for use in boat hulls, and construction pipes.

Efficient separation technology may turn a corn wet mill into an economical producer of ethylene glycol, propylene glycol, and other sugar-derived products for the commodity chemical industry. Currently, most of these chemicals are produced from petrochemical reagents. Corn fiber fractionation promises to turn a corn wet mill into a low-cost producer of industrial chemicals.

The innovative fractionation technology is being developed to cleanly and selectively remove hemicellulose from the corn fiber and to subsequently separate and isolate the xylose and arabinose fraction. Hemicellulose makes up 60 to 70 percent of the weight of corn fiber, and xylose and arabinose make up about 60 to 70 percent of the weight of the hemicellulose. Catalytic conversion of xylose and arabinose into ethylene and propylene glycol would produce a valuable feedstock with a very large market and a variety of applications.

Currently most ethylene glycol and propylene glycol are produced in a similar reaction by acid or thermal catalysis of ethylene oxide and propylene oxide, respectively. The yield of glycol in this process usually exceeds 95 percent. The conditions of the reaction are dependent of whether or not an acid catalyst is used. Less severe reaction conditions are needed in the presence of a catalyst. The non-catalytic process requires higher temperatures and pressures. Fractionation of corn fiber offers 12 percent overall energy savings in the production of glycols and a payback period of under two years. Other benefits include the use of a plant-based, renewable corn feedstock.



Ethylene glycol and propylene glycol are used to produce a variety of products such as antifreeze, and also as a major feedstock for the plastics industry. In this analysis, we have considered the plastics industry as the main market for these two chemicals for the sake of calculating their future demand. According to the Annual Energy Outlook 2000, the plastics industry is expected to grow by 2.9 percent annually until 2015. We have also assumed that 30 percent of all new capacity for producing ethylene and propylene glycol. The new facilities will be located at current wet-milling sites. This would allow the mills to sell a much more high-valued product, in addition to the feed that they already sell.

Some of the barriers to the implementation of this technology include the variable price of corn and the relatively high initial capital equipment costs of equipping a corn mill with fractionation equipment. The success of this technology is perhaps most highly dependent on a low corn purchase price. The barrier of capital cost could perhaps be overcome by the attractive payback of this technology.

## Clean Fractionation Data Table

	Units	Notes	
Clean Fractionation			
Chem-1			
Replace petrochemical glycol production			
Market Information:			
Industries		Chemicals	SIC 28
End-use(s)		Process heating, other	The process requires a heated and pressurized reaction vessel
Energy types		Electricity, gas, coal, other	
Market segment		New	
2015 basecase	tons	5600000	Scaled up production (1997) using EIA 1999 growth in plastics industry - this represents 0.01% of the energy use in the U.S. chemical industry and 0.5% of the energy use in industrial organic chemicals
Reference technology			
Description	Petrochemically derived ethylene glycol and propylene glycol (by acid or thermally catalyzed hydration of ethylene or propylene)		
Throughput or annual operating hours	tons	1.0	4.67% electric - EIA 1997
Electricity use	kWh	0.000056	
Fuel use	MBtu	3.9	61% natural gas, 26.9% other, 6.72% coal - EIA 1997
Primary Energy use	MBtu	3.9	Ethylene glycol production uses 4.09 * 10^9 btu/ton - DOE 2000a
New Measure Information:			
Description	Separation of corn fiber to produce ethylene glycol, propylene glycol, and xylitol		
Electricity use	kWh	0.00012	10.98% electric - EIA 1997
Fuel use	MBtu	3.4	45% coal, 39.31% n.g., 2.89% other, 0.578% resid fuel oil - EIA 1996
Primary Energy use	MBtu	3.4	OIT 1999
Current status		Pilot plant	
Date of commercialization		2005	
Estimated average measure lifetime	Years	15	
Savings Information:			
Electricity savings	kWh/%	-6.88E-05	-123%
Fuel savings	MBtu/%	0.464	12%
Primary energy savings	MBtu/%	0.464	12%
Penetration rate		Medium	
Feasible applications	%	13%	New capacity additions
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	-0.000050	Savings potential applied to 47,000 tons of fractionated product in 2015
Fuel savings potential in 2015	Tbtu	0.338	Savings potential applied to 47,000 tons of fractionated product in 2016
Primary energy savings potential in 2015	Tbtu	0.338	Savings potential applied to 47,000 tons of fractionated product in 2017
Cost Effectiveness			
Investment cost	\$	130	OIT 1999
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	-66.7	Assumed 30% of production savings based on OIT 1999
Cost of conserved energy (electricity)	\$/kWh	646484.40	
Cost of conserved energy (fuel)	\$/Mbtu	-95.84	
Cost of conserved energy (primary energy)	\$/Mbtu	-95.84	
Simple payback period	Years	1.9	
Internal rate of return	%	52%	
Key non energy factors			
Productivity benefits		Somewhat	
Product quality benefits		None	
Environmental benefits		Significant	Uses a renewable feedstock, reduces 1.8 million tons of waste by 2010
Other benefits		Significant	Lower production costs
Current promotional activity	H,M,L	Medium	Eastman Chemical has pilot plant and moving towards scale-up
Evaluation			
Major market barriers		Infrastructure	Equipping corn mills with process and distribution equipment
Likelihood of success	H,M,L	Medium	
Recommended next steps		Co-funding of production scale demonstration	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			EIA 1999
Basecase energy use			DOE-OIT 2000a
New Measure energy savings			OIT 1999
Lifetime			OIT 1999
Feasible applications			Personal Communication with Joe Bozell, NREL (303) 384-6276
Costs			OIT 1999
Key non energy factors			OIT 1999
Principal contacts			
Additional notes and sources			

## Gas Membrane Technologies (Chemicals-2)

Gas separations are some of the most challenging processes in the chemical industry. Mixtures are difficult to separate in their gas phase and generally are separated with the use of adsorbents. If useable products are desired after separation, mixtures are frequently brought into the liquid phase (through pressure or temperature control) and extracted. The use of membrane technology to separate or purify liquids is now well established. Since the early 1990's, this technology has been used in a variety of industries including the food and beverage industry, water companies and the chemical industry (CADET 1999c).

One of the most energy-intensive unit operations in the chemical industry is separation (DOE-OIT 2000a). Separation technologies include distillation, fractionation, and extraction. Certain mixtures of chemicals cannot be separated beyond a certain point by standard distillation processes and must undergo extraction. Azeotropic mixtures such as isopropyl alcohol and water fall into this category. Extraction takes advantage of the relative solubilities of solutes in immiscible solvents. If the solutes are in an aqueous solution, an organic solvent that is immiscible with water is added. The solutes will dissolve either in the water or in the organic solvent. If the relative solubilities of the solutes differ in the two solvents, a partial separation occurs. The upper, less dense solvent layer is physically separated from the lower layer. The separation is enhanced if the process is repeated on each of the separated layers.

Gas membranes offer an alternative to liquid-liquid extraction that uses much less energy. This technology can be used to separate organic mixtures. The example of separating a mixture of methanol and water, membrane separation uses 17 percent less fuel than liquid-liquid extraction. Separation processes account for one quarter of the process energy to produce isopropyl alcohol. Membrane separators also tend to cost about 10 percent less than traditional separation units. The annual operating costs of membranes tend to run a bit higher than other separators. Membranes must be replaced rather frequently and foul easily.

The aim of this gas separation technology is to avoid the energy consumption associated with the condensation of an azeotropic vapor mixture of methanol and water. The process is necessary because the azeotropic nature of the original mixture makes it impossible to separate the two fractions by simple distillation. The membrane used in this example acts like a molecular sieve. It separates a mixture of methanol and water by allowing the water molecule to pass through the filter, while retaining most of the methanol. The entire process takes place in the vapor phase.

A large potential market for gas membrane separators is mobile and stationary fuel cells. One of the types of fuel cells that has promise for mobile applications is the proton exchange membrane (PEM) fuel cell. The U.S. Department of Energy along with the U.S. Department of Transportation has been conducting research and demonstration projects in this area. Progress in gas membrane technologies will aid the commercialization of this technology as well.

The market for gas membrane separators will encompass every portion of the chemical industry. While industrial organic chemicals will dominate the market for membranes, other industries such as the food and pulp and paper industries can benefit from improvement of membrane processes. The organic chemical industry is forecasted to grow by 15 percent between the years 2000 and 2015. The market for membranes remains even larger because of the relatively few processes for which they are currently used for separation.

Membrane science continues to be evolving. Membranes with varying qualities are continuously being developed for the separation of specific gas mixtures. One of the ways in which membranes could be improved is by increasing their lifetime and by decreasing their sensitivities to fouling. Many gas membranes for example are fouled by exposure to sulfur. Sulfur-resistant membranes would be a great improvement for many processes in the petrochemical industries.

# Gas Membrane Technologies Data Table

	Units	Notes	
Gas Membrane Technologies			
Chem-2			
Replace liquid/liquid extraction			
Market Information:			
Industries		Chemicals	SIC 28
End-use(s)		Process heating, other	
Energy types		Electricity, gas, coal, other	
Market segment		New, replace on failure	
2015 basecase	tons	6915000.0	Projected production of methanol EIA 1999, DOE 2000a. As much as 50 percent (2135 trillion btu/year) of the energy use in the organic chemical industry is used for separations.
Reference technology			
Description	Distill the mixture to its azeotropic point, then do a liquid/liquid extraction		
Throughput or annual operating hours	tons	1.0	
Electricity use	kWh	11.36	CADDET 1999a
Fuel use	MBtu	2.32	Assumed that the heat for distillation required 20% more energy than mem sep.
Primary Energy use	MBtu	2.42	
New Measure Information:			
Description	Distill the mixture to its azeotropic point, separate with gas membrane		
Electricity use	kWh		
Fuel use	MBtu	1.93	
Primary Energy use	MBtu	1.93	CADDET 1999a
Current status		Commercialized	
Date of commercialization		1997	
Estimated average measure lifetime	Years	15	
Savings Information:			
Electricity savings	kWh/%	11.36	100%
Fuel savings	MBtu/%	0.386	17%
Primary energy savings	MBtu/%	0.483	20%
Penetration rate		Medium	
Feasible applications	%	3%	Estimated market share of separated methanol
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	1.96	Savings potential applied to 5% of the methanol market in 2015
Fuel savings potential in 2015	Tbtu	0.067	
Primary energy savings potential in 2015	Tbtu	0.084	
Cost Effectiveness			
Investment cost	\$	-1.0	1,100,000 for installation of new unit CADDET 1999c (for 20 ton/day facility)
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	1.62	Operating costs are lower, but membrane must be replaced frequently (\$11,823 annually for 20ton/day facility)
Cost of conserved energy (electricity)	\$/kWh	0.13	
Cost of conserved energy (fuel)	\$/Mbtu	3.75	
Cost of conserved energy (primary energy)	\$/Mbtu	3.00	
Simple payback period	Years	10.2	Based on fuel mix in US from EIA 1997
Internal rate of return	%	8%	
Key non energy factors			
Productivity benefits		None	
Product quality benefits		Somewhat	
Environmental benefits		Significant	Decreases CO2 emissions by 0.1325 tons/ton product per year
Other benefits		Significant	Investment 10% less below conventional installation
Current promotional activity	H,M,L	Medium	Morton International BV has operating facility
Evaluation			
Major market barriers		Availability	Limited production of specific membranes
Likelihood of success	H,M,L	High	
Recommended next steps		Establish markets	Membrane technology can be used in the food and petrochem industries
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			CADDET 1999c, EIA 2000
Basecase energy use			CADDET 1999c
New Measure energy savings			CADDET 1999c
Lifetime			CADDET 1999c
Feasible applications			Assumption of analyst
Costs			CADDET 1999c
Key non energy factors			CADDET 1999c
Principal contacts			
Additional notes and sources			

### **Heat Recovery Technologies for Harsh Environments in Chemical Manufacturing (Chemicals-3)**

The use of heat recovery in the chemicals industry is very common. The various processes used in the industry require extreme temperatures and often need rapid changes in temperature. Heat exchangers are used throughout the industry to provide efficient use of energy and to improve process control. Compact heat exchangers, which have a comparatively large amount of surface area in a given volume, are highly efficient and offer greater flexibility. There are, however, applications where conventional heat exchanger technology cannot be applied. This is true when the conditions include excessive temperature or high pressure, or when the medium passing through the heat exchanger is corrosive or caustic.

Recent advances in the construction of heat exchangers have yielded equipment that can be used in environments that were previously too extreme (Reay 1999). These advances have come in two ways. First, new materials that are resistant to corrosion are used in the construction of heat exchangers. Second, novel designs and manufacturing techniques have led to heat exchangers that can tolerate higher temperatures and pressures. Because heat exchangers can now be used in these extreme situations, more heat from the process can be captured and utilized, therefore leading to energy savings. This profile highlights two opportunities for heat exchangers under harsh conditions.

The production of sodium hydroxide (caustic soda) begins with the electrolysis of brine to generate chlorine and an aqueous solution of sodium hydroxide. The sodium hydroxide solution needs to be evaporated to various extents to yield the concentrations of the marketed products. This solution is highly corrosive and reaches temperatures up to 195°C during evaporation. Conventional heat exchangers are damaged and show leakage in this application. They can be replaced by printed circuit heat exchangers (PCHE), which are made by chemically milling channels into flat metal plates that are then diffusion bonded into blocks. Nickel is used to resist corrosion. An installation of this type of PCHE at a sodium hydroxide plant required an investment of roughly \$20,000, and led to annual energy savings of 3,980 Mbtu (4,200 GJ). The greatest benefit of this project was that it permitted large increases in production, generating additional revenue of approximately \$200,000 for the plant (CADET 1992).

Another corrosive application for novel heat exchangers is the production of nitric acid. Nitric acid is produced by burning ammonia in air at high temperature, then oxidizing the product and absorbing it into water. During production, the gas must be cooled from roughly 900°C to below 60°C before absorption can take place. The heat released while the gas is cooled down to 200°C is captured for use in other processes at the plant. Below 200°C, the gas can condense and corrode the heat exchanger, so heat recovery has not been possible. To avoid the corrosion problem, the heat exchanger can be constructed with a nickel/chromium alloy and can be designed to prevent acid re-evaporation. A plant adopted this novel approach and recorded annual energy savings of 130,000 Mbtu (137,000 GJ). This led to a three-year payback on the \$1.2 million investment (CADET 1993b).

The PCHE used in the sodium hydroxide application was produced by Heatric Ltd, located in Dorset, UK. This company reports that the majority of their sales for compact heat exchangers are to offshore oil processing plants because these heat exchangers are much more compact and lighter than their conventional counterparts, making them economical in offshore applications where expensive structural supports are needed (McCormack 2000). Heatric has experience with the chemical industry, including both sodium hydroxide and nitric acid production, and reports that the drivers behind the use of compact heat exchangers are corrosion resistance, multi-stream capability, and debottlenecking. Many other companies market compact heat exchangers to the chemical industry, including Alfa Laval and APV.

U.S. production of sodium hydroxide and nitric acid in 1997 was 11.8 million tons (10.7 million tonnes) and 9.5 million tons (8.6 million tonnes), respectively. These two products fall under the industrial groupings Alkalies and Chlorine (SIC 2812) and Nitrogenous Fertilizers (SIC 2873). Energy consumption for these two classifications totaled just over 500 TBtu of primary energy use for 1994, which accounts for one-eighth of total energy use in the chemical industry (AEO 1999). Assuming that these sub-sectors follow the same growth path forecast for the chemical industry as a whole, and assuming they experience the same changes in energy intensity expected across the sector, their primary energy use will grow to 613 TBtu by 2015.

# Heat Recovery Chemicals Data Table

Units		Notes	
Heat Exchangers for the Chemical Industry			
Chem-3			
Novel heat exchangers for aggressive environments: high temperature and pressure, corrosive products			
Market Information:			
Industries		Chemical products	Specifically, manufacture of sodium hydroxide and nitric acid, SIC 2812 and SIC 2873
End-use(s)		Process heat	
Energy types		Fuels	
Market segment		Retrofit	
2015 basecase use	Tbtu	613.2	1994 Use by SIC 2812, SIC 2873, assuming same growth and change in intensity as the chemicals sector as a whole, EIA 1997, EIA 1999
Reference technology			
Description	No heat recovery in highly corrosive applications		
Throughput or annual op. hrs.			
Electricity use	TWh	17	Combined output of sodium hydroxide (10.6 Mt) and nitric acid (8.6 Mt), 1997
Fuel use	TBtu	356	These energy values for summed for 2 four-digit sectors: 2812 Alkalis and Chlorine, and 2873 Nitrogenous Fertilizers, MECS 1994
Primary energy use	TBtu	502.2	
New Measure Information:			
Description	New heat exchanger design to tolerate harsh environments and allow for greater heat recovery		
Electricity use	TWh	17	
Fuel use	TBtu	334	
Primary Energy use	TBtu	480	
Current status		Commercialized, Research	Depends on specific application
Date of commercialization		1995	
Est. avg. measure life	Years	10	Despite high tolerance, will eventually foul in extreme environments
Savings Information:			
Electricity savings	TWh/%	0	0%
Fuel savings	TBtu/%	22.0	6%
Primary energy savings	TBtu/%	22.0	4%
Penetration rate		Medium	
Feasible applications	%	30%	
Other key assumptions			Savings observed in the case studies are for typical plants of each type.
Elec svgs potential in 2015	TWh	0	
Fuel svgs potential in 2015	TBtu	8.1	
Primary energy svgs potential in 2015	TBtu	8.1	
Cost Effectiveness			
Investment cost	\$/Mbtu	8	Estimate of capital investment based on sample projects
Type of cost		Full cost	
Change in other costs	\$	0	Too variable to quantify
Cost of saved energy (elec)	\$/kWh	0.01	
Cost of saved energy (fuel)	\$/Mbtu	1.63	
Cost of saved energy (primary)	\$/Mbtu	1.63	Discount rate for all CCE calculations is 15%
Simple payback period	Years	2.4	
Internal rate of return	%	42%	
Key non energy factors			
Productivity benefits		Moderate (site-specific)	Improve plant operation (debottle-necking), increased yield
Product quality benefits		None	
Environmental benefits		None	
Other benefits		Somewhat	Small volume and weight lowers installation costs relative to standard heat exchangers
Current promotional activity	H,M,L	Medium	
Evaluation			
Major market barriers		Awareness,Perceptions	Fears of fouling and corrosion, conservatism in user industries.
Likelihood of success	H,M,L	Medium	
Recommended next steps		Dissemination,demonstration	projects in US link with training about process integration & pinch analysis
Data quality assessment	E,G,F,P	Fair	Own estimates based on literature survey
Sources:			
2015 basecase			EIA, 1999; EIA 1997
Basecase energy use			EIA, 1997
New measure energy savings			Average of CADDET studies
Lifetime			Author judgement
Feasible applications			Author judgement
Costs			Average of CADDET studies
Key non energy factors			
Principal contacts			Heatric, Ltd. (Des McCormack),
Additional notes and sources			



While these heat exchangers are also applicable to other harsh chemical environments, we focus in this assessment on nitric acid and sodium hydroxide production. We estimate that these heat exchanger technologies could be adopted in 30 percent of all nitric acid and sodium hydroxide production in the U.S. by 2015. This would lead to energy savings of 8.1 TBtu per year. Based on the reported projects, the cost for these installations would be roughly \$8 per MMBtu saved annually, which, given an average fuel price to the chemical industry of \$3.42 per MMBtu, indicates a payback period of 2.4 years. The payback could be considerably faster depending on the site-specific factors of the application. For example, if the introduction of the heat exchanger alleviates a bottleneck in production the increase in output provides a large productivity benefit (Reay 1999). In the sodium hydroxide project, the increased productivity lowered the payback period to five weeks (CADDET 1992). Other benefits that accompany compact heat exchangers in these applications are reduced maintenance and replacement costs, and lower installation costs due to the reduced size and weight of the equipment.

This technology is likely to be successful. The entire class of compact heat exchangers accounts for only 5-10 percent of the sales at this time, but their sales are increasing much more rapidly than total heat exchanger sales (Reay 1999). The key to promoting these technologies is to disseminate information and establish demonstration projects in the U.S. that illustrate the use of compact heat exchangers in harsh environments.

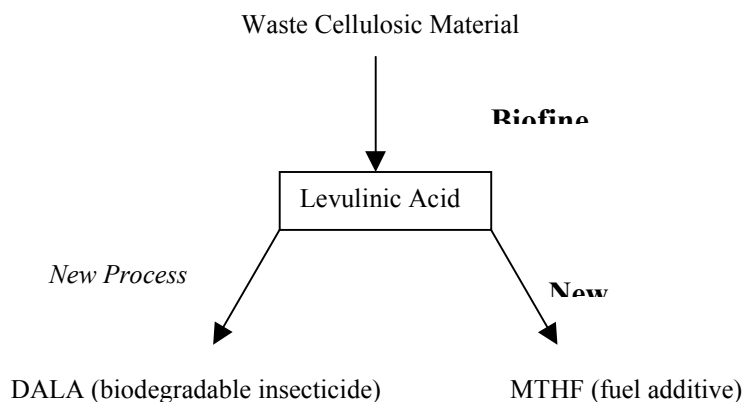
## Levulinic Acid for the Manufacture of Chemicals (Chemicals-4)

Biomass can be used as a raw material to produce large numbers of chemicals (or chemical intermediates), yet to date, many of these products have failed in the marketplace because they frequently are not economically viable and face high production costs.

Levulinic acid (LA) holds promise as an inexpensive feedstock for producing many industrial chemicals and products. The two chemicals that could significantly increase the market for levulinic acid are methyltetrahydrofuran (MTHF), a fuel additive, and delta-amino levulinic acid (DALA), a biodegradable herbicide/pesticide. This measure is actually a group of process technologies that aims to create a greater market for levulinic acid from biomass by improving the production methods of MTHF and DALA.

The Biofine Corporation developed a process using acid hydrolysis of 6-carbon sugars as the key step for LA production. This process minimizes side product formation and the resulting separation problems associated with them by significantly improving the tradition engineering of the LA production process through a novel, two reactor system. The figure below demonstrates the path for DALA and MTHF production. The technology is being demonstrated on a one ton/day scale at a facility in South Glens Falls, New York.

The MTHF is produced in a greater than 80 percent yield via a single stage catalytic hydrogenation process. The process for forming DALA affords a product with a purity of greater than 90 percent, giving a process that is commercially viable. The DALA process is currently being improved in three areas: converting by-products of DALA production for use in plastics manufacturing, using new reagents to simplify the production of DALA, and purifying the final product to remove a salt generated during production. To minimize waste streams, solvent and by-products are being recovered and reused at each step of the process.



Currently, levulinic acid has a worldwide market of about one million pounds per year at a price of \$4-6 per pound. Large-scale commercialization of the Biofine process could produce levulinic acid for as little as \$0.32 per pound, spurring increased demand for LA and its derivatives. The current levulinic acid demonstration plant in South Glens Falls, NY uses paper mill sludge as the raw material. The plant was originally producing 1-2 tons of levulinic acid per day and has increased its output to 4-6 tons per day.

Commercialization efforts have been underway with support from Biometrics, Inc. Engineers are currently attempting to increase production capacity and reduce operation and maintenance costs. The demonstration plant is still on a pilot-scale. Many cost issues can be resolved once the plant is operating at full scale. Once the economics are in place, other producers of levulinic acid may consider implementation of the Biofine method of production. Levulinic acid holds the most promise as a precursor to the fuel additive MTHF. Especially in the American gasoline market, where per capita fuel consumption continues to increase, MTHF is becoming an important product.

## Levulinic Acid Data Table

	Units	Notes	
Levulinic Acid from Biomass (biofine)			
Chem-4			
Replace dehydrative treatment with acid			
Market Information:			
Industries		Chemicals	
End-use(s)		Process heating, other	
Energy types		Electricity, gas, coal, other	
Market segment		New	
2015 basecase	tons	150000	DOE 2000a, EIA 1999 - currently, levulinic acid is a niche chemical, but new product applications could increase the market.
Reference technology			
Description		Dehydrative treatment of biomass or carbohydrates with acid	
Throughput or annual operating hours	tons	1	www.epa.gov/greenchemistry/sba99.htm
Electricity use	kWh	85	www.epa.gov/greenchemistry/sba99.htm
Fuel use	MBtu	42	www.epa.gov/greenchemistry/sba99.htm
Primary Energy use	MBtu	42.7	
New Measure Information:			
Description		Acid hydrolysis of 6-carbon sugars	
Electricity use	kWh	80	www.epa.gov/greenchemistry/sba99.htm
Fuel use	MBtu	38.0	www.epa.gov/greenchemistry/sba99.htm
Primary Energy use	MBtu	38.7	
Current status		Demonstration	4-6 ton per day plant in South Glens Falls, NY
Date of commercialization		2002	
Estimated average measure lifetime	Years	20	
Savings Information:			
Electricity savings	kWh/%	5.00E+00	6%
Fuel savings	MBtu/%	4.000	10%
Primary energy savings	MBtu/%	4.043	9%
Penetration rate		High	
Feasible applications	%	15%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	0.113	
Fuel savings potential in 2015	Tbtu	0.090	
Primary energy savings potential in 2015	Tbtu	0.091	
Cost Effectiveness			
Investment cost	\$	1000	\$344,000 for installation of demonstration scale plant www.pnl.gov/news/1998/98mth
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	-640	\$0.32/lb www.epa.gov/greenchemistry/sba99.htm
Cost of conserved energy (electricity)	\$/kWh	-96.05	
Cost of conserved energy (fuel)	\$/Mbtu	-120.06	
Cost of conserved energy (primary energy)	\$/Mbtu	-118.80	
Simple payback period	Years	1.53	
Internal rate of return	%	65%	
Key non energy factors			
Productivity benefits		Significant	Produces high yield capacity with less waste and fewer byproducts
Product quality benefits		None	
Environmental benefits		Significant	Reduces landfill waste
Other benefits		Significant	Makes the production of levulinic acid economical
Current promotional activity	H,M,L	High	Biometrics, Honeywell, NYSERDA involved in development
Evaluation			
Major market barriers			
Likelihood of success	H,M,L	High	The demonstration plant is increasing capacity
Recommended next steps		Scale-up	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			DOE 2000a, EIA 1999
Basecase energy use			www.epa.gov/greenchemistry/sba99.htm
New Measure energy savings			www.epa.gov/greenchemistry/sba99.htm
Lifetime			www.epa.gov/greenchemistry/sba99.htm
Feasible applications			www.epa.gov/greenchemistry/sba99.htm
Costs			www.epa.gov/greenchemistry/sba99.htm
Key non energy factors			
Principal contacts			
Additional notes and sources			

## Liquid Membrane Technologies - Chemicals (Chemicals-5)

The U.S. chemicals industry makes up more than 10 percent of the U.S. manufacturing gross domestic product. This is greater than any other sector including food, machinery, motor vehicles, aerospace, and electronics (Census 1996). The industry employs nearly 850,000 workers at 12,000 plants nationwide (Census 1996). The industry produces so many products that it eludes clear definition. Most industrial chemicals, in fact, are consumed by chemical-related businesses. Steel and aluminum mills, paper mills, semiconductor manufacturers, drug companies, carpet mills, and battery producers are all relatively large customers. The chemical industry uses many different fuel sources for its energy needs (i.e. natural gas, electricity, coal, and fuel oils), with nearly 50 percent of the total used as feedstocks (DOE-OIT 2000a). Although they vary widely from product to product, energy expenditures can represent a significant portion of manufacturing costs in the industry.

One of the most energy-intensive unit operations in the chemical industry is separation. Separation technologies include distillation, fractionation, and extraction. Certain mixtures of chemicals cannot be separated beyond a certain point by standard distillation processes and must undergo extraction. Azeotropic mixtures such as isopropyl alcohol and water fall into this category. Extraction takes advantage of the relative solubilities of solutes in immiscible solvents. If the solutes are in an aqueous solution, an organic solvent that is immiscible with water is added. The solutes will dissolve either in the water or in the organic solvent. If the relative solubilities of the solutes differ in the two solvents, a partial separation occurs. The upper, less dense solvent layer is physically separated from the lower layer. The separation is enhanced if the process is repeated on each of the separated layers.

Liquid membranes offer an alternative to liquid-liquid extraction, and use much less energy. This technology can be used to separate both aqueous and organic mixtures. The example of separating a mixture of isopropyl alcohol and water, membrane separation uses 60 percent less fuel than liquid-liquid extraction. Separation processes account for one quarter of the process energy to produce isopropyl alcohol. Membrane separators also tend to cost about 10 percent less than traditional separation units. The annual operating costs of membranes tend to run a bit higher than other separators. Membranes must be replaced rather frequently and foul easily.

The market for liquid membrane separators will encompass every portion of the chemical industry. While industrial organic chemicals will dominate the market for membranes, other industries such as the food and pulp and paper industries can benefit from improvement of membrane processes. The organic chemical industry is forecasted to grow by 15 percent between the years 2000 and 2015. The market for membranes remains even larger because of the relatively few processes for which they are currently used for separation.

One of the largest barriers facing liquid membranes is limited production. Liquid membranes are highly specific with regards to the compounds that they can separate, therefore differing processes will require differing membranes. More research and development is needed to improve the performance of these technologies.

## Liquid Membrane Technologies - Chemicals Data Table

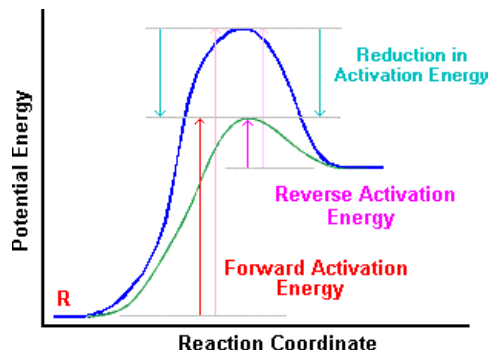
	Units	Notes	
Liquid Membrane Technologies			
Chem-5			
Replace liquid/liquid extraction			
Market Information:			
Industries		Chemicals	SIC 28
End-use(s)		Process heating, other	
Energy types		Electricity, gas, coal, other	
Market segment		New, replace on failure	
2015 basecase	tons	805680	2015 production of isopropyl alcohol AEO 2000,DOE 2000a (15% up from 1997). As much as 50 percent (2135 trillion btu/year) of the energy use in the organic chemical industry is used for separations.
Reference technology			
Description	Distill the isopropyl/water mixture to its azeotropic point, then do a liquid/liquid extraction		
Throughput or annual operating hours	tons	1.0	
Electricity use	kWh	120.90	11% electricity EIA 1997
Fuel use	MBtu	8.36	89% fuel EIA 1997
Primary Energy use	MBtu	9.39	25% of energy (4693 btu/lb) is for separation. DeBeer 1994
New Measure Information:			
Description	Distill the mixture to its azeotropic point, separate with liquid membrane		
Electricity use	kWh	120.90	
Fuel use	MBtu	3.34	Technology saves 60% of separation fuel input
Primary Energy use	MBtu	4.38	
Current status		Commercialized	
Date of commercialization		2000	
Estimated average measure lifetime	Years	10	
Savings Information:			
Electricity savings	kWh/%	0.00	0%
Fuel savings	MBtu/%	5.016	60%
Primary energy savings	MBtu/%	5.016	53%
Penetration rate		Medium	
Feasible applications	%	20%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	0.0	
Fuel savings potential in 2015	Tbtu	0.81	
Primary energy savings potential in 2015	Tbtu	0.81	
Cost Effectiveness			
Investment cost	\$	-7	\$62.6/ton for full installation of membrane separator DeBeer 1994
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	17	Operating costs are lower, but membrane must be replaced frequently
Cost of conserved energy (electricity)	\$/kWh	-	
Cost of conserved energy (fuel)	\$/Mbtu	3.11	
Cost of conserved energy (primary energy)	\$/Mbtu	3.11	
Simple payback period	Years	11.2	Fuel mix in US from EIA 1997
Internal rate of return	%	6%	
Key non energy factors			
Productivity benefits		None	
Product quality benefits		None	
Environmental benefits		Significant	Decreases CO2 emissions
Other benefits		Significant	Investment 10% less than conventional installation
Current promotional activity	H,M,L	High	Dow Chemical promoting
Evaluation			
Major market barriers		Availability	Limited production of specific membranes
Likelihood of success	H,M,L	Medium	
Recommended next steps		Establish markets	Membrane technology can be used in the food and petrochem industries
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			DOE 2000a, EIA 2000
Basecase energy use			DeBeer 1994
New Measure energy savings			DeBeer 1994
Lifetime			DeBeer 1994
Feasible applications			DeBeer 1994
Costs			DeBeer 1994
Key non energy factors			
Principal contacts			
Additional notes and sources			

## New Catalysts (Chemicals-6)

Catalysis is the phenomenon by which certain chemicals (catalysts) can speed up a chemical reaction without undergoing any permanent chemical change themselves. They can be recovered after a reaction and used repeatedly (although most catalysts have finite lifetimes). Catalysts lower the activation energy required for a reaction to complete. Without the right catalyst, many reactions do not progress. Furthermore, the chemical nature of the catalyst can have a radical effect in selecting reaction pathways leading to different chemical products. Over recent decades there has been enormous progress in understanding the underlying molecular mechanisms, which has had an explosive effect on the development of new catalyst systems.

About 80 per cent of processes in the chemical industry now depend on catalysts to work efficiently, and the number is rising. New catalysts are being designed and new catalytic processes being devised that aim to produce cleaner and more efficient chemical processes. These use less energy, and environmentally acceptable agents (for example, air or oxygen as an oxidant instead of hydrogen peroxide) and perhaps water as a solvent, resulting in less noxious waste.

Since the chemical industry is so diverse and produces such a large quantity of chemicals, the exact impact of new catalysts is difficult to predict. For this analysis, a very common industrial chemical, ethylene, was used as an example. Current production of ethylene consumes 8,197 Btus/lb. A new catalyst could lower the energy consumption by 20 percent.



One of the more promising areas in catalytic research is the area of nanoscale catalysts. One typical objective of nanoscale catalyst research is to produce a material with exceedingly high selectivity at high yield in the reaction product or product slate, that is, chemicals by design, with the option of altering the product by changing the surface functionality or composition at the nanoscale. For instance, new catalysts with increasing specificity are now being fabricated in which only one or two spatial dimensions are of nanometer size. A second objective is to discover nanoscale materials or structures with exceedingly high storage capacity per unit volume and weight for gases such as H<sub>2</sub> or CH<sub>4</sub>, which would then be more economic for use either as a combustion fuel or as the means to power fuel cells for ultralow-emission vehicles or for electric power generation. A third objective is to fabricate molecular sieving membranes using inorganic crystalline materials such as zeolites. For molecular sieving membranes, one critical challenge rests on discovering ways to create large-scale, thin, nearly defect-free membranes.

Most large chemical companies have a research group that is devoted solely to the development of new catalysts. Improvements are constantly occurring, although many of the technologies are proprietary. One of the barriers that faces catalyst research is the high cost of catalytic ligands. Many of these, especially in the specialty pharmaceutical industries can cost upwards of \$50,000 per pound. This presents a problem in the commodity chemical sector where products are sold for minimal or no profit. The largest market for catalysts may be in the industries with high-valued products such as pharmaceuticals and biotechnology.

## New Catalysts Data Table

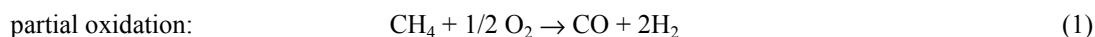
	Units		Notes
New Catalysts			
Chem-6			
Replace pyrolysis of hydrocarbons to produce ethylene (example)			
Market Information:			
Industries		Chemicals	SIC 28
End-use(s)		Process heating, other	
Energy types		Electricity, gas, coal, other	
Market segment		New, retrofit	
2015 basecase	tons	27743750	2015 production of ethylene EIA 1999, DOE 2000a (15% up from 1997). This is an example - virtually all chemical processes use catalysts, therefore improvements would greatly lower energy use in the industry.
Reference technology			
Description	Distill the isopropyl/water mixture to its azeotropic point, then do a liquid/liquid extraction		
Throughput or annual operating hours	tons	1.0	
Electricity use	kWh	528.40	11% electricity EIA 1997
Fuel use	MBtu	14.59	89% fuel EIA 1997
Primary Energy use	MBtu	16.39	Process energy of 8197 Btu/lb, DOE 2000a
New Measure Information:			
Description	Pyrolysis of hydrocarbons		
Electricity use	kWh	423	DOE 2000a
Fuel use	MBtu	11.67	DOE 2000a
Primary Energy use	MBtu	13.11	Catalysts could save 20% of primary energy use (average)
Current status		R&D	
Date of commercialization		2005	
Estimated average measure lifetime	Years	20	
Savings Information:			
Electricity savings	kWh/%	105.68	20%
Fuel savings	MBtu/%	2.917	20%
Primary energy savings	MBtu/%	3.278	20%
Penetration rate		Low	
Feasible applications	%	15%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	439.8	
Fuel savings potential in 2015	Tbtu	12.14	
Primary energy savings potential in 2015	Tbtu	13.64	
Cost Effectiveness			
Investment cost	\$	50	Catalyst ligands costs \$30k-\$50k per pound
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	4	Operating costs are lower, but catalyst must be replaced frequently
Cost of conserved energy (electricity)	\$/kWh	0.11	
Cost of conserved energy (fuel)	\$/Mbtu	4.11	
Cost of conserved energy (primary energy)	\$/Mbtu	3.66	
Simple payback period	Years	7.9	Fuel mix in US from EIA 1997
Internal rate of return	%	11%	
Key non energy factors			
Productivity benefits		None	
Product quality benefits		None	
Environmental benefits		Somewhat	Decreases need for process heat and pressurization
Other benefits			
Current promotional activity	H,M,L	Medium	All major chemical companies are involved in catalyst research
Evaluation			
Major market barriers			
Likelihood of success	H,M,L	Medium	
Recommended next steps		R&D	
Data quality assessment	E,G,F,P	Fair	
Sources:			
2015 basecase			DOE 2000a, EIA 2000
Basecase energy use			DOE 2000a, EIA 2000
New Measure energy savings			DOE 2000a, and judgement of analyst
Lifetime			Judgement of analyst
Feasible applications			Judgement of analyst
Costs			DOE 2000a, EIA 2000
Key non energy factors			
Principal contacts			
Additional notes and sources			

## Autothermal Reforming (or Combined Reforming) (Chemicals-7)

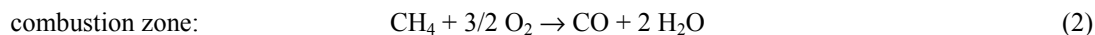
The production of nitrogenous fertilizer is very energy-intensive and the nitrogenous fertilizer industry produces a variety of fertilizers and other nitrogen-compounds. Ammonia is the most important intermediate chemical compound, used as the basis for almost all fertilizers. In the U.S. ammonia is one of the major chemicals produced, with an estimated production of 18.0 Million tons (16.3 Mt) (CMA 1996). About 80 percent of the ammonia is used for fertilizer production and the remainder is used for a variety of products, mainly explosives and plastics. Annual fuel use is estimated at 254 TBtu (excluding feedstocks) (268 PJ) while 349 TBtu (368 PJ) natural gas is used as feedstock. Natural gas is the main fuel used for ammonia manufacture in the U.S. Electricity consumption is estimated at 3.9 TWh. We estimate the energy intensity of ammonia manufacture at 33.8 MBtu/ton (39.3 GJ/t) (including feedstocks, HHV) and 127 kWh/short ton (140 kWh/t), resulting in an estimated primary energy consumption of 35.2 MBtu/short ton ammonia (HHV), equivalent to 37.1 GJ/t ammonia (LHV) (Worrell et al. 2000). No recent new ammonia plants have been built in the U.S., limiting uptake of new autothermal reforming technology to expansion projects and retrofit of existing plants.

The ammonia synthesis starts with the production of syngas from natural gas. Reforming takes place in two stages, the primary and the secondary reformer. The inputs for the reforming process are NG (mainly CH<sub>4</sub>), water (steam) and air. Desulfurized CH<sub>4</sub> is heated and led into the primary reformer. Because the reforming reaction is endothermic, heat has to be supplied externally in this stage. Product gas from the primary reformer, a mixture of H<sub>2</sub>, CO and CO<sub>2</sub> (still containing CH<sub>4</sub>), is passed to the secondary reformer. Here it is mixed with pre-heated air and passed over a nickel catalyst at 1100°C. CH<sub>4</sub> is partly burned with oxygen from the air to generate the energy that is necessary for the steam reforming reaction. Oxygen is also used to oxidize a part of the CH<sub>4</sub> to CO and H<sub>2</sub>. The syngas leaves the reactor at a temperature of approximately 980°C. In some processes (ICI-AMV, Braun), excess air is supplied to the secondary reformer, so the primary reformer can be smaller and facilitates milder reforming conditions (Worrell and Blok 1994).

In the development of new, more efficient syngas production processes, more attention is paid to syngas production using the *partial oxidation* method. The chemical reaction is:



Reforming processes that combine steam reforming and partial oxidation are the most efficient. These processes are called *advanced processes*. In one of these advanced processes, autothermal reforming (ATR) process, both reaction (1) and (3) play an important role. The processes of partial oxidation and steam reforming are highly integrated, i.e. both reactions take place in one reactor. This reactor has similarities to the secondary reformer of the steam reforming process. The reactions that take place are combinations of combustion and steam reforming (Christensen and Primdahl 1994). In the combustion zone, the reaction is:



This reaction is without CO<sub>2</sub> production because CO is the primary combustion product, which is converted to CO<sub>2</sub> by a slow secondary reaction. In the thermal and catalytic zones, the reactions (1) and (2) occur to form H<sub>2</sub>. The oxygen content of the oxidant in the reforming process depends on the application of the syngas. For the production of NH<sub>3</sub>, air is needed because this contains the N<sub>2</sub> necessary for the synthesis of ammonia.

Autothermal reforming has been used since the 1960s on a small scale. Research has been done to upgrade the process and make it suitable for large scale production. Haldor Topsøe has used autothermal reforming in small scale designs since the 1960s, and has adapted its design for CO-rich synthesis gas, especially for methanol production (Rostrup-Nielsen 1993). Statoil, the Norwegian oil company, is building a new methanol factory on the north-west coast of Norway. The plant will use an ATR designed by Haldor Topsoe with a capacity of 2,400 tpd. Other producers (e.g. Lurgi) also market ATR methanol plants.

Uhde in Germany developed the Combined Autothermal Reformer (CAR) process and has built a demonstration plant. According to Uhde the energy requirement would be around 24.5 MBtu/ton NH<sub>3</sub> (LHV) at plant scales larger than 500 tpd (Christensen and Primdahl 1994, Marsch and Thiagarajan 1993).



## Autothermal Reforming Data Table

	Units	Notes	
Autothermal Reforming			
Chemicals-7			
Autothermal or combined eforming replaces conventional steam reforming			
Market Information:			
Industries		Ammonia Making	SIC 2873
End-use(s)		Process Heating	
Energy types		Natural Gas	
Market segment		New, Expansion	
2015 basecase use	Mtons	18.0	1994 production; no growth expected in this industry
Reference technology			
Description	Average steam reforming ammonia plant		
Throughput or annual op. hrs.	tpy	1	Plants size varies between 33,000 and 1,800,000 tons/year
Electricity use	kWh	127	
Fuel use	MBtu	33.8	
Primary energy use	MBtu	34.9	
New Measure Information:			
Description	Autothermal reformer		
Electricity use	kWh	127	
Fuel use	MBtu	26.8	
Primary Energy use	MBtu	27.9	
Current status		Commercial	Technology can also be used for hydrogen and methanol production
Date of commercialization		1996	
Est. avg. measure life	Years	30	
Savings Information:			
Electricity savings	kWh/%	0	0%
Fuel savings	MBtu/%	7.0	44%
Primary energy savings	MBtu/%	7.0	20%
Penetration rate		Low	Slow market development for ammonia limits uptake technology
Feasible applications	%	30%	
Other key assumptions			
Elec svgs potential in 2015	GWh	0	
Fuel svgs potential in 2015	Tbtu	38	
Primary energy svgs potential in 2015	Tbtu	37.8	
Cost Effectiveness			
Investment cost	\$	55	
Type of cost		Retrofit	Due to slow market, assume retrofit existing plants
Change in other costs	\$	-0.5	Estimate
Cost of saved energy (elec)	\$/kWh	N/A	
Cost of saved energy (fuel)	\$/Mbtu	1.13	
Cost of saved energy (primary)	\$/Mbtu	1.13	
Simple payback period	Years	3.7	
Internal rate of return	%	26%	
Key non energy factors			
Productivity benefits		Somewhat	Authothermal plants have lower maintenance and production costs
Product quality benefits			
Environmental benefits		Significant	
Other benefits			
Current promotional activity	H,M,L	Low	
Evaluation			
Major market barriers		Commercial	Slow market development for ammonia limits uptake technology
Likelihood of success	H,M,L	Medium	
Recommended next steps		Marketing, Retrofit assistance	
Data quality assessment	E,G,F,P	Fair	
Sources:			
2015 basecase			Worrell et al., 2000
Basecase energy use			Worrell et al., 2000
New measure energy savings			Czuppon et al., 1996
Lifetime			Author's estimate
Feasible applications			Author's estimate
Costs			Christensen and Primdahl, 1994; Smit et al., 1994
Key non energy factors			EFMA, 1995
Principal contacts			Mike Grant, Haldor Topsoe, Houston, TX (281) 228 5095
Additional notes and sources			

The advanced KRES (Kellogg Reforming Exchanger System) process (Czuppon 1994) is also based on autothermal reforming.

The KRES system has first been installed in Canada (at Ocelot Ammonia, Co, Kitimat, BC) to provide syngas for an equivalent of 350 tpd ammonia. The KRES process has also been integrated in a new ammonia plant design: Kellogg Advanced Ammonia Process (KAAP), of which the first have been built in Trinidad and other countries. The specific energy consumption of the KRES-process is estimated at 25.9 MBtu/ton (HHV) (equivalent to 27.2 GJ/tonne (LHV), including feedstocks (Czuppon et al. 1996).

For 2015 we assume that retrofit of an existing ammonia plant by replacing the reformer with an autothermal reformer and integrating into the plant may reduce natural gas use to 26.8 MBtu/ton ammonia (HHV) (Czuppon et al. 1996), or (28.1 GJ/tonne, LHV). We assume that power consumption does not increase (assuming the KRES-process without additional oxygen consumption).

The capital costs for a new greenfield plant for a modern ammonia plant using autothermal reforming are smaller than current technology (Czuppon et al. 1996). Exact investments are not given by the developers of the processes, and will depend on the local situation and capacity. Christensen and Primdahl (1994) estimated the investment costs of an autothermal reformer to be lower than the investments in both the primary and the secondary reformer of the AMV-ICI process. The reformers in the AMV-process count for 21 percent of the total investment (300 US\$/tonne). The investments for an ATR will probably be around than 55 US\$/ton (Smit et al. 1994), assuming retrofit of an existing plant. O&M costs are lower compared to that of a conventional steam reformer.

An autothermal reformer, reducing the fluegasses from a fired primary reformer, may reduce NO<sub>x</sub> emissions by 50 percent (EFMA 1995). Next steps include the commercial application of an integrated autothermal reformer.

## Plastics Recovery (Chemicals-8)

In the United States, plastics production has grown significantly over the past two decades at rates of 3-8 percent annually with total plastics production of 29 million tons (26 Mt) in 1996 (Chemical and Engineering News 1997). Some of the main plastic products include polyethylene, (low (PET) and high density(HDPE)), polypropylene, polystyrene, and polyvinyl chloride (PVC); markets have seen particularly strong growth in PVC, polypropylene, and high-density polyethylene. While not as energy-intensive as the production of bulk chemicals, the production of plastic materials in SIC 2821 accounts for an important share of chemical energy use due to the large volume of production. Primary energy consumption for plastics and resins production in 1994 was 400 TBtu (400 PJ) or 2 percent of manufacturing energy consumption.

While some progress has been made in recovering plastics from some waste streams, the overall recovery rate for post consumer waste in the U.S. is extremely low, about 9 percent (Denison, 1997). There are still large opportunities to greatly increase recycling in the U.S. In many cases, economics prevent the increase in recycling since the cost of collecting and processing post-consumer plastics is higher than the cost of producing virgin materials (Kobler 2000).

Complex or mixed waste streams are particularly challenging to separate and make pure enough to be useful. Aside from the PET and HDPE bottle markets, one of the single largest concentrated supplies can be found in automobile shredder residue (ASR). ASR includes plastics, rubber, glass, fibers, and amounts to 3 to 5 million tons (2.7-4.5 Mt) annually (DeGaspari 1999). It is estimated that 20-31 percent of this is 20 different types of plastic materials; however, the two major types of plastic are polypropylene and ABS (acrylonitrile, butadiene, and styrene) (Kobler 2000). Currently, virtually no post-consumer plastics are used in today's new vehicles (USCAR 1998, Salyp 2000, Kobler 2000). Of these plastics, thermoplastics such as polypropylene, polyethylene, polycarbonate, nylon, and polyurethane can potentially be melted and re-used while thermosets do not re-melt and are more challenging to recycle (Kobler 2000, Betts 1999).

Various technologies are being developed to recover and reuse plastics. MBA polymers developed a mechanical separation process that allows plastics of similar densities to be separated for reuse. This has been used to separate and recover different plastics from computer housings. Early development of this process was partially supported by the U.S. Department of Energy's NICE<sup>3</sup> program, the Vehicle Recycling Partnership (VRP), and the American Plastics Council (APC) (OIT 1999, Biddle 2000, Yester 2000). Argonne National Laboratory has developed a separation technology called froth flotation to separate and recover ABS and HIPS from appliance wastes (USCAR 2000, DeGaspari 1999, Daniels 2000, Kobler, 2000). This technology is receiving developmental support from the U.S. Department of Energy's Office of Industrial Technology in collaboration with the VRP and the American Plastics Council (OIT 1999) and could be applied to ASR in the future. A small-scale trial using appliance waste streams was conducted at the Appliance Recycling Centers of America with support from the VRP but no pilot plant has been constructed (Daniels 2000, Yester 2000). Recovery Plastics International (RPI) has developed a skin flotation technology that recovers about 80 percent of the plastic stream from ASR (Kobler 2000). This technology has also received R&D funding support from VRP and a one- ton/hour pilot plant is currently operating.

In the froth flotation technology, plastics of similar densities are placed in an aqueous solution, and the wetting characteristics of various plastic types are selectively adjusted. This preparation allows for small gas bubbles to attach to particular plastics thereby allowing for separation in the solution (USCAR 1999, DeGaspari 1999). The skin flotation technique at RPI puts on a skin of plasticizer on the plastic surface selectively which makes it hydrophobic. That targeted plastic type, which preferentially absorbed the plasticizer, is the only one to float (Kobler, 2000). Only with skin flotation technology has raw ASR been used as the primary feedstock material, and also is able to separate out plastics from rubbers improving the quality of the separated product (Kobler 2000).

Energy savings from this system can be significant. Including the embodied energy in plastics, savings estimates range from 50-75 Mbtu/ton (58-87 GJ/t) material recycled (Daniels 2000, Richman 2000). Fisher and Mark (1999) note that the plastics content of ASR is about 13 percent by weight. Based on this analysis we estimate a savings of 13 Mbtu/ton (15 GJ/t) (Fisher and Mark 1999, Lipinsky and Wesson 1995).

# Plastics Recovery Data Table

	Units		Notes
<b>Plastics recovery</b>			
<b>Chem-8</b>			
<b>Plastics recovery for ASR</b>			
<i>Market Information:</i>			
Industries		Plastics	SIC 2821
End-use(s)		Process heating	
Energy types		Fuels	
Market segment		New	
2015 basecase use	Mtons	0.3	Based on assumption of growth in automobile plastics content
<i>Reference technology</i>			
Description		Plastics manufacture for automobiles	
Throughput or annual op. hrs.	ton	1	
Electricity use	kWh	887	Worrell et al., 1994
Fuel use	MBtu	49.4	
Primary energy use	MBtu	57.0	
<i>New Measure Information:</i>			
Description		Advanced recovery technologies	
Electricity use	kWh	1065	Electricity for mechanical recycling and for ASR & other thermoplastics recovery
Fuel use	MBtu	7.8	
Primary Energy use	MBtu	16.9	
Current status		Near commercial	
Date of commercialization		2002	
Est. avg. measure life	Years	20	
<i>Savings Information:</i>			
Electricity savings	kWh/%	-178	-20%
Fuel savings	MBtu/%	41.6	84%
Primary energy savings	MBtu/%	40.1	70%
Penetration rate		Medium	
Feasible applications	%	70%	
Other key assumptions			
Elec svgs potential in 2015	GWh	-40	
Fuel svgs potential in 2015	Tbtu	9	
Primary energy svgs potential in 2015	Tbtu	9.0	
<i>Cost Effectiveness</i>			
Investment cost	\$	225	Costs of \$150-300/ton recovered material
Type of cost		Full	
Change in other costs	\$	0	Assume that operations competitive in cost with virgin plastics (Kobler, 2000)
Cost of saved energy (elec)	\$/kWh	N/A	
Cost of saved energy (fuel)	\$/Mbtu	0.86	
Cost of saved energy (primary)	\$/Mbtu	0.90	Discount rate for all CCE calculations is 15%
Simple payback period	Years	2.8	
Internal rate of return	%	36%	
<i>Key non energy factors</i>			
Productivity benefits		Somewhat	May be lower cost than existing processes
Product quality benefits		None	
Environmental benefits		Compelling	Reduced landfilling
Other benefits			
Current promotional activity	H,M,L	Medium	
<i>Evaluation</i>			
Major market barriers		Technical	Need to further develop and demonstrate technology
Likelihood of success	H,M,L	High	Still significant support for the technology. High activity in Europe as well.
Recommended next steps			U.S. demonstration, regulatory changes
Data quality assessment	E,G,F,P	Fair	
<i>Sources:</i>			
2015 basecase			Salyp, 2000; DeGaspari, 1999
Basecase energy use			Worrell et al., 1994
New measure energy savings			Kobler, 2000
Lifetime			Author estimate
Feasible applications			Author estimate
Costs			Daniels, 2000; Kobler, 2000
Key non energy factors			DeGaspari, 1999
Principal contacts			Recovery Plastics Int'l (801-973-4774); Ed Daniels, ANL (630-252-2000)
Additional notes and sources			

Aside from energy savings, the environmental implications of recycling technologies are significant. Roughly 25 percent of the weight of the vehicle is currently landfilled, which includes plastics, foam,

copper, trace metals, rubber, and fluff. ASR recycling is estimated to divert at least 40 percent of this currently landfilled materials (Kobler 2000).

Installation cost estimates for plastics separations technologies vary in range from \$100-350/ton (\$110-390/t) recovered material based on annual recovery capacity (Daniels 2000, Kobler 2000). Operations costs are claimed to be competitive or lower than existing virgin plastics and estimates have been given of 15-20 cents/pound for the RPI process and 50-75 cents/pound for the ANL process (Daniels 2000, Kobler 2000). The relative payback will also depend on the market price for the various recovered materials, assuming they meet market specifications. Ranges for the virgin prices for various polymers are shown in the table below (Kobler 2000).

<b>Material</b>	<b>Market price (¢/lb.)</b>
Polypropylene (PP)	32-40
PP Filled	40-50
ABS	55-70
PUR foam	30-35
PC	60-85
Nylon	80-98

These processes are both pre-commercial. Paybacks are estimated to be 2 years or less on new plant investment although the technology has not been fully deployed (Kober 2000, USCAR 2000, Daniels 2000)

These recovery technologies are pre-commercial. MBA polymers began commercial operations 1999 and processes several million pounds of recovered plastics per month of computer housings (MBA Polymers 2000). The company claims to have an operational commercial separations process applicable for ASR at its Richmond (CA) facility (Biddle 2000). An ANL froth flotation system was demonstrated in the U.S. at the Appliance Recycling Centers of America in Minneapolis, Minnesota, but no permanent demonstration facility has been constructed (USCAR 2000). In 1999, Argonne signed a licensing agreement with N.V. Salyp, a recycler in Belgium, to incorporate the foam cleaning system into demonstration facilities, but it is not clear whether Salyp will also incorporate the plastics recycling component of the system into their manufacturing process (DeGaspar, 1999, Fisher 2000). Also, skepticism has been raised on the efficacy of the froth flotation technology as compared to other technologies in producing a high quality product (Schedler 2000). RPI may have the most market ready system as they have been operating a 1-ton/hour demonstration plant in Utah since 1998. RPI claims that it is within a year or two of commercialization (Kobler 2000, USCAR 1998).

Aside from technical and economic feasibility, the full commercialization of this technology is dependent on changes in U.S. environmental regulations. Existing regulations promulgated in 1976 under the Toxic Substances Control Act are unclear but apparently do not allow the reintroduction of any product containing more than 2 parts per million of toxic polychlorinated Biphenyls (PCBs) (Kobler 2000, USCAR 2000, EPA 2000a)<sup>17</sup>. Shredder residue on average has concentrations of 10-30 ppm PCBs, however this residue is primarily on the *surface* of the plastics and generally not embedded in the plastic material itself (Kobler 2000). ASR technologies that wash the plastic surfaces are able to remove the PCBs and produce products below the 2 ppm PCBs level. Clarification in the regulations to account for this will help to stimulate the ASR plastics recovery market (Kobler 2000). R&D support by the VRP was curtailed because of this issue but there is optimism that this will be remedied soon and the EPA is looking into modification possibilities (Yester 2000, Fisher 2000).

Other key issues in the development of large-scale recovery facilities include ensuring access to a consistent source and volume of ASR streams so that recovered plastics customers such as auto manufacturers can be ensured of continued uninterrupted supply. Were this technology successful, it could significantly affect the plastics supply market for automobiles and other applications requiring higher-end plastics. We believe that there is a high likelihood of the potential for a growing domestic market over the near term assuming the resolution of the regulatory issues.

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<sup>17</sup> The original legislation states that “no person may manufacture, process, or distribute in commerce or use any polychlorinated biphenyl in any manner other than in a totally enclosed manner” (i.e. any manner that would expose human beings to PCBs) (EPA 2000).

## Biodesulfurization of Gasoline (Refining-1)

As the overall sulfur content of gasoline has increased over the past few years, gasoline manufacturers have had to find better and more efficient ways of desulfurizing their supplies. The average sulfur content of gasoline in the U.S. gasoline pool is about 300 ppm. In California, standards instituted in 1996 require gasoline that has a sulfur content of 30 ppm. Technologies that can consistently and economically deliver fuel with no more than 50 ppm sulfur will be required when EPA Tier II air regulations take full effect in 2003. Biodesulfurization, the process in which live microorganisms selectively remove sulfur from fuel, promises to deliver low-sulfur gasoline economically and with fewer environmental emissions.

Currently, the Merox process is the primary technology employed for the removal of sulfur in gasoline. In this process, gasoline and a small quantity of air are processed over a heterogeneous catalyst at high temperatures and pressures. The gasoline then comes in contact with a caustic solution to remove sulfur. The caustic solution is then contacted with air and a catalyst, thereby converting the extracted compounds to disulfides.

The advantage of oxidative biodesulfurization processes is that the reaction takes place at ambient temperatures and pressures and produces non-toxic by-products, eliminating the need for collateral processing of hydrogen sulfide. Biocatalysis is more selective than the Merox process and has the ability to target individual groups of sulfur which contain species such as mercaptans, alkylmercaptans, and polysulfides. The biocatalytic process may be designed as a batch process in which the reactants and biocatalyst are maintained in a reaction vessel for a period of time. Alternatively, the bioprocess can be designed as a continuous flow process in which the reactants are only brought into contact with the biocatalyst for a limited period of time.

The initial capital investment for a biodesulfurization unit will be around \$18 million for a 25,000 barrel per day facility in 2015 (OIT 1999). This is a significant improvement over the estimated \$36 million for a standard desulfurization facility. The yearly operating and maintenance costs run a bit higher for a biodesulfurization unit – about an additional \$620,000 annually. The unit saves enough energy to deflect this cost and result in a payback of just under two years.

Once EPA Tier II regulations come into effect, virtually all gasoline produced for domestic use will require desulfurization. Gasoline production in 2015 is estimated to be 11.73 million barrels per year, according to the Annual Energy Outlook 2000. Biodesulfurization is estimated to use 10-15 percent less energy than the Merox process. The decrease in energy use is attributable to the lower temperature and pressure of the bioprocess as well as the reduced need for separation of subsequent streams.

The biotechnology is still in the bench-scale test state. A market-ready product can be expected in 2005. Future developments for this technology include: elucidation of the desulfurization pathway including the isolation, identification, and quantification of the pathway intermediates; enhancement of solvent tolerance of the catalyst; definition of the basis for the required genetic improvements of the organisms; and determination of the rate and extent of gasoline desulfurization.

Most refineries and gasoline processing facilities operate continuous reactions. It is relatively easy to maintain and operate a batch bioreactor, but it requires significant startup time to initiate the microbial activity and allow products to accumulate. Future research is needed to develop continuous flow reactions since these processes are more prone to contamination with undesired microorganisms, making quality control difficult to maintain.

## Biodesulfurization Data table

	Units	Notes	
Biodesulfurization of Gasoline			
Refin-1			
Replace hydrodesulfurization			
Market Information:			
Industries		Refining	SIC 2911
End-use(s)		Process heating, other	http://www.oit.doe.gov/factsheets/petroleum/pdf/gasbiopet.pdf
Energy types		Electricity	DOE-OIT 1998a
Market segment		New, replace on failure	
2015 basecase	million barrels	4,281	2% annual growth -personal communication w/ J. Decicco 2000
Reference technology			
Description	Hydrodesulfurization of the feed to the fluid catalytic cracking unit (Merox Process)		
Throughput or annual operating hours	barrels	1.0	
Electricity use	kWh	11.14	DOE-OIT 1998a
Fuel use	MBtu	0	DOE-OIT 1998a
Primary Energy use	MBtu	0.09	DOE-OIT 1998a
New Measure Information:			
Description	Biocatalytic removal of sulfur from gasoline		
Electricity use	kWh	9.99	Assumed 10% savings over conventional technology http://www.oit.doe.gov/factsheets/petroleum/pdf/gasbiopet.pdf
Fuel use	MBtu	0	
Primary Energy use	MBtu	0.09	
Current status		Bench scale trials	http://www.oit.doe.gov/factsheets/petroleum/pdf/gasbiopet.pdf
Date of commercialization		2005	
Estimated average measure lifetime	Years	15	
Savings Information:			
Electricity savings	kWh/%	1.15	10%
Fuel savings	MBtu/%	0	0%
Primary energy savings	MBtu/%	0.01	10%
Penetration rate		Medium	
Feasible applications	%	45%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	2210	
Fuel savings potential in 2015	Tbtu	0	
Primary energy savings potential in 2015	Tbtu	18.85	
Cost Effectiveness			
Investment cost	\$	-131506	ANL 1998 Based on 25,000 bbl/day facility 18M for biodesulf vs. 36M for hydro
Type of cost			
Change in annual costs (O&M/other benefits)	\$	72118	O&M costs are higher for biodesulfurization units
Cost of conserved energy (electricity)	\$/kWh	43268	
Cost of conserved energy (fuel)	\$/Mbtu		
Cost of conserved energy (primary energy)	\$/Mbtu	5072392.48	
Simple payback period	Years	1.823	
Internal rate of return	%	55%	
Key non energy factors			
Productivity benefits			
Product quality benefits		Significant	Biodesulfurization does not reduce octane the way hydrodesulfurization does
Environmental benefits		None	
Other benefits			
Current promotional activity	H,M,L	Medium	
Evaluation			
Major market barriers		Capital and equipment intensive	
Likelihood of success	H,M,L	High	
Recommended next steps		Research, scale-up	Improve biocatalyst stability, faster kinetics, broader substrate specificity
Data quality assessment	E,G,F,P	Excellent	
Sources:			
2015 basecase			EIA 1999
Basecase energy use			Personal communication with John Decicco 2000
New Measure energy savings			http://www.oit.doe.gov/factsheets/petroleum/pdf/gasbiopet.pdf
Lifetime			Argonne National Laboratory 1998
Feasible applications			EIA 1999
Costs			Argonne National Laboratory 1998
Key non energy factors			
Principal contacts			
Additional notes and sources			

## Fouling Minimization (Refining-2)

The petroleum refining industry is one of the largest energy consumers in the manufacturing sector. Primary energy consumption in 1994 was 3,300 TBtu (3,500 PJ), or 16 percent of total manufacturing energy consumption. Modern refineries are complex integrated systems that transform crude oil into transport fuels, residual fuel oil, and other products. The energy required for processing a unit of crude oil input in a complex refinery is roughly equal to about 10 percent of the energy content of the input crude, although this can vary (WEC 1995). The main processes in refining involve crude distillation (the separation of crude oil into various distillate products through pyroprocessing and fractionation), conversion (the addition of hydrogen into hydrocarbon chains to produce higher quality products), reforming (the “reorganization” of hydrocarbon molecules to increase the octane) and finishing or treating processes (removal of sulfur and other impurities) (WEC 1995). Crude distillation alone consumes about 4-5 percent of the energy content of the oil (Worrell 1994).

In a complex refinery most processes occur under high temperature and pressure conditions; the management and optimization of heat transfer among processes is therefore key to increasing overall energy efficiency. Fouling, a deposit buildup in units and piping which impede heat transfer, require the combustion of additional fuel. For example, the processing of many heavy crude oils in the U.S. increases the likelihood of localized coking deposits in the heating furnaces, thereby reducing furnace efficiency and creating potential equipment failure. An estimate by the Office of Industrial Technology at the U.S. Department of Energy noted that the cost penalty for fouling could be as much as \$2 billion annually in material and energy costs (OIT 1999).

Several methods of investigation have been underway to attempt to reduce fouling including the use of sensors to detect early fouling, physical and chemical methods to create high temperature coatings (without equipment modification), the use of ultrasound, as well as the improved long term design and operation of facilities. The U.S. Department of Energy initially funded preliminary research into this area, but funding has been discontinued (Huangfu 2000, Bott 2000).

Initial analysis on fouling effects of a 100,000 bbl/day crude distillation unit found an additional heating load of 12.3 kBtu/barrel (13.0 MJ/barrel) processes (Panchal and Huangfu 2000). Reducing this additional heating load could result in significant energy savings.

This technology is still in the conceptual and basic research stage and therefore it is difficult to assess capital costs at this time. Argonne National Laboratory (ANL) has been the lead in working with the refining industry in the area. Progress so far has included: a basic understanding of fouling mechanisms developed (for example, the presence of iron sulfide in crude oil and its link to fouling), the development of a threshold fouling model by ANL, the testing of prototype fouling detection units, the development of a Heat Exchanger Design Handbook (1999 Edition) incorporated ANL’s petroleum fouling threshold model, and the preparation of a guideline document on Heat Exchanger Fouling in the Crude Oil Distillation Unit (Panchal 2000).

It is likely that a well-designed heat exchange network would have fewer cleaning requirements, thereby saving in operations and maintenance costs. Also, were this technology to be more fully developed, it would have a potentially large market, given the size of the U.S. refining sector.

While the issue of fouling is now on the radar screen of plant managers (there is a bi-annual Fouling Mitigation conference held by Argonne and the American Institute for Chemical Engineers), a stronger commitment by the refining industry would be needed to advance this technology to the next stage of development. Some sources believe that the future development of in this area is expected to be in the area of Condition-Based Maintenance of Heat-Transfer Equipment that will be based on Knowledge-Based and Monitoring -Based Mitigation of Fouling/Corrosion (Panchal 2000).



## Fouling Minimization Data Table

	Units	Notes	
<b>Fouling Minimization</b>			
<b>refin-2</b>			
<b>Improve heat exchanger operations</b>			
<i>Market Information:</i>			
Industries		Refining	SIC 2911
End-use(s)		Process heating, other	
Energy types		Fuels	DOE-OIT 1998a
Market segment		New, replace on failure	
2015 basecase	mill. bbl/day	8712.6	EIA 1999
<i>Reference technology</i>			
Description	Domestic refining		
Throughput or annual operating hours	bbl	1.0	
Electricity use	kWh	5.17	
Fuel use	MBtu	0.47	EIA 1995b (Petroleum Supply Annual); EIA 1997
Primary Energy use	MBtu	0.5	
<i>New Measure Information:</i>			
Description	Fouling minimization practices		
Electricity use	kWh	5.17	
Fuel use	MBtu	0.40	Potential for reduction in 30% of heating energy use
Primary Energy use	MBtu	0.4	
Current status		Bench scale trials	
Date of commercialization		2005	
Estimated average measure lifetime	Years	15	
<i>Savings Information:</i>			
Electricity savings	kWh/%	0.00	0%
Fuel savings	MBtu/%	0.07	15%
Primary energy savings	MBtu/%	0.07	14%
Penetration rate		Low	
Feasible applications	%	20%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	0	
Fuel savings potential in 2015	TBtu	123	
Primary energy savings potential in 2015	TBtu	123	
<i>Cost Effectiveness</i>			
Investment cost	\$	N/A	Not currently available
Type of cost			
Change in annual costs (O&M/other benefits)	\$	N/A	Not currently available
Cost of conserved energy (electricity)	\$/kWh	NA	
Cost of conserved energy (fuel)	\$/Mbtu	NA	
Cost of conserved energy (primary energy)	\$/Mbtu	NA	
Simple payback period	Years	N/A	
Internal rate of return	%	N/A	
<i>Key non energy factors</i>			
Productivity benefits		Significant	Reduce downtime
Product quality benefits		None	
Environmental benefits		None	
Other benefits			
Current promotional activity	H,M,L	Low	
<i>Evaluation</i>			
Major market barriers		Technical	Need for further R&D
Likelihood of success	H,M,L	Low	
Recommended next steps			
Data quality assessment	E,G,F,P	Fair	
<i>Sources:</i>			
2015 basecase			EIA 1999
Basecase energy use			EIA 1997
New Measure energy savings			Panchal and Huangfu, 2000
Lifetime			
Feasible applications			
Costs			
Key non energy factors			
Principal contacts			Ehr-ping Huangfu, U.S. Dept. of Energy (202-586-5000)
Additional notes and sources			

## Roller Kiln (Ceramics-1)

Roller kilns can be used in the manufacture of structural clay products and ceramics. Structural clay products are mainly building bricks, roof tiles and sewer pipes. In the U.S. approximately 15.1 million short tons (13.6 Mt) of clay are consumed for the production of these products (Virta 1998). Of this, 98 percent is used for making bricks. In 1998 8.26 billion bricks were produced with a value of \$1.5 billion. Bricks are manufactured in most states, but production is concentrated in Alabama, North Carolina, Texas, Georgia, Ohio, South Carolina, Missouri, Arkansas, California, and Pennsylvania. Ceramic production in the U.S. is concentrated mainly in the production of tiles (42 percent) and sanitary ware (18 percent). Tile production in 1997 is estimated at 154 million m<sup>2</sup> (Virta 1998). Total clay consumption for ceramic production was 1.84 million short tons (1.67 Mt) in 1997 (Virta 1998).

No statistical information is available on energy use for production of ceramics and structural clay products. A recent survey of ceramic industry kilns showed that energy use for tunnel kilns varied between 2.52 and 3.82 MBtu/short ton brick (2.93-4.44 GJ/t) (Whittemore 1999). Intermittent kilns used between 2.91 and 8.46 MBtu/ton (3.38-10.4 GJ/t) (Whittemore 1999). We assume a predominant use of tunnel kilns with an average specific fuel consumption of 3.6 MBtu/ton (4.2 GJ/t). Based on the production volumes and clay consumption we estimate fuel use for baking at 46 TBtu (49 PJ) for bricks and 14 TBtu (15 PJ) for ceramic products, or a total fuel consumption of 60 TBtu (63 PJ). Average specific fuel consumption for both industries is estimated at 4.5 MBtu/ton dry product (5.2 GJ/ton dry product). Natural gas is probably the main fuel used, although there are kilns that use other fuels (e.g. oil, and even wood chips for example at a plant in Mississippi), while sawdust is added to the bricks and partially combusted in the baking process.

Bricks, tiles and other ceramics are baked from clay. The clay is formed, dried and then baked. Previously flame and ring-kilns were used with long production cycles (up to 14 days). Today, the most common process is the tunnel kiln. Tunnel kilns have a relatively short production cycle of 75-140 hours. The firing process in the tunnel kiln is automated, and consists of three zones through which the bricks travel: preheating, baking and cooling.

A new technology is the rapid firing technology for bricks and tiles, called the roller kiln. In the rapid firing process the clay is prepared dry with appropriate additives to maintain the forming and baking characteristics required. The amount of water is thus reduced to 6-8 percent (compared to 18-20 percent in the current process). The fired products are transported on refractory rollers, rather than on lorries. A roller kiln makes it possible to reduce the heating time (to approximately 8-9 hours (Tomasseti 1995) and use shorter firing curves). The flue gas volumes in the roller kilns are lower, compared to the tunnel kiln, reducing the heat losses (Elmi 1993). This reduces not only the heat demand, but also the power consumption for air circulation. Roller kilns are the state-of-the-art for the production of sanitary ware and wall and floor-tiles. They can be found in modern facilities across the world, and also in the U.S. (e.g. in Ohio and Texas). They are not yet used in the production of bricks in the U.S.

In The Netherlands a roller kiln was demonstrated for sanitary ware (CADDET 1993c). The kiln reduced energy consumption by 60 percent relative to the previously used tunnel kiln and reduced the specific energy consumption to 4.2 MBtu/ton product (3.8 GJ/t) (CADDET 1993c), compared to 9.3 MBtu/ton (10.8 GJ/t) (LHV). The performance can be even further improved by heat recovery from the flue gases. The technology is under investigation for more massive products like tiles and bricks. In Italy a new plant produces 50,000 lightened and specially shaped bricks per day using the rapid firing technology. In 1996, two roller kilns for bricks were in operation in Europe (Italy and Germany) while two were under construction in Indonesia and Mexico. The plant in Italy was designed to consume 1.2 MBtu/ton (1.4 GJ/t) (LHV) (Tomasseti 1995). Initially it consumed 1.4 MBtu/ton (1.6 GJ/t) (LHV) (Tomasseti 1995). We estimate average energy consumption for a future roller kiln in the U.S. at 1.85 MBtu/ton dry product (2.15 GJ/t) (HHV, using the 1997 production volume structure).

To shorten the firing time in the kiln the heat distribution needs to be optimal, and the temperature needs to be distributed evenly through all material travelling through the kiln. The first roller kilns have a single

## Roller Kiln Data Table

	Units	Notes	
Roller Kiln			
Ceramics-1			
Energy-efficient roller kiln replacing tunnel kiln			
Market Information:			
Industries		Clay Products	SIC 325, 326
End-use(s)		Process Heating	
Energy types		Natural Gas	
Market segment		New	
2015 basecase use	Mt	14.6	Estimated 1994 energy use 71 Tbtu: 60 Tbtu fuel, 11 Tbtu electric, slow growth expected
Reference technology			
Description	Tunnel Kiln		
Throughput or annual op. hrs.		100,000 tpy	
Electricity use	kWh	0	
Fuel use	MBtu	4.5	
Primary energy use	MBtu	4.5	
New Measure Information:			
Description	Roller Kiln		
Electricity use	kWh	0	
Fuel use	MBtu	1.9	
Primary Energy use	MBtu	1.9	
Current status		Commercial	Commercial for ceramics, first uses for small-capacity brick kilns
Date of commercialization		1993	
Est. avg. measure life	Years	30	
Savings Information:			
Electricity savings	kWh/%	0	0%
Fuel savings	MBtu/%	2.7	59%
Primary energy savings	MBtu/%	2.7	59%
Penetration rate		Medium	Competition of improved tunnel kilns
Feasible applications	%	15%	Half of kiln turnover will use roller kiln technology
Other key assumptions			
Elec svgs potential in 2015	GWh	0	
Fuel svgs potential in 2015	Tbtu	6	
Primary energy svgs potential in 2015	Tbtu	5.8	
Cost Effectiveness			
Investment cost	\$	10	Estimated investment costs are 10\$/ton annual capacity over a tunnel kiln
Type of cost		incremental	Incremental costs over that of a tunnel kiln
Change in other costs	\$	0	
Cost of saved energy (elec)	\$/kWh	N/A	
Cost of saved energy (fuel)	\$/Mbtu	0.57	
Cost of saved energy (primary)	\$/Mbtu	0.57	
Simple payback period	Years	1.9	
Internal rate of return	%	N/A	
Key non energy factors			
Productivity benefits		None	
Product quality benefits		Somewhat	
Environmental benefits		Significant	Reduced NOx emissions
Other benefits			
Current promotional activity	H,M,L	Low	
Evaluation			
Major market barriers		Demonstration for bricks	Slow stock turnover of kilns
Likelihood of success	H,M,L	Medium	
Recommended next steps		Demonstration for bricks	
Data quality assessment	E,G,F,P	Fair	
Sources:			
2015 basecase			Virta 1998: production equal to 1997
Basecase energy use			Author's estimate on basis of Whittemore (1999)
New measure energy savings			Tomassetti 1995; CADDET 1993c
Lifetime			Author's estimate
Feasible applications			Tomassetti 1995; Elmi 1993
Costs			Tomassetti 1995; CADDET 1993c
Key non energy factors			Author's estimate
Principal contacts			
Additional notes and sources			

layer of products, while new designs have a double layer. This is well suited for ceramic products. However, it is less suited for the larger capacity brick kilns. Developers like the Italian firm Mori (the main developer of the rollerkiln for ceramics) are trying to develop multi-layer kilns. Other suppliers of roller kilns are SACMI (an Italian firm with a U.S. subsidiary), Lex Kiln (CA), and Keller (Germany).

Investment costs for a tunnel kiln with a capacity of 110,000 tons/year (100,000 t/year) were estimated at \$2.1 million (Tomassetti 1995), equivalent to approximately \$19/ton-capacity (\$21/t-capacity). Tomassetti (1995) expects roller kilns to be less expensive than a tunnel kiln. Kilns for sanitary ware have a lower capacity and higher typical investment costs. The roller kiln for ceramics as described in the demonstration project in The Netherlands had higher investment costs of \$38/ton-capacity (\$41/t), with a payback period of 2 to 2.5 years with Dutch gas prices of \$3.00/MBtu (\$2.80/GJ) (CADDET 1993c). The 1994 natural gas price for the stone, clay and glass industries in the U.S. was \$2.83/MBtu (\$2.68/GJ), which would give an average U.S. payback period of 2.7 years. For this study we will assume that the investments of a roller kiln are equal to that of a tunnel kiln, both for bricks and other ceramic products. The maintenance costs are lower or equal compared to that of a conventional tunnel kiln.

Roller kilns will likely be implemented when the conventional tunnel kilns need to be replaced, or when expanding capacity at an existing facility. Competing technologies will be more efficient tunnel kilns as developed in Europe and the U.S., or retrofitting existing facilities with improved insulation with low thermal mass materials (LTM), LTM-carts, and improved heat recovery. The DOE NICE3-program sponsors the demonstration of a new kiln with LTM-insulation in Southern California, reducing energy use by half and reducing NO<sub>x</sub> emissions by 40 percent.

R&D is needed to develop materials that can hold the heavy weight of tiles and bricks while withstanding the stresses of rapid heating and cooling. R&D is also directed at the construction of a kiln with a good air circulation and at ensuring good brick quality. The applicability of the technology for different types of bricks should be demonstrated, before implementation is feasible (Elmi 1993).

## **100 Percent Cullet Use & Cullet Preheating in Container Glass Manufacture (Glass-1)**

The glass industry is a capital- and energy-intensive industry and serves four distinct markets: glass containers, fiberglass for insulation and structural applications, flat glass for windows, and specialty glass such as tableware, light bulbs, television tubes, and fiber optics. The industry had shipments of about \$27 billion, and spent over \$1.9 billion on new capital equipment in 1997. The industry spent about \$1.4 billion on fuels and energy, representing over 5 percent of its value of shipments in 1997. The glass industry includes major corporations but also small businesses and is spread across the nation, concentrated in Ohio, Pennsylvania, California, North Carolina, Texas, Indiana, Michigan, New Jersey, New York, and Wisconsin. In 1997, the glass industry produced approximately 21 million tons (19 Mt) of glass products and used 2.25 million tons (2.04 Mt) of recycled glass, which are known as cullets. The glass industry used in excess of 250 TBtu (260 PJ) annually (EIA 1996). Nearly 80 percent of this energy is supplied by natural gas for the glass melting, with electricity accounting for the majority of the remaining energy used (EIA 1996).

We focus on the production of container glass. In the U.S., the glass industry produces approximately 10.3 million tons (9.4 Mt) of glass containers annually and more than 650,000 tons (590,000 t) are also imported (GPI, 2000). Approximately 35 percent (or 3.8 million tons (3.4 Mt)) of all glass containers available to consumers are recycled, of which 2.25 million tons (2.04 Mt) are recycled into glass containers. The other recovered glass containers may be used for secondary recycling, e.g. abrasives, asphalt. The production of container glass in the U.S. consumed 66 TBtu (70 PJ) natural gas, 2 TBtu (2 PJ) oil and 4.3 TWh in 1994 (EIA 1997). This is approximately 114 TBtu (120 PJ) on a primary energy basis. The average specific fuel consumption based on the MECS data is estimated to be 6.6 MBtu/ton (7.7 GJ/t), of which an estimated 5.8 MBtu/ton (6.7 GJ/t) is used in the smelting furnace. Energy use for container glass furnaces could be somewhat lower, although wide variations in energy intensity exist.

Although glass containers already contain on average over 20 percent cullets in the U.S., higher use of cullets is possible. In Europe container glass manufacturers sometimes use 80 percent cullets, while the first furnaces using 100 percent cullets are now being introduced. Increasing cullet use by 10 percent will reduce fuel use by approximately 2.5 percent (Enneking 1994). Increasing cullet use to 100 percent will allow larger energy savings as the temperature can be lowered below the typical melt temperature of 1550°C, since the sand does not need to be melted. We assume energy savings of 19 percent on fuel for glass melting, or equivalent to 1.13 MBtu/ton (1.31 GJ/t) glass for furnaces switching to 100 percent cullet use. Energy is also saved in the production of soda ash, which constitutes approximately 20 percent of the raw material feed. We assume that 0.15 ton of soda ash is used per ton of container glass in the U.S. Increasing cullet use to 100 percent will save energy use for soda ash manufacture with 1.3 MBtu/ton glass (1.5 GJ/t) (assuming 8.8 MBtu/ton soda ash (10.2 GJ/t)) (Enneking 1994). However, increased use of cullets will lead to increased processing of recovered glass, as the quality of the cullets becomes more important to maintain product quality. We assume 0.17 MBtu/ton (0.20 GJ/t) (Enneking 1994) for glass separation and cleaning, consuming approximately 0.13 MBtu/ton glass (0.15 GJ/t). Net energy savings at the glass plants are estimated at 1.0 MBtu/ton (1.2 GJ/t), and indirect energy savings at 1.3 MBtu/ton glass (1.5 GJ/t).

Energy efficiency can be further improved by batch cullet preheating. Especially in oxy-fuel-fired furnaces preheating is an efficient way to recover the heat contained in the flue gases. Currently, the fluegases can be used to generate steam. Cullet preheaters have been under development since the 1980s. Commercial applications can be found in a few kilns around the world (e.g. in Germany, The Netherlands). Cullet preheating development projects are ongoing in the United States (supported by DOE, NYSERDA) and Europe. In the cullet preheater the cullets are preheated to a temperature of 570 – 1000°F (300-540°C) in direct contact with the flue gases (OIT 1999, Lubitz 1999). Preheating reduces energy use in the furnace, reduces oxygen use, and improve productivity of the furnace by reducing melting time and increasing furnace longevity (OIT 1999). For a cullet load of 90 percent the fuel savings are estimated at 0.40 MBtu/ton, HHV (0.42 GJ/t, LHV) (Lubitz 1999). Higher preheating temperatures may lead to fuel savings of 0.5 MBtu/ton glass (0.6 GJ/t) (OIT 1999).

## Glass Cullet Pre-Heating Data Table

	Units	Notes	
100% Recycled Cullet Feed and Cullet Preheating			
Glass-1			
Use of 100% recycled cullet feed into glass melting furnace, combined with cullet preheating in an oxy-fuel furnace			
Market Information:			
Industries		Glass Containers	SIC 3221
End-use(s)		Process heating	
Energy types		Natural Gas, Oil	
Market segment		New, Retrofit	
2015 basecase use	Mtons	12.3	Based on 1997 container glass production and AEO2000 forecast
Reference technology			
Description	Average Glass Melting Furnace		
Throughput or annual op. hrs.	ton/yr	95500	250 metric tonnes per day
Electricity use	kWh	39	
Fuel use	MBtu	5.8	
Primary energy use	MBtu	6.1	
New Measure Information:			
Description	Use of 100% recycled cullet feed into glass melting furnace, combined with cullet preheating in an oxy-fuel furnace		
Electricity use	kWh	39	
Fuel use	MBtu	4.4	
Primary Energy use	MBtu	4.7	
Current status		Demonstration	
Date of commercialization		2000	
Est. avg. measure life	Years	25	
Savings Information:			
Electricity savings	kWh/%	0	0%
Fuel savings	MBtu/%	1.4	24%
Primary energy savings	MBtu/%	1.4	23%
Penetration rate		Medium	
Feasible applications	%	25%	
Other key assumptions			
Elec svgs potential in 2015	GWh	0	
Fuel svgs potential in 2015	Tbtu	4	
Primary energy svgs potential in 2015	Tbtu	4.3	
Cost Effectiveness			
Investment cost	\$	10	New furnace would have lower capital cost than conventional furnace
Type of cost		Full cost	Assuming retrofit
Change in other costs	\$	-2	
Cost of saved energy (elec)	\$/kWh	N/A	
Cost of saved energy (fuel)	\$/Mbtu	-0.33	
Cost of saved energy (primary)	\$/Mbtu	-0.33	Discount rate for all CCE calculations is 15%
Simple payback period	Years	2.0	
Internal rate of return	%	49%	
Key non energy factors			
Productivity benefits		Marginal	
Product quality benefits			Depends on cullet quality
Environmental benefits		Significant	
Other benefits			
Current promotional activity	H,M,L	Medium	
Evaluation			
Major market barriers		Cullet quality, lifetime	
Likelihood of success	H,M,L	High	
Recommended next steps		Full scale demonstration	
Data quality assessment	E,G,F,P	Good	Feasible applications: Fair
Sources:			
2015 basecase			EIA, 1999
Basecase energy use			EIA, 1997
New measure energy savings			Enneking, 1994; Pieper et al., 1995
Lifetime			Pieper et al., 1995
Feasible applications			
Costs			Pieper et al., 1995
Key non energy factors			Enneking, 1994; Lubitz, 1999; Portner, 1999
Principal contacts			
Additional notes and sources			

Due to increased productivity, a furnace with cullet preheating can be smaller than a furnace without preheating. This leads to reduced capital costs. The typical investment costs for a furnace without preheating are estimated at \$55 million and with cullet preheating at \$51 million for a furnace capacity of 276 tons/day (250 tonnes/day) (Pieper et al. 1995). Hence, the replacement costs would be \$40/annual ton (\$44/annual tonne) lower than a conventional furnace. It is also possible to add a cullet preheater to an existing furnace, as was done at PLM Glasindustrie, Dongen, The Netherlands. The specific costs for this project were \$9.9/ton (\$10.9/t) (Dfl2.45 Million for a 320 tonnes/day furnace, 1996) (CADDET 1997d). The change in operating costs depends on the oxygen costs. At oxygen costs of 8.5cts/Nm<sup>3</sup>, the cullet preheater would reduce operating costs by approximately \$4/ton (based on German conditions, 1995) (Pieper et al. 1995). We will assume production cost savings of \$2/ton. Campaign life (i.e. the period that the furnace is used continuously, before being rebuilt) of a furnace is about 10-12 years, while the total operating lifetime is approximately 21-25 years (Pieper et al. 1995).

The reduced fuel use and lower flame temperature will lead to reduced  $\text{NO}_x$  emissions, while  $\text{SO}_x$  emissions can be reduced if the sodium sulfate content of the raw material is reduced. In a German oxyfuel-furnace with cullet preheating the  $\text{NO}_x$  emissions were reduced to 0.5 lb./ton glass (0.25 kg/tonne) (Lubitz 1999), or less than 500 mg/Nm<sup>3</sup>. Oxyfuel furnaces without preheating can achieve about 0.6-0.7 lb./ton glass (0.30-0.36 kg/tonne) (Portner 1999). Uncontrolled PM emissions may increase without sufficient emissions control equipment, as cullet preheating may increase the emissions (Enneking 1994). Hence, efficient gas cleanup is needed. Also, high preheating temperatures and long preheating times may lead to increased CO-emissions, due to combustion of organics in the cullet-mix (Enneking 1994), and dioxin emissions. At a furnace with preheating in Germany dioxin emissions of 0.04 ng/Nm<sup>3</sup> were measured (ng = 10<sup>-9</sup>) (Lubitz 1999).

The main barrier is quality control of the cullets, e.g. sorting and removal of inert contamination. To reduce CO emissions from the preheater, organic matter should be removed as much as possible from cullets. Based on glass collection schemes in Europe we estimate that approximately 60 percent of waste glass can be recovered, and that 60 percent of that can be used for glass manufacture, estimated at 4.8 Million tons by 2015. Hence, we estimate the maximum penetration of this technology at 25 percent of the 2015 container glass production. At an average lifetime of 25 years for a glass furnace 60 percent of the current furnace capacity will be replaced by 2015. If all retired furnaces would be replaced by new pre-heating, oxy-fuel furnaces the energy savings would be higher. We have not accounted for this in the estimated savings. Savings could be an additional 17 TBtu (18 PJ) due to installing pre-heating furnaces.

Future needs consist of two parts. Firstly, demonstration of the technology at commercial scale at a US plant. Secondly, the collection of waste glass has to become more effective (i.e. larger volume of waste glass recovered) and efficient (i.e. increased separation on color, and at low cost), so that more waste glass can be used by the container industry.

## Gas and Heat Recovery at Basic Oxygen Furnace (Steel-1)

The iron and steel industry is one of the largest industrial energy consumers. The U.S. iron and steel industry is made up of integrated steel mills that produce pig iron from raw materials (iron ore, coke) using a blast furnace and steel using a basic oxygen furnace (BOF) and electric arc furnace steel mills that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). In 1994, 2,180 TBtu (2,300 PJ) (about 11 percent of manufacturing primary energy use) was consumed in the production of about 100 Mton (91 Mt) of crude steel products (EIA 1997). Within steelmaking, the largest energy use is required to reduce iron ore in the integrated mills and to re-melt steel scrap in electric arc furnace mills (Worrell et al. 1999). Primary steel is produced using the basic oxygen furnace (BOF). In the BOF process liquid pig iron (hot metal), scrap and limestone are mixed. Oxygen is injected to reduce the carbon content of the hot metal from about 5 percent to less than 2 percent. Steel contains less than 2 percent carbon. At the same time some other impurities are reduced in the steel. The BOF process replaced the last open hearth furnace in the U.S. by 1992 due to its greater productivity and lower capital costs. Several configurations exist depending on the way the oxygen is injected. BOF crude steel production in 1994 was 61 million tons (55.3 million metric tons). The 2015 production is assumed to be 66.7 million tons (60.5 million metric tons) (AEO 1999).

Fuel and electricity consumption in the BOF is estimated at 18 TBtu (19 PJ) and 1.7 TWh, respectively in 1994. Energy intensity for this process step in 1994 was 0.30 MBtu/short ton fuel (0.3 GJ/t) and 27 kWh/short ton steel (30 kWh/t) (Worrell et al. 1999). In the U.S. no BOF gas seems to be recovered (Margolis 1996). According to the EPA, the BOF-process is an important source of CO emissions, emitting 617,000 tons in 1992, or equivalent to 21 lb./short ton liquid steel (Margolis 1996).

Carbon in the hot metal reacts to carbon monoxide (CO), which is emitted as BOF gas. The BOF gas has a heating value between 7.4 and 9.1 MJ/Nm<sup>3</sup> (mean value of 8.5 MJ/Nm<sup>3</sup>, LHV) (IISI 1998). By reducing the amount of air entering over the converter, the CO is not converted to CO<sub>2</sub>. The BOF gas can be recovered and used as fuel gas in the steel plant or for steam and power production. The hot off-gases must be cooled before gas cleanup, and the heat can be recovered by generating steam and hot water. BOF gas combined with sensible heat recovery (repressed combustion) is the single most energy-saving process improvement in this process step, making the BOF process a net energy producer. Repressed combustion is very common in integrated steel plants in Europe and Japan as an efficient means for energy recovery, emission control and dust recycling (IISI 1998). Repressed combustion reduces CO and dust emissions and, since the metal content of the dust is high, about 50 percent of the dust can be recycled in the sinter plant or in the steel plant (Stelco 1993, IISI 1998).

Two systems exist for gas cleanup. The dry system uses a dry cylindrical precipitator while the wet system uses a venturi scrubber and a wet precipitator. The wet system uses about 8 kWh/tonne (7.3 kWh/t) liquid steel, while the dry system uses only 2 kWh/tonne (1.8 kWh/t) liquid steel. The wet system also needs additional water and a water clarification system (IISI 1998). The dry system needs an additional pelletizing plant, but allows recycling of the dust in the steel plant rather than the sinter plant. In this analysis we assume a dry system, as many integrated plants have closed sinter plants for environmental reasons and it has lower investment costs.

The amount of gas recovered depends on the hot metal charge in the BOF as the main source of carbon. Assuming a hot metal charge of 1800 lb./ton liquid steel (900 kg/tonne liquid steel), approximately 2860 cu.ft. (or 81 Nm<sup>3</sup>) of BOF gas can be recovered, accounting for flaring and air leakage into the system (IISI 1998). This is equivalent to 607 kBtu/ton (706 MJ/t). Steam recovery can be up to 120 lb./ton of steel (60 kg/tonne) (IISI 1998). We assume steam recovery of approximately 100 lb./ton, equivalent to 130 kBtu/ton (150 MJ/t). The total fuel savings are equivalent to 737 kBtu/ton (857 MJ/t) with increased power consumption of 2 kWh/ton.

The costs will depend on the need for extra gas holders, as well as the size and layout of the BOF plants. We assume that installation is only feasible for large scale BOF plants with annual capacities of around 3 million tons/year (2.7 Mt). This is assumed to be 45 percent of the 2015 BOF capacity. Estimated capital costs are \$20/ton crude steel (\$22/t), based on plants in Japan (Inoue 1995) and The Netherlands (Worrell et al. 1993). There are additional O&M costs.



## Gas and Heat Recovery at Basic Oxygen Furnace Data Table

	Units	Notes	
<b>BOF gas and sensible heat recovery steel-1</b>			
<b>Recovery of BOF-Gas and Heat</b>			
<i>Market Information:</i>			
Industries		Iron and Steel	331
End-use(s)		Process Heating	Steelmaking Converter in Primary Steelmills
Energy types		Fuel, Steam	Recovery of BOF-gas and Steam
Market segment		Retrofit	
2015 basecase use	Mtons	66.7	
<i>Reference technology</i>			
Description	Basic Oxygen Furnace Plant with 2 or 3 converters		
Throughput or annual op. hrs.	ton steel	1	Capacity may vary between 1 and 5 Million tons/year
Electricity use	kWh	27	
Fuel use	MBtu	0.3	
Primary energy use	MBtu	0.5	
<i>New Measure Information:</i>			
Description	Repressed Combustion system with waste heat boiler and dry gas cleaning system		
Electricity use	kWh	29	
Fuel use	MBtu	-0.4	
Primary Energy use	MBtu	-0.2	
Current status		Commercial	
Date of commercialization		1980's	Technology common in Europe and Japan and in all new BOF-steel plants
Est. avg. measure life	Years	30	
<i>Savings Information:</i>			
Electricity savings	kWh/%	-2	-7%
Fuel savings	MBtu/%	0.7	246%
Primary energy savings	MBtu/%	0.7	136%
Penetration rate		Low	No plants recover BOF-gas in the U.S.
Feasible applications	%	23%	50% of Large Scale BOF-plants by 2015
Other key assumptions			
Elec svgs potential in 2015	GWh	-30	
Fuel svgs potential in 2015	Tbtu	11	
Primary energy svgs potential in 2015	Tbtu	10.8	
<i>Cost Effectiveness</i>			
Investment cost	\$	20	
Type of cost		Full cost	
Change in other costs	\$	0.1	
Cost of saved energy (elec)	\$/kWh	-1.57	
Cost of saved energy (fuel)	\$/Mbtu	4.27	
Cost of saved energy (primary)	\$/Mbtu	4.37	Discount rate for all CCE calculations is 15%
Simple payback period	Years	14.7	
Internal rate of return	%	3%	
<i>Key non energy factors</i>			
Productivity benefits		Small	Recovery of iron-containing dust and recycling in steel plant
Product quality benefits		None	
Environmental benefits		Significant	Reduced CO and PM emissions
Other benefits			
Current promotional activity	H,M,L	Low	
<i>Evaluation</i>			
Major market barriers		Capital Cost	
Likelihood of success	H,M,L	Low	Strict environmental regulation for PM and CO may make technology attractive
Recommended next steps			
Data quality assessment	E,G,F,P	Good	Cost data are assessed to be fair
<i>Sources:</i>			
2015 basecase			EIA, 1999
Basecase energy use			Worrell et al., 1999
New measure energy savings			IISI, 1998
Lifetime			
Feasible applications			Based on review steelmaking facilities
Costs			Worrell et al, 1993; Inoue, 1995
Key non energy factors			IISI, 1998; VAI
Principal contacts			Voest Apline Industries, Pittsburgh, PA
Additional notes and sources			

## Near Net Shape Casting/Strip Casting (Steel-2)

The iron and steel industry is one of the largest industrial energy consumers. The U.S. iron and steel industry is made up of integrated steel mills that produce pig iron from raw materials (iron ore, coke) using a blast furnace and steel using a basic oxygen furnace (BOF) and electric arc furnace steel mills that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). In 1994, 2,180 TBtu (2,300 PJ) (about 11 percent of manufacturing primary energy use) was consumed in the production of about 100 Mton (91 Mt) of crude steel products (EIA 1997). Currently, the casting and rolling process is a multi-step process. The liquid steel is first cast continuously into blooms, billets, or slabs. Liquid steel flows out of the ladle into the tundish (or holding tank), and then is fed into a water-cooled copper mold. Solidification begins in the mold, and continues through the caster. The strand is straightened, torch-cut, then discharged for intermediate storage (Kozak and Dzierzawski 2000). Most steel is reheated in reheating furnaces, and rolled into final shape in hot and cold rolling mills or finishing mills. A recent LBNL study estimated that casting and rolling consumed 332 TBtu (350 PJ) of primary energy in 1994 (Worrell et al. 1999). The reheating furnaces are usually gas and oil operated and consume roughly 2.8 MBtu/ton (3.3 GJ/t) of energy.

Near net shape casting is a new technology that integrates the casting and hot rolling of steel into one process step, thereby reducing the need to reheat the steel before rolling it.

As applied to flat products, instead of casting slabs in a thickness of 120-300 millimeters, strip is cast directly to a final thickness between 1 and 10 mm. (De Beer et al. 1998a, Opalka 1999, Worrell, Bode, and de Beer 1997). The steel is essentially cast and formed into its final shape without the reheating step. An intermediate technology, thin-slab casting casts slabs 30-60 mm thick and then reheats them (the slabs enter the furnace at higher temperatures than current technology thereby saving energy). This technology is already commercially applied in the U.S. and other countries.

The energy consumption of a thin strip caster is significantly less than the current process of continuous casting. For the intermediate thin slab casting process, energy consumption is 0.8 MBtu/ton (0.9 GJ/t) fuel and 39 kWh/ton (43 kWh/tonne) electricity (Fleming 1995). Near net shape casting is expected to consume even less energy. Based on average U.S. practices in 1994, we estimate a primary energy savings of 4.0 Mbtu/ton crude steel (4.7 GJ/t) based on the difference between energy consumed in the current process and energy consumed in near net shape casting (Worrell et al. 1999).

In the U.S., near net-shape casting has so far been applied to the production of near net beams. This technology was introduced by Nucor at their joint venture company Nucor-Yamato Steel Company in Blytheville, Arkansas and later applied at Nucor's plant in Berkeley County, South Carolina (Worrell et al. 1999, Wechsler 2000) and is also being used by Chaparral steel., all electric arc furnace producers (Worker 1998).

Currently, two German suppliers, SMS and Mannesmann-Demag, supply near net casters for flat products using the thin slab technology (Worrell, Bode, and de Beer 1997).

No strip caster for carbon steel products has yet been built and operated in full scale and production capacity. However, a demonstration strip caster for flat rolled carbon steel operated at full scale (though at reduced capacity due to molten steel constraints) from 1995 through 1999 in Australia, and the first commercial strip caster for flat rolled stainless steel products came on line in 1999 in Japan's Nippon Steel corporation casting line (Isenberg-O'Loughlin 1998, Opalka 1999). A flat rolled carbon steel caster has not yet been commercially applied for flat rolled products in the U.S but the successful Australian caster is now in the process of being relocated to Nucor's plant in Crawfordsville, Indiana. It is expected to begin first production in December 2001 (33Metalproducing.com 2000a, Wechsler 2000).

Based on a review of the 1999 casting roundup and other literature, we estimate that the current U.S. market share for near net shape products or thin strip products is less than 5 percent (Iron and Steelmaker 1999). However, there is a large effort to develop new potential applications and markets. More than 30 R&D projects have been undertaken on this technology (DeBeer 1999). Large research programs are

## Near Net Shape Casting Data Table

	Units		Notes
Near net shape casting/strip casting steel-2			
Replace current continuous casting with direct near net shape casting			
Market Information:			
Industries		Iron and Steel	SIC 331
End-use(s)		Process heating	
Energy types		Gas, electricity	
Market segment		New	Greenfields & refit of existing facilities. Some retrofit applications
2015 basecase use	Mtons	115.6	AEO 2000, continuous casting output
Reference technology			
Description	Continuous casting/hot rolling		
Throughput or annual op. hrs.	tons	1	Unit consumption presented. Casters range from 150 kton/y to 3,000 kton/y
Electricity use	kWh	206	Worrell et al., 1999
Fuel use	MBtu	2.8	Worrell et al., 1999
Primary energy use	MBtu	4.6	Worrell et al., 1999
New Measure Information:			
Description	Near net shape casting/thin strip casting		
Electricity use	kWh	30	Worrell et al., 1997, DeBeer, 1998a
Fuel use	MBtu	0.3	Worrell et al., 1997. DeBeer, 1998a estimates 0.0
Primary Energy use	MBtu	0.6	
Current status		Commercialized	Near net beams but not yet flat rolled products
Date of commercialization		1995	No flat rolled caster yet commercial
Est. avg. measure life	Years	20	Worrell et al., 1999
Savings Information:			
Electricity savings	kWh/%	176	90%
Fuel savings	MBtu/%	2.5	90%
Primary energy savings	MBtu/%	4.0	90%
Penetration rate		High	
Feasible applications	%	30%	Apply to non high end steel products, Worrell et al.,1999
Other key assumptions			
Elec svgs potential in 2015	GWh	6093	Savings applied to feasible applications for 2015 output
Fuel svgs potential in 2015	Tbtu	86	Savings applied to feasible applications for 2015 output
Primary energy svgs potential in 2015	Tbtu	138	6% savings.
Cost Effectiveness			
Investment cost	\$	-18	Assume 15% less than conventional casting systems. Full retrofit cost \$103
Type of cost		Incremental	
Change in other costs	\$	-40	Worrell et al. 1997
Cost of saved energy (elec)	\$/kWh	-0.24	
Cost of saved energy (fuel)	\$/Mbtu	-17.35	
Cost of saved energy (primary)	\$/Mbtu	-10.82	Discount rate for all CCE calculations is 15%
Simple payback period	Years	-0.4	Based on \$2/Mbtu average 1994 primary energy for steel
Internal rate of return	%	#DIV/0!	
Key non energy factors			
Productivity benefits		Significant	Reduced production time, reduced capital costs
Product quality benefits		Somewhat	Improved surface properties
Environmental benefits		Somewhat	Reduced emissions
Other benefits			
Current promotional activity	H,M,L	High	Conferences, marketing by suppliers, research consortiums
Evaluation			
Major market barriers		Technical challenges	Also, CSP flat rolling plants limited
Likelihood of success	H,M,L	High	
Recommended next steps		R&D	
Data quality assessment	E,G,F,P	Good	Significant literature; limited field data
Sources:			
2015 basecase			EIA, 1999
Basecase energy use			Worrell et al. 1999
New measure energy savings			Worrell et al., 1997
Lifetime			Worrell et al. 1999
Feasible applications			SMS, 1995; Tomasseti, 1995, Kuster, 1996
Costs			DeBeer, 1998a
Key non energy factors			Flemming, 1995; Tomasseti, 1995, Kuster, 1996, Worrell et al. 1999
Principal contacts			
Additional notes and sources			

ongoing, with the cooperation of European and Japanese steel companies (Worrell 1995, Opalka 1999). The U.S. Department of Energy has identified near net casting as one of its focus technologies in the steel Industries of the Future and is currently devoting its effort to evaluating strip cast steel in conventional applications (DOE 1999)

Capital costs for near net shape casting plants are expected to be lower than current practice due to the elimination of the reheating furnaces. Estimates on the reduction of capital costs have ranged from 30-60 percent below current practice (SMS 1995, Tomasseti 1995, Kuster 1996). Given that this technology is still new, we currently estimate a capital cost 15 percent below conventional continuous casting. Operations and maintenance costs are also expected to drop by 20-25 percent, although these reductions will depend on local circumstances (Worrell 1995, Tomasseti 1995). Tomasseti 1995 has also noted that integration of casting and rolling has also significantly reduced dust emissions resulting in a near dust-free environment.

While this technology looks promising, there are also some important technical challenges that need to be addressed. The US steel industry noted in their technology roadmap the need to develop a better knowledge of the variations of heat transfer, develop new models, sensors, and control systems, develop new techniques of liquid flow control, and finally to develop post-processing steps to improve strip steels mechanical properties (AISI 1998). Maintaining a high level surface quality has been a big hurdle in many demonstration projects (Opalka 1999). Additional technical work is needed on mold level control, mold cooling, deformation, and wear, surface roughness of the roll, and resistance of components to liquid steel, and atmospheric and surface oxidation (Kuster 1996, de Beer 1999). A much tighter control on upstream operations and flows are needed so as to ensure that the caster does not bottleneck the process (Kuster 1996, Worker 1998). There is also the issue of many mills having invested considerable resources into existing more conventional casting technologies. Finally, as the DOE research shows, it is unclear as to whether thin strip cast steel can compete with cold rolled steel for high end markets such as automobiles and appliances (Kuster 1996).

However, given the significant research efforts that are being undertaken on this technology by consortia in Europe, Japan, and Australia, to address technical concerns, we believe that the penetration rate for non-high end applications before 2015 is likely to be high, yielding potential savings of 9 percent of steel energy use. Our recommended next steps on this technology include further research and development to overcome remaining technical barriers and the use of small scale flat rolling demonstration projects.

### **New EAF Processes (Steel-3)**

The U.S. iron and steel industry is made up of integrated steel mills that produce steel using a blast furnace and the Basic Oxygen Furnace (BOF), and electric steel mills that produce steel from scrap steel or direct reduced iron (DRI) using an electric arc furnace (EAF). In the EAF scrap is melted and refined, using a strong electric current. DRI can be used to enhance product quality. Several process variations exist, using either AC or DC currents, and fuels can be injected to reduce electricity use. The majority of steel produced in the U.S. is from integrated steel mills, although the share of electric steel mills is increasing, growing from 15 percent of production in 1970 to 40 percent in 1995. Electric steel mills are located throughout the U.S., with some concentration in the South, near waterways for shipping and in areas with lower-cost electricity. In 1997 there were 85 electric steel companies operating 122 mills with 226 EAFs. These facilities are spread throughout 35 states, with the largest number of plants in Pennsylvania, Ohio, and Texas. The electric arc furnaces at these mills range in age from brand new to 74 years, with an average age of 24 years (Worrell et al. 1999). Total annual nominal capacity listed in 1994 was 55.6 million tons (50.5 Mt). Between 1995 and 1997 an additional 13 million tons (12 Mt) of EAF capacity was built.

In electric steelmaking, energy is mainly consumed in the EAF and the rolling. On basis of the literature and statistics we estimated the energy consumption in different steps of electric steelmaking. In 1994, EAF based mills produced 39.6 million tons (35.9 Mt) of crude steel, consuming 23 TWh of electricity and 154 TBtu (162 PJ) of fuels (Worrell et al. 1999). Of this EAFs consumed 17 TWh and 5.7 TBtu (6.0 PJ) injection fuels (Worrell et al. 1999). The average rated power consumption is 436 kWh/ton (480 kWh/tonne) and fuel consumption for injection and preheating is estimated at 0.14 MBtu/ton (0.16 GJ/t). While modern EAFs are generally more energy efficient many technologies exist to improve energy efficiency in existing furnaces, such as process control, efficient transformers, oxy-fuel injection, bottom stirring, post-combustion, eccentric bottom-tapping and scrap preheating (Worrell et al. 1999).

Several new EAF-designs are under development, which combine energy saving features like increased fuel and oxygen injection with scrap preheating (Greissel 2000, IISI 2000b). The aim is to produce a semi-continuous process with enhanced productivity through reduced resource use (e.g. refractories, electrodes) and reduced tap-to-tap times. At the same time increased product quality also demands increased feedstock flexibility (e.g. scrap, DRI or pig iron). Different developers are involved in new EAF-process design, the most important being the Twin Electrode DC (IHI, Japan), Comelt (Voest Alpine, Austria) and Contiarc and Conarc (SMS Demag, Germany).

IHI (Japan) is currently developing a new process consisting of a shaft type preheater with twin electrode DC furnace (Takeuchi et al. 1995, Jones 1997). By using two DC electrodes the heat flux is directed to the middle of the furnace, reducing the heat losses in the furnace walls. Process operation is fully automated. Two pilot/demonstration plants are in operation in Japan. The process parameters are estimated at an electricity consumption of 236 kWh/ton (260 kWh/tonne), a fuel consumption of 0.69 MBtu/ton (0.80 GJ/t), and an oxygen injection of 1165 cubic feet/ton (33 NM<sup>3</sup>/tonne steel) (Jones 1997). The capital costs are expected to be lower than that of conventional DC furnaces due to the higher productivity.

The Contiarc process is being developed by Mannesmann Demag (Germany). The Contiarc process consists of a continuous scrap smelting process (instead of the current batch process) with a capacity of 1 Mt/year. The design aims to be energy efficient and low emission (Reichelt and Hofman 1996; Möllers et al. 1997). The designed and expected electric energy consumption is estimated to be 227-234 kWh/ton (250-258 kWh/tonne), while injecting 0.41 MBtu/ton (0.48 GJ/t) (Reichelt and Hofman 1996; Mannesmann 1998). The production costs are expected to be \$9-13 lower per ton steel produced (Reichelt and Hofman 1996; Mannesmann 1998), or up to a 20 percent reduction. The first two orders for Contiarc were apparently placed in early 1999.

The Comelt process (Voest Alpine, Austria) aims to develop a highly efficient semi-continuous process (Jones 1997). The process has four graphite electrodes and one bottom return electrode. The whole furnace is tilted to tap the heat. The position of the electrodes enables increased heat recovery as the shaft preheater can be located on top of the furnace. Electricity consumption is estimated to be 278 kWh/ton (307 kWh/tonne), natural gas use of 0.21 MBtu/ton (0.24 GJ/t, plus additional carbon use), with an electrode consumption of

## New EAF Processes Data Table

	Units	Notes	
<b>New EAF furnace processes steel-3</b>			
<b>Advanced Electric Arc Furnaces</b>			
<i>Market Information:</i>			
Industries		Iron and Steel	331
End-use(s)		Process Heating	Electric Arc Furnace to melt scrap into liquid steel
Energy types		Electricity, fuel	
Market segment		New, Replacement	Replacement at end of life existing furnaces
2015 basecase use	Mtons	58.0	
<i>Reference technology</i>			
Description	Electric arc furnace (average performance in 1994)		
Throughput or annual op. hrs.	ton/yr	1	EAF annual capacities vary between 5,000 and 1.5 Million tons/year
Electricity use	kWh	436	
Fuel use	MBtu	0.14	
Primary energy use	MBtu	3.8	
<i>New Measure Information:</i>			
Description	Advanced Electric Arc Furnaces with Scrap Preheating and High Use of Oxygen		
Electricity use	kWh	240	
Fuel use	MBtu	0.4	
Primary Energy use	MBtu	2.5	
Current status		Field Test	
Date of commercialization		2000	
Est. avg. measure life	Years	40	
<i>Savings Information:</i>			
Electricity savings	kWh/%	436	100%
Fuel savings	MBtu/%	-0.3	-193%
Primary energy savings	MBtu/%	1.4	36%
Penetration rate		Low	No advanced EAFs in use, although some are very efficient designs
Feasible applications	%	12%	Half of potential market between 2000 and 2015 Between 2000 and 2015 potentially 14 Mtons EAF capacity will be build
Other key assumptions			
Elec svgs potential in 2015	GWh	3032	
Fuel svgs potential in 2015	Tbtu	-2	
Primary energy svgs potential in 2015	Tbtu	23.9	
<i>Cost Effectiveness</i>			
Investment cost	\$	4	Additional costs over conventional AC-EAFs
Type of cost		Incremental	
Change in other costs	\$	-8	
Cost of saved energy (elec)	\$/kWh	-0.02	
Cost of saved energy (fuel)	\$/Mbtu	27.40	
Cost of saved energy (primary)	\$/Mbtu	-5.30	Discount rate for all CCE calculations is 15%
Simple payback period	Years	0.3	
Internal rate of return	%	305%	
<i>Key non energy factors</i>			
Productivity benefits		Significant	Reduced tap-to-tap time, reduced electrode and refractory consumption
Product quality benefits		None	Improved feedstock flexibility
Environmental benefits		Somewhat	Reduced offgas volumes; easier to clean
Other benefits			
Current promotional activity	H,M,L	Medium	Promotional
<i>Evaluation</i>			
Major market barriers		Technical, marketing	
Likelihood of success	H,M,L	High	
Recommended next steps		Field Test, Marketing	
Data quality assessment	E,G,F,P	Fair	
<i>Sources:</i>			
2015 basecase			EIA, 1999
Basecase energy use			Worrell et al. 1999
New measure energy savings			Jones 1997; Worrell et al 1999; Mannesmann 1998
Lifetime			Worrell et al., 1999
Feasible applications			
Costs			Worrell et al., 1999
Key non energy factors			Jones, 1997; Mannesmann, 1998; Reichelt and Hofmann, 1996
Principal contacts			
Additional notes and sources			

only 3.6 lb./ton steel (1.8 kg/tonne) (Jones 1997). The capital costs of a large Comelt-unit are expected to be equal to that of a DC furnace (Jones 1997), and higher for small capacities. The production costs are estimated to be \$8-10/ton lower than conventional DC or AC furnaces (Berger and Mittag 1995).

Based on the projects discussed above, we assume for the year 2015 a new electric arc furnace to have an electricity consumption of 240 kWh/ton (265 kWh/metric tonne), fuel injection of 0.41 MBtu/ton (0.48 GJ/t) and oxygen injection of 1060 cubicfeet/ton (30 Nm<sup>3</sup>/metric ton). Energy consumption estimates are based on a 100 percent scrap charge. Increased use of DRI will increase power consumption, while hot metal charging will decrease power consumption. Oxygen production consumes approximately 0.68 kWh/Nm<sup>3</sup> (IISI 1998). Total power consumption is estimated at 261 kWh/ton (287 kWh/t).

The capital costs of a new concept electric arc furnace are lower than costs for a DC-furnace, but higher than capital costs of an AC furnace. The costs of an AC-furnace are approximately 10-15\$/ton. We estimate the incremental capital costs at approximately \$4/ton based on the additional capital costs of DC furnaces and scrap preheating systems as given in Worrell et al. (1999).

The new furnace designs will result in lower operating costs due to reduced tap-to-tap time, lower electrode and refractory use, reduced air cleaning costs, as well as reduced energy costs. Based on the expectations of the various processes we estimate total production cost decreases at \$8/ton.

New furnace designs will be first applied in greenfield EAFs, followed by replacement of old EAFs in existing plants. Assuming an EAF-production of 58 Million tons in 2015 (EIA, 1999) we assume that an additional 8 million tons (7.3 Mt) of greenfield capacity will be constructed by the year 2015. Additionally 5.5 million tons (5.0 Mt) of existing capacity is likely to be replaced by 2015. We assume that half of this capacity will use the discussed EAF-concepts, or 7 million tons (6.4 Mt).

Implementation barriers can be found in the perceived risks of the advanced technology, as well as higher capital costs. Although first orders are apparently placed for some of the processes, the technology needs full-scale commercial demonstration in the U.S. The suppliers of these technologies are well placed in the U.S. market with U.S. subsidiaries and manufacturing facilities.

## Low NO<sub>x</sub> Oxy-Fuel Burners in Steel Reheating Furnaces (Steel-4)

The iron and steel industry is one of the largest industrial energy consumers. The U.S. iron and steel industry is made up of integrated steel mills that produce pig iron from raw materials (iron ore, coke) using a blast furnace and steel using a basic oxygen furnace (BOF) and electric arc furnace steel mills that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). In 1994, 2,180 TBtu (2,300 PJ) (about 11 percent of manufacturing primary energy use) was consumed in the production of about 100 Mton (91 Mt) of crude steel products (EIA 1997). Within steelmaking, the largest energy use is required to reduce iron ore in the integrated mills and to re-melt steel scrap in electric arc furnace mills. After the liquid steel is produced, it is cast and shaped. After casting, the shaped products are further rolled to produce sheet, strip, plate, and other structural products. In 1994, 88 Mtons (79.6 Mt) of steel was hot rolled with an estimated energy requirement of 245 TBtu (259 PJ) of fuel and 53 TBtu (56 PJ) of electricity, resulting in a primary energy intensity of 4.6 Mbtu/ton (5.3 GJ/t). Reheating furnaces consume approximately 2.2 MBtu/ton (2.6 GJ/t). In the reheating furnace steel is heated to temperatures between 1100 and 1300 °C. Hot rolled production in 2015 is estimated at 116.6 million tons (106 Mt) (EIA 1999).

The high temperatures in the rolling furnace require high flame temperatures. However, high flame temperatures also lead to high NO<sub>x</sub>-emissions with standard furnace and burner designs. Existing efficient burners have aimed to recover the waste-heat to pre-heat the combustion air in the furnace, but this can lead to higher NO<sub>x</sub>-emissions. However, this is not necessarily the case since there is a lot of experience with the use of recuperative burners in the steel industry, and good designs do not lead to higher NO<sub>x</sub>-emissions (Flanagan 1993).

An alternative way to increase efficiency is the use of oxy-fuel burners. Oxy-fuel burners are now extensively used in glass furnaces. Older designs of oxy-fuel burners for steel reheating furnaces led to higher NO<sub>x</sub>-emissions (Farrell et al. 1993). However, new designs provide close to the stoichiometric amount of oxygen to the fuel, limiting the formation of NO<sub>x</sub>. The high velocities of the gases in the burner ensure that the fuel is completely combusted at a lower temperature zone of the flame. The high velocities also lead to a better heat distribution in the furnace, improving productivity in furnaces.

Several manufacturers offer different designs of low NO<sub>x</sub> oxy-fuel burners for steel reheating furnaces. In the U.S. the main suppliers with experience in reheating furnaces are American Combustion (Atlanta, GA), Praxair (Tarrytown, NY) and Bricmont (Canonsburg, PA). Other manufacturers have developed oxy-fuel burners, but not yet used in steel reheating furnaces (e.g. Air Liquide, Air Products).

Praxair has been experimenting and testing low-NO<sub>x</sub> oxy-fuel burners in steel reheating furnaces for the past decade. Their oxy-fuel burners have been tested at two steel furnaces: a furnace at Bethlehem Steel at Burns Harbor and at Auburn Steel (NY). The project at Bethlehem Steel is sponsored by the NICE3 program of DOE. Expected energy savings at Bethlehem steel were 35 percent, and actual energy savings were almost 50 percent (Selines 2000). At Auburn Steel no savings were achieved as the burners were primarily used to increase the production rate of a furnace, and the positioning of the burners did not allow them to achieve energy savings. In the original project up to 30 percent energy savings were expected (Valenti 1998). Older tests with oxy-fuel burners in continuous reheating furnaces demonstrated fuel savings of 28-39 percent (Farrell et al. 1993). Praxair is marketing the technology and talking to a couple of other prospective customers in the steel industry.

American Combustion's Pyretron® burner is based on the similar concept, using high-velocities and selective oxygen supply to increase efficiency and reduce NO<sub>x</sub>-emissions. The technology has been used in reheating furnaces for many metals, including steel. In a pusher-type steel reheating furnace application of the new burner has led to increased productivity (25 percent) and fuel savings of 1.07 MBtu/ton (1.24 GJ/t), with an oxygen use of 0.5 million cubic feet/ton (or 14 Nm<sup>3</sup>/tonne) (American Combustion 2000).

We estimate average 2010 fuel savings at 30 percent, or 0.66 MBtu/ton (0.77 GJ/t) with additional oxygen use of 0.3 mcf/ton (9 Nm<sup>3</sup>/tonne). Oxygen production consumes approximately 0.68 kWh/Nm<sup>3</sup> (IISI 1998). Total power consumption is estimated at 6.1 kWh/ton (6.8 kWh/metric tonne). Net primary energy savings are estimated at 0.63 MBtu/ton (0.73 GJ/t).



Low NO<sub>x</sub> Oxy-Fuel Burners in Steel Reheating Furnaces Data Table

Units		Notes	
Oxy-Fuel Burners in Reheating Furnaces			
Steel-4			
Advanced Oxy0Fuel Burners in Steel Reheating Furnaces Improve Efficiency and Reduce NOx-Emissions			
Market Information:			
Industries		Iron & Steel	SI 33
End-use (s)		Process Heating	Reheating furnaces in hot rolling mill
Energy types		Fuel	Natural gas, coke oven gas
Market segment		Retrofit, New	
2015 basecase use		116.6	Estimated throughput in 2015 (EIA, 1999)
Reference technology			
Description	Average reheating furnace (continuous and batch)		
Throughput or annual ops.		1	Ton, capacity may range from a few t/h to over 300 t/h
Electricity use	kW h	0	Electricity use for fans is very small
Fuel use	MBtu	2.2	
Primary energy use	MBtu	2.2	
New Measure Information:			
Description	Rapid firing oxy-fuel burners with Low-NOx combustion characteristics		
Electricity use	kW h	6	
Fuel use	MBtu	1.5	
Primary Energy use	MBtu	1.6	
Current status		Field Test/Commercialized	NIE3 project of one of the products
Date of commercialization		1998	
Est. avg. measure life	Years	10	
Savings Information:			
Electricity savings	kW h/%	-6	90%
Fuel savings	MBtu/%	0.7	90%
Primary energy savings	MBtu/%	0.6	90%
Penetration rate		Low	
Feasible applications	%	30%	
Other key assumptions			
Electricity savings potential in 2015	GW h	-213	
Fuel savings potential in 2015	Tbtu	23	
Primary energy savings potential in 2015	Tbtu	21.2	
Cost Effectiveness			
Investment cost	\$	2	
Type of cost		Full cost	
Change in other costs	\$	-0.67	
Cost of saved energy (elec)	\$/kW h	0.03	
Cost of saved energy (fuel)	\$/MBtu	-0.32	
Cost of saved energy (primary)	\$/MBtu	-0.35	Discount rate for all CCE calculations is 15%
Simple payback period	Years	1.2	
Internal rate of return	%	82%	
Key non energy factors			
Productivity benefits		Significant	Production capacity increase by up to 25%
Product quality benefits		None	
Environmental benefits		Significant	NOx emission reduction of up to 70-90%
Other benefits			
Current promotional activity	H M L	Medium	Marketing by producers, DOE-OIT
Evaluation			
Major market barriers		Economic	
Likelihood of success	H M L	High	
Recommended next steps		Dissemination	
Data quality assessment	E G F P	Fair	
Sources:			
2015 basecase			EIA 1999
Basecase energy use			Wong et al., 1999
New measure energy savings			Fan et al., 1993; American Combustion, 2000, Selnes, 2000
Lifetime			Fanagan, 1993
Feasible applications			
Costs			Derived from Wong et al., 1999
Key non energy factors			Fan et al., 1993; American Combustion, 2000, Selnes, 2000
Principal contacts			Ron Selnes, Praxair (914) 345-6457 Toly Pamas, American Combustion (770) 564-4180 (ext. 251)

The oxy-fuel-burner can be installed in existing furnaces without rebuilding the furnace. Based on the costs of other burner systems we estimate the investment costs at \$2.3/ton-capacity (\$2.5/t-capacity) (Worrell et al. 1999). Assuming oxygen-supply is present, we only include the costs for oxygen delivery in the capital costs, and the production costs in the operation and maintenance costs. Oxygen costs are estimated at 0.04\$/Nm<sup>3</sup> (De Beer et al. 1998a).

Application of oxy-fuel burners may result in productivity increases (up to 25 percent) and up to 70-90 percent reduction in NO<sub>x</sub> emissions. Although, oxy-fuel burners can lead to increased productivity, the value will depend on the utilization of the furnace. We assume that the productivity increase is on average valued at 1\$/ton (derived from Worrell et al. 1999).

The technology is likely to be successful. The applicability of the technology depends on the furnace design and the use of competing technologies. Competing technologies may be other low-NO<sub>x</sub> burner designs as well as recuperative burners. We assume that the technology could potentially be applied to 30 percent of the hot rolled steel production by 2015. Further dissemination of experiences with these burners to industry and air quality regulators is needed to increase the penetration of this technology in the market.

## Smelting Reduction Processes (Steel-5)

The iron and steel industry is one of the largest industrial energy consumers. The industry is made up of integrated steel mills that produce pig iron from raw materials (iron ore, coke) using a blast furnace and steel using a basic oxygen furnace (BOF) and electric arc furnace steel mills that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). In 1994, 2,180 TBtu (2,300 PJ) (about 11 percent of manufacturing primary energy use) was consumed in the production of about 100 Mton (91 Mt) of crude steel products (EIA 1997). In 1997 there were 14 integrated steel companies operating 20 integrated steel mills with a total of 40 blast furnaces. These mills are concentrated in the Great Lakes region, near supplies of coal and iron ore and near key customers such as the automobile manufacturers. The blast furnaces in these mills range in age—accounting for furnace rebuilds—from 2 to 67 years, with an average age of 29 years. Production rates per plant vary between 0.6 and 3.4 million tons (0.5-3.1 Mt) per year. Total production of U.S. blast furnaces in 1997 was slightly over 59.5 million tons (54 Mt). Primary steel production using a basic oxygen furnace fluctuated between 44 and 83 million tons (40-75 Mt) over the period. Primary energy consumption for ironmaking is estimated at 780 TBtu (862 PJ), or equivalent to 45 percent of total energy use in the iron and steel industry (1994) (Worrell et al 1999). Pellet making at the mine-site adds 125 TBtu (132 PJ) (Margolis 1996), using 1.24 tons of pellet per ton of pig iron. Based on the AEO-2000 we estimate 2015 iron production at about 57 million short tons (52 Mt).

Smelting reduction is the latest development in pig iron production. Smelting reduction processes currently under development combine coal gasification with the direct reduction of iron oxides. In this way, smelting reduction will abandon the need for coke, while future processes will also abandon ore preparation. The COREX process is the only commercial smelting reduction process. CCF, DIOS and Hismelt are advanced research projects. Commercial COREX plants are operating in South Africa and South Korea, with new plants under construction in India and South Africa. First commercialization of the more advanced smelting reduction processes is expected around 2005-2010 (De Beer et al., 1998).

In smelting reduction iron ore is pre-reduced by gases coming from a hot bath. The pre-reduced iron is then melted in the bath. The process produces excess gas, which is used for power generation, production of direct reduced iron (an alternative iron input for scrap), or as fuel gas. Due to the different reaction conditions and the full integration of iron and steel making, the theoretical energy demand of smelting reduction is lower than that of a blast furnace. Studies estimated the energy consumption to be 20-30 percent lower than that of the conventional blast furnace route. Currently operating plants already show energy consumption levels comparable to the blast furnace routes, *but* at much smaller scales. The second generation smelting reduction technology would reduce energy use in ironmaking by 30 percent relative to current processes.

Smelting reduction has dramatically lower capital costs, and has other inherent advantages. It saves material costs, ( the process can use less expensive coal than current metallurgical coal), allows for better pollution control, and shows favorable economics at smaller capacities compared to conventional technology. The main process developers can be found in Austria/Germany (Voest Alpine), Australia/Germany (CRA/Klockner), Japan (NKK and others) and The Netherlands/UK (Corus). Current smelting reduction plants are all greenfield plants. For brownfields (rebuilds of existing sites), smelting reduction processes will compete with extension of the lifetime of existing blast furnaces and with production of DRI (mainly as input into EAFs). Environmental issues could limit the operation of (older) coke ovens in the U.S. triggering interest in smelting reduction. While replacement of coke ovens could be a reason to invest in smelting reduction (Meijer et al., 1994), this has not been the case in the U.S. where producers have shown renewed interest in non-recovery coke ovens, as well as increased imports. There is some indication of change however. Geneva Steel (Utah) has shown interest in the COREX-process and recently Nucor has shown interest in the Hismelt process to replace the failed iron carbide process in Trinidad as a source of iron for their U.S. Plants (33Metalproducing.com 2000b). AISI was involved in the development of a bath smelting process, but abandoned the research.

Coke making processes can have significant negative environmental impacts. Various emissions of environmentally hazardous compounds (e.g. sulfur compounds, poly-aromatic hydrocarbons) make

## Smelting Reduction Data Table

	Units		Notes
Smelting reduction processes			
steel-5			
New Production Route for the production of pig iron, replacing cokemaking, ore preparation and the blast furnace			
Market Information:			
Industries		Iron and Steel	SIC 33
End-use(s)		Other	Incl. Cokemaking, pelletizing, sintering and blast furnace
Energy types		Coal, oil, gas, electricity	
Market segment		New	
2015 basecase use	Mtons	57.0	Estimated 2015 production on basis of EIA 1999
Reference technology			
Description	Blast Furnace Route, including cokemaking, pelletizing, sintering and the blast furnace		
Throughput or annual op. hrs.		short ton	Characteristics expressed per ton capacity, varies between 0.8 and 3.1 Mt/yr
Electricity use	kWh	57	
Fuel use	MBtu	15.5	
Primary energy use	MBtu	16.0	
New Measure Information:			
Description	Smelting Reduction		
Electricity use	kWh	64	
Fuel use	MBtu	12.4	
Primary Energy use	MBtu	12.9	
Current status		Commercial	Three COREX plants operating worldwide, others pilot-plant COREX C-2000 in Sotuh-Korea, other processes expected around 2005-2010
Date of commercialization		1995	
Est. avg. measure life	Years	40	
Savings Information:			
Electricity savings	kWh/%	-7	-12%
Fuel savings	MBtu/%	3.1	20%
Primary energy savings	MBtu/%	3.1	19%
Penetration rate		Low	No U.S. plants
Feasible applications	%	18%	average lifetime 70 years for blast furnace and one greenfield
Other key assumptions			
Elec svgs potential in 2015	GWh	-72	
Fuel svgs potential in 2015	Tbtu	32	
Primary energy svgs potential in 2015	Tbtu	31.6	
Cost Effectiveness			
Investment cost	\$	-122	Smelting reduction investments: \$227/ton, BF-route investments: \$349/ton
Type of cost		Replacement	
Change in other costs	\$	-13.6	Operating cost reduction may be between 12.6 and 14.5\$/ton
Cost of saved energy (elec)	\$/kWh	4.57	
Cost of saved energy (fuel)	\$/Mbtu	-10.18	
Cost of saved energy (primary)	\$/Mbtu	-10.38	Discount rate for all CCE calculations is 15%
Simple payback period	Years	-6.1	
Internal rate of return	%	N/A.	
Key non energy factors			
Productivity benefits		Somewhat	Reduced capital, lower fuel costs (fuel shift), lower operation costs
Product quality benefits		None	
Environmental benefits		Significant	Lower air and water emissions
Other benefits			
Current promotional activity	H,M,L	Low	Limited interest with integrated steelmakers
Evaluation			
Major market barriers		Marketing, integration	Integration into brownfields, limited interest integrated steelmakers
Likelihood of success	H,M,L	Medium	
Recommended next steps		Commercial demonstration	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			EIA 1999;Margolis, 1996
Basecase energy use			Margolis, 1996; Worrell et al., 1999
New measure energy savings			De Beer et al. 1998a; IISI, 1998
Lifetime			
Feasible applications			Worrell et al., 1999
Costs			De Beer et al. 1998a
Key non energy factors			De Beer et al. 1998a, IISI 1998; Meijer et al., 1994
Principal contacts			
Additional notes and sources			

extensive gas clean-up at the coke plant necessary. Coke making and ore preparation release large amounts of particulate matter.

Inherent to the smelting reduction processing route is the absence of the formation of most of the problematic compounds in coke making, while the fuel gas produced has much lower sulfur content than coke gas. In smelting reduction, hydrocarbons are not condensed, but combusted at the high reactor temperatures. Integration, abandoning coke quenching, and reduced ore handling will reduce PM emissions.

We base the description of the energy characteristics on the analysis on De Beer et al. (1998a) and IISI (1998). Smelting reduction plants generally have a higher coal input per ton product than current blast furnaces, but export larger quantities of fuel gas. The exported offgas of the COREX-process has a heating value of approximately 7 MJ/Nm<sup>3</sup> (LHV) and is relatively clean (sulphur content of 10-70 ppm) (Pühringer et al.1991). Net energy consumption of smelt reduction is therefore lower than that of the blast furnace route. U.S. integrated steel plants use on average 16.0 MBtu/ton pig iron (18.6 GJ/t hot metal (thm), including energy use for pellet making) (Worrell et al. 1999). Net primary energy consumption of smelt reduction process may vary between 11.4 and 13.4 MBtu/ton hot metal (13.3 and 15.6 GJ/thm) (De Beer et al. 1998). We will assume a 2010-2015 performance of 12.9 Mbtu/ton pig iron (15.0 GJ/thm). In the long term further reductions leading to a net specific energy consumption (SEC) of 11.4 MBtu/ton (13.2 GJ/thm) may be expected (De Beer et al., 1998). Primary energy use estimates depend heavily on the chosen use of the off-gas (i.e. power generation in a combined cycle or steam-cycle, or for production of DRI). Currently operating COREX-plants show energy consumption levels comparable to the blast furnace routes, i.e. 16.4 Mbtu/thm (17.3 GJ/ton hot metal) (IISI 1998), but at much smaller scales. Future improvements can be achieved by new process developments, increased capacities, optimization of the carbon monoxide/ore-interaction, and optimization of fuel gas use.

Investment costs are lower compared to the conventional process route, as coke making and ore preparation may be abandoned. This will also result in lower operating costs. Capital costs of modern blast furnace-based plants are high are approximately \$349/ton hot metal (\$385/thm) (De Beer et al., 1998). The investments involve coke plants, ore preparation (sintering, pelletization) and the blast furnace. The investments required for the COREX-process are estimated to be around \$227/ton hot metal (250 US\$/thm) (excluding ore agglomeration plant) (Meijer et al.1994; De Beer et al. 1998). The capital required for a commercial sized CCF plant are estimated to be \$136-163/ton hot metal (150-180 US\$/thm) (Meijer et al.1994).

The operating costs of a smelt reduction plant will depend on local conditions, but may be expected to be significantly lower due to the abandoned processes. The reduction of operation and maintenance costs for the CCF process in Western-European conditions is estimated to be \$16/ton pig iron (18 US\$/t) pig iron (Meijer et al. 1994). Coke plants consume high grade coking or metallurgical coal types, which are more expensive than steam coal. Steam coal costs are on average \$5/ton (\$5.5/t) lower than coking coal (De Beer et al. 1998). Smelting reduction technology makes it possible to use steam coal, thereby reducing fuel costs (compared to a blast furnace). The production costs of pig iron via the blast furnace route are estimated at \$110-\$145/ton hot metal (\$122-160/thm) (De Beer et al. 1998). Smelting reduction processes will result in production costs of 5 percent to 35 percent below the costs of the conventional route (De Beer et al., 1998). For the period 2010-2015 we assume a cost reduction of 10 percent, or \$11-15/ton hot metal (\$12-16/thm).

Next steps include the commercialization of the second-generation smelting reduction process through demonstration on a near-commercial scale. Due to the large costs involved this should preferably be a project shared by (various) steel companies, technology providers and other parties.

## Advanced Forming/Near Net Shape Casting (Alum-1)

The United States is the largest aluminum producer globally, with a combined production of primary and secondary aluminum in 1999 of 8 million short tons (7.3 Mt) (USGS 2000). Primary aluminum production, which is extremely energy intensive, accounts for roughly half of the production (3.8 million short tons (3.4 Mt)) and roughly 2 percent of primary energy use in U.S. manufacturing (USGS 2000, EIA 1997). Once the smelted aluminum is produced (either by the primary process or the secondary process), it is alloyed in a holding furnace and then cast into ingots or continuously cast in a rolling mill. The ingots or continuously cast aluminum is then hot rolled and cold rolled into plate, sheet, or foil. Estimates for the energy use for casting are 5.7 Mbtu/ton (6.6 GJ/t) and between 5.1 and 7.0 Mbtu/ton (5.9 and 8.1 GJ/t) for hot and cold rolling (Margolis 1997). On a national basis this means that casting and rolling accounts for roughly 60 Tbtu (63 PJ) of energy use.

Currently, the casting and rolling process is a multi-step process. In ingot casting, the more common of the casting processes, the aluminum is cast into ingots that are then transported, reheated, and rolled. The primary form of ingot casting is vertical direct chill where the molten metal is poured through a spout into a mold and then cooled. Other casting variations include horizontal direct chill and electromagnetic casting, where an electromagnetic field is used to hold and shape the metal in a special mold (Margolis 1997). Before hot rolling ingots are pre-heated in temperature controlled furnaces (walking beam furnaces are used to heat larger ingots), and for some applications, cold rolling is used to achieve desired thickness and finish.

Near net shape or thin strip casting is a new technology that integrates the casting and hot rolling of aluminum into one process step, thereby reducing the need to reheat the aluminum ingot before rolling it. Instead of casting slabs in a thickness of 120-300 millimeters, slabs are cast much thinner, as low as 1-10 mm thickness. (Daaland et al. 1997, Erdman 1999, Opalka 1999). The aluminum is essentially cast and formed into its final shape without the reheating step.

The first successful twin roll caster for aluminum was developed by Joseph Hunter in 1956 (Ertan et al. 1999). Because of the relatively low capital costs for casters they, are increasingly becoming more popular. Alcan developed a strip caster for painted sheet (that does not require a high level of surface quality) and there are other strip casters in operation with Barmet Aluminum and Vulcan Aluminum (Kuster 1996). In 1998, Kaiser was planning on starting up a micro-mill where the strip will be hot rolled into two strands for final gauge annealing (Kuster 1996). Aluminum Pechiney has also made significant improvements on thin strip casting technology for foil and beverage cans with its 3CM caster, as has Fata Hunter with its speed caster machines (Erdman 1999, Hamer 2000, Brooks 1997).

The energy consumption of a thin strip caster is significantly less than the current process, since the pre-heating requirements are eliminated. We estimate fuel savings of 0.4 MBtu/ton (0.5 GJ/t) for hot rolled aluminum with electricity savings of 20 kWh/ton.

A key driver for this technology is the potential for increased yield and reduced operational costs with thin strip technology. One rolling mill found a 15 percent productivity improvement over a two-year period after installing the new caster technology (Daaland et al. 1997). Thin strip casting is also expected to improve the quality of the cast aluminum (surface quality, center line segregation, geometrical tolerances) since thinner cast strips could be better controlled. Finally, the technology provides an opportunity to develop new aluminum products (Daaland et al. 1997).

Dyllus et al. 1991 note that capital investment costs for continuous casting and hot rolling lines are generally lower than standard casting lines. Overall, capital costs range from \$150-\$200/ton, and incrementally are estimated to save \$70-90/ton as compared to standard processes (Dyllus et al. 1991). Also, labor and maintenance costs are expected to be lower with casting machines; we estimate a \$20/ton reduction (Dyllus et al. 1991).

Assuming that the beverage can market can be accessible to thin strip casting, the next logical step in aluminum strip casting is to develop it for larger-scale applications such as auto body sheet and for applications of less than 2.5 mm thickness. However, the technical challenges increase significantly for this

## Advance Forming Data Table

	Units		Notes
Advanced forming/near net shape technology			
alum-1			
Thin strip casting			
Market Information:			
Industries		Aluminum	
End-use(s)		Process heating	
Energy types		Fuels, electricity	
Market segment		New	
2015 basecase use	Mton	13.6	Estimate of 2015 aluminum production
Reference technology			
Description	VDC ingot casting with hot and cold rolling		
Throughput or annual op. hrs.	ton	1	
Electricity use	kWh	193	Margolis 1997
Fuel use	MBtu	4.0	Margolis 1997
Primary energy use	MBtu	5.6	
New Measure Information:			
Description	Thin strip casting		
Electricity use	kWh	174	Margolis 1997
Fuel use	MBtu	3.5	Margolis, 1997 and Daaland et al., 1997
Primary Energy use	MBtu	5.0	
Current status	Near commercial		
Date of commercialization			Commercial for foil applications, not for harder alloys
Est. avg. measure life	Years	15	
Savings Information:			
Electricity savings	kWh/%	19	10%
Fuel savings	MBtu/%	0.5	13%
Primary energy savings	MBtu/%	0.7	12%
Penetration rate		Medium	
Feasible applications	%	25%	Applies to sheet, foil, and plate
Other key assumptions			
Elec svgs potential in 2015	GWh	66	
Fuel svgs potential in 2015	Tbtu	2	
Primary energy svgs potential in 2015	Tbtu	2.3	
Cost Effectiveness			
Investment cost	\$	-50	
Type of cost		Incremental	
Change in other costs	\$	-20	
Cost of saved energy (elec)	\$/kWh	<0	
Cost of saved energy (fuel)	\$/Mbtu	<0	
Cost of saved energy (primary)	\$/Mbtu	<0	Discount rate for all CCE calculations is 15%
Simple payback period	Years	Immediate	
Internal rate of return	%		
Key non energy factors			
Productivity benefits		Compelling	15% productivity improvements shown
Product quality benefits		None	
Environmental benefits		None	
Other benefits			
Current promotional activity	H,M,L	Medium	For foils and specific applications
Evaluation			
Major market barriers		Technical	
Likelihood of success	H,M,L	High	
Recommended next steps		R&D, demonstration	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			AEO, 2000
Basecase energy use			Margolis, 1997
New measure energy savings			Margolis, 1997
Lifetime			Worrell et al. 1999
Feasible applications			Hamers 2000
Costs			Dyllus et al., 1991
Key non energy factors			Daaland et al. 1997
Principal contacts			Shaun Hamers, Fata Hunter. Shamers@aol.com
Additional notes and sources			

application and these have not yet been solved by the industry. One of the main reasons is that when casting harder alloys at thinner gauges, the rolling forces tend to separate the sheet (Erdman 1999, Hamer 2000, Ertan et al. 1999).

Near net shape casting was identified as a high mid-term research priority by the aluminum industry in its aluminum technology roadmap process undertaken with the U.S. Department of Energy. It is unclear whether the technical challenges of operating thin strip casting machines with harder alloys will be overcome. However, significant opportunities exist in the near term with foil and thin sheet. Next steps involve further research, development and demonstration.



## Efficient Cell Retrofit Designs (Alum-2)

The United States is the largest primary aluminum producer in the world, with a production of 3.8 million tons (3.4 Mt) in 1999 from 23 primary plants (USGS 2000, OIT 1999). In 1994, primary aluminum production in the U.S. consumed 53,552 million kWh of electricity, or 2 percent of primary energy use in U.S. manufacturing (EIA1997). Energy consumption represents 20-30 percent of total production costs. Average energy consumption in the U.S. for aluminum production in 1994 was 16 kWh/kg and was estimated at 15 kWh/kg in 1997 (EIA 1997, USGS 2000, Eisenhower et al. 1997).

Primary aluminum production is an energy intensive continuous process and involves the electrolytic reduction of alumina into aluminum. This process, known as the Hall-Heroult smelting process is accomplished in a series of cells or “pots” that are connected in long lines in buildings. In each cell the refractory material is overlaid with a carbon lining and a carbon cathode. The molten aluminum lies beneath a bath of cryolite that serves as the medium to dissolve incoming alumina and to conduct electricity from the anode to the aluminum. Alumina is fed into the top of each cell on top of a crust of cooler cryolite (which acts as an insulator), and the crust is periodically broken to allow the alumina to be stirred into the bath. When a strong electric current (50-225 kilo-Amperes) is passed through the electrodes into the bath, the alumina is reduced via a reaction to  $\text{Al}_2\text{F}_6$  (which is easier to reduce than  $\text{Al}_2\text{O}_3$ ), to produce molten aluminum. The voltage drop across a cell is 4-4.5V, while the voltage in a potline can exceed 1,000 volts (Gitlitz 1995). The molten aluminum is periodically siphoned off through the tops of the cell into a holding furnace and then poured into ingots or billets, which are then cast and shaped.

While a new generation of aluminum smelting technologies are being developed (see Inert Anodes for example), there are also a series of retrofit technologies that could significantly improve cell operation and reduce electricity consumption. These retrofit options are mainly geared to improving the current efficiency of the cell (i.e. closer anode-cathode spacing) and reducing heat losses. Options include improved conductivity for anode materials, bottom heat recovery, increased insulation in furnaces, advanced controls, improved design of the electrical bus components, operation with a low-ratio  $\text{AlF}_3$  electrolyte chemistry (i.e. improvements in the chemical bath), and improved housekeeping, especially for anode changes. (Blok et al. 1995, Energetics 1990, Margolis 1997). Additional enabling technologies include improved modeling, neural network process controls, continuous sensors, and signal analysis of cell voltage (Eisenhower et al. 1997).

The U.S. aluminum industry has targeted as a goal the reduction of energy intensity of aluminum production to 13 kWh/kg in the near term using retrofit technology (Energetics 1997). This reduction is consistent with other studies that have documented potential reductions of 14-16 percent between best and worst practices in modern smelting cells (Moisan 2000).

Investment costs for a retrofit project of this type can vary depending on the existing condition and layout of the facilities. A recent project reported at Aluminerie Luralco (a subsidiary of Alcoa) noted a cost of \$60 Million Canadian for a 264 pot retrofit, or a unit cost of around \$200/ton (\$220/t) (CADDET 1999d).

Aside from energy improvements, upgrading existing cell technology can also significantly reduce production costs (by increasing yield by up to 30 percent and by lowering anode replacement costs), and reduce labor costs (Moisan 2000). We note an average reduction of \$10/t aluminum in operation and maintenance costs for the new cell installations.

Cell retrofit programs are underway among several potlines in the U.S., and the market’s full potential is unclear. We believe that given the demonstrated effectiveness in retrofits elsewhere, there is a high likelihood of success that efficient retrofits will become increasingly desirable in the near term in the absence of the commercialization of advanced cell technologies.

## Efficient Cell Designs Data Table

	Units	Notes		
Efficient cell retrofit designs				
Alum-2				
New decoating and furnace technology				
Market Information:				
Industries		Aluminum	SIC 3334	
End-use(s)		Process heating		
Energy types		Fuels		
Market segment		New		
2015 basecase use	Mtons	6.1	AEO 2000, smelting output	
Reference technology				
Description	Hall-heroult cell, primary aluminum smelting			
Throughput or annual op. hrs.	tonne	1	Unit consumption presented. Smelters cell amperage range from 175-300 kA	
Electricity use	MWh	16.2	EIA, 1997, USGS, 2000	
Fuel use	MBtu	5.45	EIA, 1997, USGS, 2000	
Primary energy use	MBtu	143.4		
New Measure Information:				
Description	Efficient cell retrofits			
Electricity use	MWh	13	CADDET case study, Energetics, 1997	
Fuel use	MBtu	5.45		
Primary Energy use	MBtu	116.0		
Current status	Commercialized			
Date of commercialization				
Est. avg. measure life	Years	15		
Savings Information:				
Electricity savings	MWh/%	3.2	20%	Savings compared to 1994 baseline
Fuel savings	MBtu/%	0.0	0%	
Primary energy savings	MBtu/%	27.4	19%	
Penetration rate		High	Cost effective and easily integrated into upgrade cycles	
Feasible applications	%	30%		
Other key assumptions				
Elec svgs potential in 2015	GWh	5367		
Fuel svgs potential in 2015	Tbtu	0		
Primary energy svgs potential in 2015	Tbtu	45.6		
Cost Effectiveness				
Investment cost	\$	217	Assume full cost. Exchange rate of \$CAD 1.2/\$US	
Type of cost		Full		
Change in other costs	\$	-10	Moisan, 2000	
Cost of saved energy (elec)	\$/kWh	0.01		
Cost of saved energy (fuel)	\$/Mbtu	N/A.		
Cost of saved energy (primary)	\$/Mbtu	0.99	Discount rate for all CCE calculations is 15%	
Simple payback period	Years	2.7	Based on \$2.6/Mbtu primary energy price for electricity in the aluminum industry	
Internal rate of return	%	37%		
Key non energy factors				
Productivity benefits		Significant	Can significantly reduce production costs	
Product quality benefits				
Environmental benefits		Somewhat	Reduced emissions of fluorocarbons	
Other benefits				
Current promotional activity	H,M,L			
Evaluation				
Major market barriers		Cost, risk perception		
Likelihood of success	H,M,L	High		
Recommended next steps		Demonstration		
Data quality assessment	E,G,F,P	Fair		
Sources:				
2015 basecase			EIA, 1999	
Basecase energy use			EIA, 1999; USGS 2000	
New measure energy savings			Energetics, 1997	
Lifetime			Author estimate	
Feasible applications			Author estimate	
Costs			CADDET, 1999d	
Key non energy factors			CADDET, 1999d	
Principal contacts				
Additional notes and sources				

### Improved Recycling Technologies (Alum-3)

The United States is the largest aluminum producer globally, with a combined total production of primary and secondary aluminum of 8 million short tons (7.3 Mt) in 1999 (USGS 2000). Primary aluminum production, which is extremely energy intensive, accounts for roughly half of the production (3.8 million short tons (3.4 Mt)) and roughly 2 percent of primary energy use in U.S. manufacturing (USGS 2000, EIA 1997). Because of the lower energy and operating costs (recycled aluminum production uses 90 percent less energy), the share of recovered or secondary aluminum production has more than doubled since 1970. A potential limiting factor in the continued growth of the secondary aluminum market is the ability to continue to secure high quality aluminum scrap or to better purify low quality scrap so that secondary aluminum products can be competitive in key markets. The use of improved or advanced recycling technologies therefore can further expand the secondary aluminum market, generating significant energy savings.

The demand for recycled aluminum products is strong and expected to continue. Average growth since 1970 is nearly 5 percent per year. The transportation sector is a particularly hopeful prospect; and already accounts for 30 percent of aluminum shipments (Plunkert 1997, Aluminum Association 2000). The aluminum content of US automobiles has doubled since 1991, and is now up to 246 pounds (112 kg) per vehicle, about two-thirds of which is from recycled metal. This content is expected to double by 2005 (Pawlek 2000, Pickens 2000).

Traditionally, all scrap is sorted and shredded before being charged into a melting furnace. Contaminants are primarily removed using pyrometallurgical techniques (roasting, delacquering, sweating), but also may be removed using catalytic techniques (cryolite catalysts in a barrel furnace) or hydrometallurgical techniques (use of water) (Margolis 1997). The treated scrap is then charged in furnaces designed for relatively dirty scrap (high-emitting furnaces) or relatively clean scrap (low-emitting furnaces). Molten salts (NaCl and KCl) are sometimes added to standard reverberatory furnaces to help separate out impurities and improve furnace efficiency. The black dross is periodically removed, and itself contains aluminum (8-13 percent) which can be captured in dross or rotary furnaces, or more advanced plasma furnaces. Salt cake, a residual product after processing in rotary furnaces, has a metal content of about 4-6 percent. About 750,000 short tons (680,000 t) of dross/salt cake are generated annually in the US, most of which is landfilled and environmentally harmful given potential leaching of salts into the water table (Margolis 1997, Pawlek 2000, Pickens 2000). Because the demand for secondary aluminum continues to grow, finding cost-effective ways to further increase metals recycling will be highly valued.

Several new technologies have emerged that help to improve the recovery or processing of scrap or reduce energy use in the preparing and melting of scrap. The New York State Energy Research and Development Authority, Energy Research Company (ERCo), Philip Services Co., and Stein Atkinson Stordy, Ltd developed a new decoating kiln (the IDEX™) that reduces kiln energy use by 41 percent while also improving product quality and increasing metal yield by 1 percent (ERCo and Wabash Alloys 1998, CADDET 1996c, OIT 2000). ERCo is now developing a new generation of decoating and melting technology called the vertical flotation dryer (VFD) where high velocity gases strip oils from the scrap in a VFD cone, and the oils are subsequently combusted reducing energy requirements.<sup>18</sup> As well as reducing energy use, this decoater increases productivity (run times per decoating batch are significantly reduced) (De Saro et al. 1999, OIT 2000). Other new melt designs include a universal melting plant (Nottingham metal recyclers) that pre-heats and decoats the scrap in a dry hearth furnace and then melts the scrap in a closed well furnace. This technology achieved a 25 percent energy savings and a 2-8 percent increase in metal recovery (CADDET 1993d).

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<sup>18</sup> The VFD is also being designed to be used as a melter and can replace existing side-well reverberatory furnaces and electric induction melters, while offering additional gains in efficiency. In this write up however, we do not address new melt technologies but focus on decoating technologies. We do recognize that these two steps are likely to become increasingly integrated (as the VFD/VFM design suggests) into new combined designs in the future.

# Improved Recycling Technologies Data Table

Units		Notes	
Improved recycling technologies			
alum-3			
Scrap decoating and new secondary furnace technologies			
Market Information:			
Industries		Aluminum	SIC 333
End-use(s)		Process heating	
Energy types		Electricity	
Market segment		Retrofit, new	Primarily retrofit applications. Also greenfields
2015 basecase use	Mtons	7.5	Estimate of secondary output based on AEO 2000
Reference technology			
Description	Existing scrap preparation and secondary furnace systems		
Throughput or annual op. hrs.	tonne	1	Unit consumption presented.
Electricity use	kWh	0.0	De Saro, 1998
Fuel use	MBtu	2.00	De Saro, 1998
Primary energy use	MBtu	2.0	
New Measure Information:			
Description	New recycling technologies		
Electricity use	kWh	0	
Fuel use	MBtu	1.00	IDEX kiln consumption of 500 btu/lb
Primary Energy use	MBtu	1.0	
Current status	Commercialized		
Date of commercialization			
Est. avg. measure life	Years	15	
Savings Information:			
Electricity savings	MWh/%	0.0	n.a. Savings compared to 1994 baseline
Fuel savings	MBtu/%	1.0	50%
Primary energy savings	MBtu/%	1.0	50%
Penetration rate		High	
Feasible applications	%	30%	Strong demand expected for improved decoating technology
Other key assumptions			
Elec svgs potential in 2015	GWh	0	
Fuel svgs potential in 2015	Tbtu	2	
Primary energy svgs potential in 2015	Tbtu	2.2	
Cost Effectiveness			
Investment cost	\$	20	Estimated incremental cost
Type of cost		incremental	
Change in other costs	\$	0	
Cost of saved energy (elec)	\$/kWh	n.a.	
Cost of saved energy (fuel)	\$/Mbtu	3.42	
Cost of saved energy (primary)	\$/Mbtu	3.42	Discount rate for all CCE calculations is 15%
Simple payback period	Years	4.5	Based on \$2.6/Mbtu primary energy price for electricity in the aluminum industry
Internal rate of return	%	22%	
Key non energy factors			
Productivity benefits		Somewhat	
Product quality benefits			
Environmental benefits		Significant	Reduced emissions - eases compliance for environmental regulation
Other benefits			
Current promotional activity	H,M,L	medium	
Evaluation			
Major market barriers		Cost, risk perception	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Demonstration	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase			EIA, 1999
Basecase energy use			De Saro, 1999
New measure energy savings			De Saro, 1999
Lifetime			Author estimate
Feasible applications			Author estimate
Costs			De Saro, 2000
Key non energy factors			De Saro, 1999
Principal contacts			Robert DeSaro, ERCo (rdesaro@er-co.com); John Pickens, ALUMITECH (JohnPickens@Alumitechinc.com)
Additional notes and sources			

In the area of dross/salt cake recovery, ALUMITECH began operation of a commercial closed loop dross/salt cake recycling facility in Cleveland which allows for additional aluminum recovery (between 4-8 percent increase over existing processes) and the processing of the non-metallic portion (NMP) of the dross into usable products such as calcium aluminate for steel refining (Pickens 2000). The recycling of by-products nearly eliminates landfilling costs (\$20-40/ton) (Pickens 2000). Similar approaches for metal and salt recovery are also taking place in Europe and Japan. One system manufactured by Altek increases the initial recovery of dross through a dross press to very high levels, and requires further dross processing (Pawlek 2000).

The costs of recovery systems vary. A modern beverage can recycling facility can cost \$180 to \$360 per ton annual capacity (\$200-400/tonne annual capacity) (Pawlek 2000). About 20 percent of all recovered aluminum is from beverage cans (Aluminum Association 2000). The incremental investment cost for IDEX™ kiln technology is expected to be greater than existing decoating kiln technology, but is highly dependent on the initial kiln's sophistication (DeSaro 2000).

Environmental regulation may also be a driver for adopting new decoating kiln technologies. Recent regulations directed at the secondary aluminum industry regulate the emissions of particulate matter and of hazardous air pollutants (HAP) by limiting total hydrocarbon emissions (as a proxy for HAP). (DeSaro 2000, Federal Register 2000). New decoating and melt technologies that reduce emissions (the IDEX eliminates nearly all volatile organic compounds and significantly cuts other emissions) have become increasingly attractive for that reason. Yet, even these new technologies may still require add-on controls to meet EPA emission requirements (Santiago 2000).

This combination of drivers (productivity and environmental) promises for a rapidly growing market for advanced recycling technologies. Since its introduction as a commercial technology in 1999, there have been 2 IDEX™ kilns sold in the US market and 10 in other countries. Given standard uptake, this is fairly rapid (DeSaro 2000). These types of technologies should become standard for greenfield facilities since any increased installation costs are outweighed by the significance of environmental compliance as well as increased yield. Next steps include continued demonstration of recycling technologies.

## Inert Anodes/Wetted Cathodes (Alum-4)

The United States is the largest primary aluminum producer globally, with a production of 3.8 million tons (3.4 Mt) in 1999 from 23 primary plants (USGS 2000, OIT 1999). In 1994, primary aluminum production in the U.S. consumed 53,552 million kWh of electricity, or 2 percent of primary energy use in U.S. manufacturing. Average energy consumption in the US for aluminum production in 1994 was 16 kWh/kg and was estimated at 15 kWh/kg in 1997 (EIA 1997, USGS 2000, Energetics 1997). Energy consumption represents 20-30 percent of total production costs.

Primary aluminum production is an energy intensive continuous process and involves the electrolytic reduction of alumina into aluminum. This process, known as the Hall-Heroult smelting process, is accomplished in a series of cells or “pots” that are connected in long lines in buildings. In each cell the refractory material is overlaid with a carbon lining and a carbon cathode. The molten aluminum lies beneath a bath of cryolite that serves as the medium to dissolve incoming alumina and to conduct electricity from the anode to the aluminum. Alumina is fed into the top of each cell on top of a crust of cooler cryolite (which acts as an insulator), and the crust is periodically broken to allow the alumina to be stirred into the bath. When a strong electric current (50-225 kilo-Amperes) is passed through the electrodes into the bath, the alumina is reduced via a reaction to  $\text{Al}_2\text{F}_6$  (which is easier to reduce than  $\text{Al}_2\text{O}_3$ ), to produce molten aluminum. The voltage drop across the cell is 4-4.5V, while the voltage in a potline can exceed 1,000 volts (Gitlitz 1995). The molten aluminum is periodically siphoned off through the tops of cell into a holding furnace and then poured into ingots or billets, which are then cast and shaped. Most US cells use the pre-baked carbon anode technology in which multiple anodes are baked prior to consumption in the pots. As the anodes are consumed and periodically replaced every 14 to 20 days of operation, they produce carbon dioxide and carbon monoxide (about ½ pound of carbon per pound of aluminum produced) (EPA 1995).

Inert anode/wetted cathode technology is the next generation technology capable of significantly improving cell efficiency. The development of this technology is a high priority for the US primary aluminum industry (Margolis 1997). *Inert anodes* are made from materials that are not consumed during the electrolysis reaction. These new materials (such as cermets of nickel oxide or iron oxide, or copper) allow for a closer anode-cathode distance (thereby reducing electrolysis energy consumption), and eliminate the carbon anode production process as well as emissions of perfluorocarbons. *Wettable cathodes* (or drained cell technology) refer to cell designs that use new cathode materials (such as titanium diboride ( $\text{TiB}_2$ ) that are wetted by aluminum. The cathode can be sloped. This design eliminates the use of metal pads found in existing cells thereby reducing magnetically induced turbulence (the turbulence causes power loss and production inefficiency). It also allows for reduced anode-cathode distance better aluminum drainage, and improved cell operation (Welch 1999, Margolis and Eisenhauer 1998, ICF 1998, ASME 1999). The use of *bipolar electrode designs* (the packing of cells with many electrodes) as opposed to existing monopolar designs not only have the potential to increase cell productivity, but also may be the only configuration that can effectively utilize the inert anodes to reduce anode-cathode distance (ASME 1999, Welch 1999). The combination of these designs point toward the need for a systems approach to anode and cathode designs (ASME 1999).

Combined inert anode/wettable cathode technologies are estimated to reduce energy requirements by up to 25 percent or more from current levels, and the U.S. aluminum industry has set a long-term goal of 11 kWh/kg (Margolis and Eisenhauer 1998). As a separate retrofit, wettable cathodes can achieve savings of 2 kWh/kg (ASME 1999).

Inert anode technologies are not yet commercially available, and research has been ongoing for several decades. The most recent technical assessment report on this technology indicated that while various pilot scale designs are being tested by companies such as Moltech, Brooks Rand Ltd., Alcoa, and others, to date no fully acceptable inert anode materials have been revealed (ASME 1999, Brumm 2000). However, Van Leeuwen (2000) believes that Alcoa’s inert anode development is near commercial.

The wettable cathode technology appears to be near commercial as well. In the U.S., Reynolds (now Alcoa) and Kaiser (with U.S. DOE support) field-tested  $\text{TiB}_2$ -G material cathodes at the Kaiser Mead plant. These

## Inert Anode/Wettable Cathode Data Table

	Units		Notes	
inert anodes/wetted cathodes				
alum-4				
Inert anode technology				
Market Information:				
Industries		Aluminum		SIC 3334
End-use(s)		Process heating		
Energy types		Electricity		
Market segment		Retrofit, new		Primarily retrofit applications. Also greenfields
2015 basecase use	Mt	5.5		AEO 2000, smelting output
Reference technology				
Description	Hall-heroult cell, primary aluminum smelting			
Throughput or annual op. hrs.	tonne	1	Unit consumption presented. Smelters cell amperage range from 175-300 kA	
Electricity use	MWh	16.2	EIA, 1997, USGS, 2000	
Fuel use	MBtu	0.00	EIA, 1997, USGS, 2000	
Primary energy use	MBtu	137.9		
New Measure Information:				
Description	Efficient cell retrofits			
Electricity use	MWh	11	Margolis et al., 1998	
Fuel use	MBtu	0.00		
Primary Energy use	MBtu	93.5		
Current status	Not yet commercialized			
Date of commercialization	2005-2015			
Est. avg. measure life	Years	10	ASME 1999	
Savings Information:				
Electricity savings	MWh/%	5.2	32%	Savings compared to 1994 baseline
Fuel savings	MBtu/%	0.0	N/A.	
Primary energy savings	MBtu/%	44.4	32%	
Penetration rate	Medium			
Feasible applications	%	15%		
Other key assumptions				
Elec svgs potential in 2015	GWh	3943		
Fuel svgs potential in 2015	Tbtu	0		
Primary energy svgs potential in 2015	Tbtu	33.5		
Cost Effectiveness				
Investment cost	\$	1000	Assume replacement of existing potlines (ASME, 1999)	
Type of cost		Incremental	Incremental costs assumed	
Change in other costs	\$	-50	Credit Suisse, 2000	
Cost of saved energy (elec)	\$/kWh	0.03		
Cost of saved energy (fuel)	\$/Mbtu	N/A.		
Cost of saved energy (primary)	\$/Mbtu	3.36	Discount rate for all CCE calculations is 15%	
Simple payback period	Years	4.0		
Internal rate of return	%	25%		
Key non energy factors				
Productivity benefits		Significant	Reduced costs for anodes; reduced material losses	
Product quality benefits		Somewhat		
Environmental benefits		Significant	No CO2 emissions or perfluorocarbons	
Other benefits		Somewhat	Safety	
Current promotional activity	H,M,L	High		
Evaluation				
Major market barriers		Technical	Identifying appropriate materials, design and testing	
Likelihood of success	H,M,L	Medium		
Recommended next steps		RD&D		
Data quality assessment	E,G,F,P	Good		
Sources:				
2015 basecase			EIA 1999	
Basecase energy use			EIA 1999; USGS 2000	
New measure energy savings			Margolis et al. 1998; Van Leeuwen 2000	
Lifetime			ASME 1999	
Feasible applications			Author estimate	
Costs			ASME 1999; Van Leeuwen 2000	
Key non energy factors			Van Leeuwen 2000; ASME 1999	
Principal contacts			S. Dillich (OIT, U.S. DOE) sara.dillich@ee.doe.gov	
Additional notes and sources				

materials proved too difficult to maintain required quality in their manufacture (ASME, 1999). However, industrial research laboratories (Alcoa, Pechiney, Comalco, Commonwealth Aluminum, Kaiser) have all been continuing to work on wetted cathode technologies. Comalco (New Zealand) has built 25 TiB<sub>2</sub> wettable cathode commercial demonstration cells over the past decade (with government support) (ASME 1999). The Comalco technology combines TiB<sub>2</sub> with pitch to layer the cell bottom, while Reynolds and Kaiser are pursuing an approach to develop TiB<sub>2</sub> metal tiles for the cell bottom. The tile design might extend the wear life of the cell. The U.S. DOE is also supporting research with Northwest Aluminum Technology, Advanced Refractory Technologies, Material Modification Inc., Electrochemical Technology Corp., Brooks Rand Ltd., and Pacific Northwest Laboratory on wettable cathode development (DOE 2000c).

Since neither the inert anode nor the wetted cathode technology is commercially available, it is difficult to estimate the investment costs for the technology. Van Leeuwen (2000) asserts that inert anodes can be used in existing cells with minimal refit costs \$5-18/short ton (\$6-22/metric tonne) while wettable cathodes would have no refit costs. The use of a combined advanced anode/cathode cell in a bi-polar combination would probably be more appropriate for a greenfield facility. Current costs for total aluminum plants are \$3600-4000/short ton annual capacity (\$4,000-4,500/t) capacity, (Brumm 2000, Margolis and Eisenhauer 1998). The reduction of the anode baking facility would reduce costs by \$900/short ton (\$1,000/t). While advanced cell manufacturing would clearly be more expensive, the reduction in the cost of the anode production facility would offset some of the increase. ASME 1999 estimates a wide range of capital investment cost of \$3200-\$6800/short ton (\$3,500-7,500/t). We conservatively assume in our analysis an incremental cost of \$900/ton (\$1,000/t) capacity.

In addition to energy savings, advanced cell technologies could have significant environmental benefits since they would eliminate the emissions of carbon dioxide and per-fluorocarbons, which are greenhouse gases (GHGs) with very high global warming potentials (Margolis and Eisenhauer 1998, ASME 1999). These environmental benefits could become significant in light of increasing concern about global warming and reduction of GHGs. However, just as important are several productivity benefits drive the development of this technology. Van Leeuwen (2000) estimates reduced costs in potroom labor and up to 20 percent increases in productivity, as well as improved health and safety. Also, product quality is likely to improve since less material is contaminated by anode dissolution into the metal (Margolis and Eisenhauer 1998).

The barriers to the development of advanced cells incorporating inert anodes and wettable cathodes are primarily technical and economic. Appropriate anode materials have yet to emerge, and additional modeling and systems based research approaches are going to be needed to achieve commercialization. The American Society of Mechanical Engineers rated the likelihood of success of an inert anode breakthrough as low (ASME 1999). However, a recent evaluation of the potential of both the inert anode and wettable cathode technology from Credit Suisse/First Boston rated the likelihood of success of both technologies as high, with commercialization of the anode and cathode technology separately within five years (Van Leeuwen 2000). Even if inert anode and wettable cathode technologies emerge as retrofit options for existing potlines within the next 5 years, a combined advanced cell technology, more likely suited for greenfield facilities is a more distant reality and could limit rapid expansion into the domestic market. Additional research and demonstration are needed to move the market forward in for this technology.



### **Continuous Melt Silicon Crystal Growth (Electron-1)**

Semiconductor devices are primarily fabricated from monocrystalline silicon, which is produced from polycrystalline silicon. The most common process used to produce single crystals from molten silicon is the Czochralski (CZ) method. In the CZ process, crushed polycrystalline silicon is doped with arsenic, boron, phosphorus, or antimony and melted at high temperatures in a quartz crucible. A pull rod with a small silicon “seed” at the end is lowered into the molten liquid and rotated in a clockwise direction. When the rod is slowly pulled from the melt, a surface tension between the seed and the molten silicon is created, thereby causing a small amount of the liquid to rise with the seed. This liquid cools because of the lower temperature above the melt and forms a single crystal silicon ingot that has the same structural orientation as the seed. The crucible is rotated in a counterclockwise direction to create an eddy current that carries contaminants away from the crystal. The crucible and other components are surrounded by a containment structure that is filled with argon gas. The purpose of the gas is to carry away oxygen, a contaminant, before it reaches the crystal at the melt surface. The ingot diameter is determined by the temperature of the melt pool and the speed at which the rod is extracted. Most ingots are produced in 150mm and 200mm. The length of the ingot is determined by the amount of molten silicon in the crucible.

Siemens Solar Industries has developed a process to improve the production of silicon ingot. The project is expected to reduce energy consumption by 40 percent, reduce cycle times by 15 percent, and improve silicon quality. The key changes to the process include additional insulation in the walls of the crucible and at the top of the molten hot zone, the addition of a conical shield above the crucible, and the addition of a continuous recharge system. The additional insulation reduces heat transfer from the melt surface, improves control over the temperature gradients at the melt surface, and allows the rod to be pulled more rapidly.

All silicon produced for both semiconductor and solar photovoltaic end-uses are produced in batch. A continuous recharge system would allow the introduction of material during the run and would permit the growing of longer silicon ingots. The challenges to continuous melt growth include maintaining the growing environment, maintaining acceptable temperatures and temperature gradients when introducing materials, insuring the uniformity of the melted material, avoiding disturbance of the melt surface, and avoiding contaminating the silicon being drawn from the melt.

The market for monocrystalline silicon for semiconductors and photovoltaics is projected to grow at about 11 percent per year (EIA 1999). There are currently seven major manufacturers in the US who produce semiconductor grade silicon. They are Wacker, SHE, Komatsu, Mitsubishi Silicon America, MEMC, Sumitomo-SiTiX, and Motorola. The market for semiconductor silicon was about 12,100 short tons in 1995 and is estimated to reach over 60,000 short tons by 2015.

The market for solar photovoltaic silicon represents about 5 percent of the total market for silicon. The solar industry has been dominated by single crystal silicon, of which Siemens is a major player in the market. The other companies involved in the solar market include Solarex, BP Solar, Evergreen Solar, ASE Americas, Photowatt, Sharp, and Kayocera. There has been a continued demand for solar products that is expected to continue. Even though the current market for monocrystalline silicon is primarily for semiconductor manufacture, the continuous melt technology may bring down the costs of photovoltaics to a more competitive level and create an even larger demand for the material. This technology has a high likelihood of success.

## Continuous Melt Silicon Growth Data Table

	Units		Notes
<b>Continuous Melt Silicon Crystal growth</b>			
<b>Electron-1</b>			
<b>Replace batch crystal growth - Czochralski (CZ) method</b>			
<b>Market Information:</b>			
Industries		Semiconductor	SIC 3674
End-use(s)		Process heating, other	
Energy types		Electricity	
Market segment		New, replace on failure, retrofit	
2015 basecase	tons	60309.00	Gross output increases 598% between 1995 (12,100 tons) and 2015
<b>Reference technology</b>			
Description		Czochralski (CZ) method	
Throughput or annual operating hours	tons	1.00	
Electricity use	kWh	54540	Reed, et al. 1999
Fuel use	MBtu	0	
Primary Energy use	MBtu	465.2	OIT 1998
<b>New Measure Information:</b>			
Description		Continuous melt silicon crystal growth	
Electricity use	kWh	27273	Personal communication with Greg Mihalik, 2000
Fuel use	MBtu	0	
Primary Energy use	MBtu	232.6	
Current status		Pilot plant	Personal communication with Greg Mihalik, 2000
Date of commercialization		2003	
Estimated average measure lifetime	Years	7	Personal communication with Greg Mihalik, 2000
<b>Savings Information:</b>			
Electricity savings	kWh/%	27267	0.50
Fuel savings	MBtu/%	0.00	0.00
Primary energy savings	MBtu/%	232.6	0.50
Penetration rate		Medium	
Feasible applications	%	40%	
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	657.8	
Fuel savings potential in 2015	Tbtu	0	
Primary energy savings potential in 2015	Tbtu	5.61	
<b>Cost Effectiveness</b>			
Investment cost	\$	629076	Cost of modifications to the grower plus cost of recharge system
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	125815	Estimate 20 percent of incremental cost
Cost of conserved energy (electricity)	\$/kWh	10.16	
Cost of conserved energy (fuel)	\$/Mbtu		
Cost of conserved energy (primary energy)	\$/Mbtu	1191	
Simple payback period	Years	-5.04	
Internal rate of return	%	#DIV/0!	
<b>Key non energy factors</b>			
Productivity benefits		Significant	Pot scrap has been reduced from about 8.8 to 2.2 lbs per run
Product quality benefits		Somewhat	
Environmental benefits		Somewhat	Reduced scrap
Other benefits			
Current promotional activity	H,M,L	High	
<b>Evaluation</b>			
Major market barriers		Dependent on markets	
Likelihood of success	H,M,L	High	
Recommended next steps		Research, scale-up	Testing to create a truly continuous process
Data quality assessment	E,G,F,P	Excellent	
<b>Sources:</b>			
2015 basecase			Reed, et al. 1999
Basecase energy use			EIA 1999
New Measure energy savings			Personal communication with Greg Mikalik, 2000
Lifetime			Personal communication with Greg Mikalik, 2000
Feasible applications			Reed, et al. 1999
Costs			Personal communication with Greg Mikalik, 2000
Key non energy factors			
Principal contacts			
Additional notes and sources			

**Advanced ASD Designs (Motorsystems-1)**

Motors consume over 60 percent of industrial electricity in the United States (Xenergy 1998). Adjustable speed drives (ASD) have revolutionized motor systems by allowing for affordable, reliable speed control using rugged conventional induction motors. ASDs work by varying the frequency of the electricity supplied to the motor, thus changing the motor's speed relative to its normal supply frequency, which in the U.S. is 60 Hz. This trick is accomplished by rectifying supplied alternating current to direct current and then synthesizing an alternating current at another frequency. The current method of synthesization is accomplished using an inverter, which is a solid-state device in modern ASDs. Ideally, the waveform of this synthesized current should look like a smooth sine wave. Unfortunately, the three major kinds of inverters in use: voltage-source (VSI), plus-width modulation (PWM) and current-source (CSI), with PWM being the most common used in integral horsepower drives. All create an approximation of a sine wave, though with some distortion. This distortion creates losses in the motor due to heating of the conductors and vibration, which have the effect of shortening the life of the motor. Special inverter duty motors are made which use a higher rating of insulation that extends motor life. The ideal solution would however be to design an inverter that produced a smoother wave pattern (Nadel et al. 2000).

A number of researchers are actively working on the development of different inverter topologies (Peng 2000, von Jouanne 2000). Most of these topologies fall into the category of soft-switching inverters, which significantly reduce the voltage spikes that characterize PWM inverters. Reductions in these spikes can dramatically increase the life of the attached motor (Kueck 2000). One example of this technology is the snubber inverter developed at Oak Ridge National Laboratory. ASDs using this technology have an efficiency of about 98 percent compared to a PWM drive at 96 percent efficiency, for drives operating in the 10-20 kHz range. These soft-switching inverters enable the design of faster switching devices, which can further improve the waveform of the output (Peng 2000).

Several manufacturers, including Rockwell Automation and Allen Bradley, have begun to offer soft-switched inverters as premium products for use in sensitive applications such as medical devices. While these advanced inverters require more complex control strategies than do PWN inverters, they allow the substitution of semiconductor devices for electronic components such as filters. In addition, the improved inverter efficiency will make thermal management in the drives easier, reducing the mass of heat sink required and allowing for more compact packaging of the drive. These tradeoffs are likely to reduce the cost to about the same level as PWM drives. In the long run, soft-switching inverters could displace PWM inverters in most applications if the costs can be brought down (Peng 2000).

These drives face a number of barriers. The most significant appears to be the cost of these drives due in large part the manufacturers' investment in existing technology. Another issue is that of intellectual property. While manufacturers have expressed interest in licensing the ORNL technology, they were unable to come to terms with the Lab. They have subsequently developed their own soft-switching technology (Peng 2000).

While it is likely that this advanced drive technology is likely to eventually succeed in the market, continued research is needed to further the development of these devices and reduce their cost.

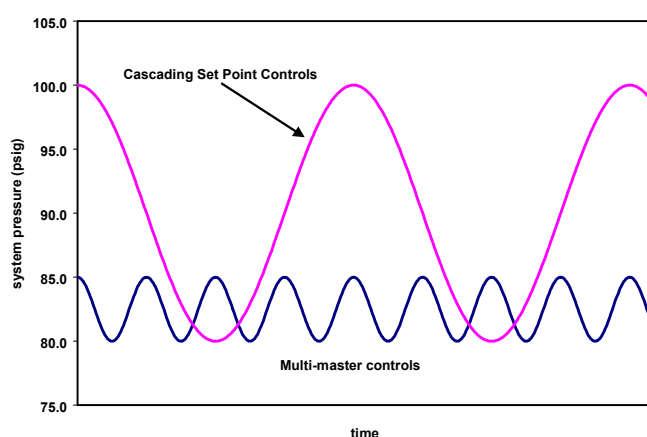
# Advanced ASD Designs Data Table

	Units	Notes	
Advanced ASD Designs			
Motorsys-1			
Replace existing ASD technologies with advanced designs			
Market Information:			
Industries		Cross cutting	
End-use(s)		Motors and drives	
Energy types		Electricity	
Market segment		New, replacement, OEM	Direct replacement for conventional ASDs
2015 basecase	GWh	7,825,322	Motor systems consume approximately 60% of industrial electricity
Reference technology			
Description	Conventional PWM inverter with 100 hp inverter-duty induction motor at 95.4% efficiency		
Throughput or annual operating hours	hours	6000	Assumes 7 day per week/16 hour per day
Electricity use	kWh	88	Based on 96% inverter efficiency and 60% of full load
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.749	
New Measure Information:			
Description	Soft-switching inverter with 100 hp inverter-duty induction motor at 95.4% efficiency		
Electricity use	kWh	86	Based on 98% inverter efficiency and 60% of full load
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.734	
Current status		Commercial	Limited production, special order for premium applications
Date of commercialization		1998	
Estimated average measure lifetime	Years	15	
Savings Information:			
Electricity savings	kWh/%	2	2%
Fuel savings	MBtu/%	NA	
Primary energy savings	MBtu/%	0.015	2%
Penetration rate		Medium	45% penetration - Because of advantages, likely to displace some current ASD technologies
Feasible applications	%	45%	Feasible in all application
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	71,865	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	24.5	
Cost Effectiveness			
Investment cost	\$	800	Assumes a 10% price premium with PWM cost at \$80/hp
Type of cost		incremental	Unlikely to be retrofitted
Change in annual costs (O&M/other benefits)	\$	(301.367)	Prorated replacement cost reflecting motor life extension from 5 to 7 years
Cost of conserved energy (electricity)	\$/kWh	< 0	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	< 0	Discount rate for all CCE calculations is 15%
Simple payback period	Years	1.11	
Internal rate of return	%	90%	
Key non energy factors			
Productivity benefits		Significant	Improved motor reliability due to reduced stress as discussed in text
Product quality benefits		Somewhat	Improved process control
Environmental benefits		None	
Other benefits			
Current promotional activity	H,M,L	Medium	Focus is largely on R&D, with some specialty deployment by manufacturers
Evaluation			
Major market barriers		Cost, more sophisticated design, intellectual property issues	
Likelihood of success	H,M,L	High	
Recommended next steps		Continued R&D	
Data quality assessment	E,G,F,P	Good	For all factors except for cost, which is a preliminary assumption.
Sources:			
2015 basecase		Nadel et al. 2000, Xenergy 1998	
Basecase energy use		Nadel et al. 2000, Peng 2000	
New Measure energy savings		Peng 2000	
Lifetime		Peng 2000	
Feasible applications		Nadel et al. 2000, Peng 2000	
Costs		Nadel et al. 2000, Peng 2000	
Key non energy factors		Nadel et al. 2000, Peng 2000	
Principal contacts		Fong Peng, ORNL	pengfz@ornl.gov
Additional notes and sources			

## Advanced Compressor Controls (Motorsystems-2)

About 9 percent of industrial electricity is used to produce compressed air (Xenergy 1998). Controls match the air supply from the compressors with system demand, regulating the pressure between two levels called the control range. They are one of the most important factors in determining the overall energy efficiency of a compressed air system. Most compressed air systems typically consist of several compressors delivering air to a common header. The objective is to shut off or delay starting a compressor until it is needed. To this end, the controls try to operate all units at full-load, except the one used for trimming (adjusting compressed air supply based on the fluctuations in compressed air demand).

In the past, control technologies were slow and imprecise. This resulted in wide control ranges and higher compressor set points than needed to maintain the system pressure above a minimum level. Most systems were controlled using an approach known as cascading set points. The set points for each individual compressor would either add or subtract the compressor capacity to follow the system load. This approach led to wide swings in system pressure, as shown in figure below (DOE 1998).



### Impacts of controls on system pressure (DOE 1998).

control, coming in systems capable of handling four or more compressors (Perry 2000). They provide both individual compressor control and system regulation by means of a network of individual controllers. The controllers share information, allowing the system to respond more quickly and accurately to demand changes. One controller acts as the lead, regulating the whole operation. This strategy allows each compressor to function at a level that produces the most efficient overall operation. The result is a highly controlled system pressure that can be reduced close to the minimum level required (DOE 1998).

These controls match system demand with compressors operated at or near their maximum efficiency points, and allow the system pressure to be set lower (Figure 1). Every 2-psi of pressure difference produces about a 1 percent change in energy consumption, so for this example, the system pressure can be reduced 15 psi, thus yielding about a 7.5 percent energy reduction. Although costing \$1000 per compressor more than other controls, these controls represent the most energy-efficient system available (Perry 2000).

In addition, to energy savings, the application of controls can eliminate the need for some existing compressors, allowing extra compressors to be sold or kept for backup. Alternatively, capacity can be expanded without the purchase of additional compressors. The reduced operating pressure will reduce system maintenance requirements. Also, a more constant pressure level can enhance production quality control by providing more precise operation of pneumatic equipment (DOE 1998).

In spite of the attractive return, there are two principal barriers to the use of this technology: higher first cost, and lack of appreciation of the importance of compressed air system efficiency. Educational efforts,

Modern microprocessor-based technologies allow for much tighter control ranges as well as lower system-pressure-control points. The largest benefits of these controls can be obtained in multi-compressor systems, which are much more complex and sophisticated. Controls for single compressors can be relatively simple. System controls coordinate the operation of multiple individual compressors when meeting the system requirements.

Two general kinds of system controllers exist: single-master (sequencing) controls and multi-master (network) controls. Multi-master controls are the latest technology in compressed air system

such as the Compressed Air Challenge (CAC 2000), are key to the expanded deployment of these technologies.

### Advanced Compressor Controls Data Table

	Units	Notes	
Advanced compressor controls			
Motorsys-2			
Use of microprocessor-based air compressor controls in place of conventional cascading setpoint controls			
Market Information:			
Industries		Cross-cutting	
End-use(s)		Motors and drives	
Energy types		Electricity	
Market segment		Retrofit, new	
2015 basecase	GWh	1,173,798	Compressed air is approximately 9% of industrial electricity
Reference technology			
Description	Multiple screw compressor system using cascading setpoint controls		
Throughput or annual operating hours	cfm/hr	100	Assumes 6,000 annual operating @ 30% of rated capacity
Electricity use	kWh	16.4	Based on average 22hp/cfm (DOE 1998)
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.140	
New Measure Information:			
Description	Multiple screw compressor system using microprocessor-based, multi-master controls		
Electricity use	kWh	15.8	System control pressure reduced from 90 to 82.5 psi w/ 1% savings per 2 psi
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.135	
Current status		Commercial	
Date of commercialization		1992	
Estimated average measure lifetime	Years	15	
Savings Information:			
Electricity savings	kWh/%	0.6	3.5%
Fuel savings	MBtu/%	NA	
Primary energy savings	MBtu/%	0.005	3.5%
Penetration rate		Medium	45% penetration in 2010
Feasible applications	%	23%	Assumes half of energy use in large, multi-compressor systems
Other key assumptions for savings	Reducing system pressure will result in additional savings from reduced leak volumes discussed in motorsys-3		
Electricity savings potential in 2015	GWh	9,244	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	3.2	
Cost Effectiveness			
Investment cost	\$	150	Prorated cost per 100 cfm assumes controls ~\$1000 per compressor for 4 or more compressors (Perry 2000)
Type of cost		Full	
Change in annual costs (O&M/other benefits)	\$	0	
Cost of conserved energy (electricity)	\$/kWh	0.0002	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	20.9	Discount rate for all CCE calculations is 15%
Simple payback period	Years	0.04	
Internal rate of return	%	5824%	
Key non energy factors			
Productivity benefits		Significant	Improved pressure control increases available capacity and improves equipment operation
Product quality benefits		Somewhat	Precise pressure control may improve equipment performance
Environmental benefits		None	
Other benefits		Significant	May avoid need for addition compressor purchase or allow retirement of existing compressor with resulting reduced O&M and salvage value
Current promotional activity	H,M,L	Low	Focus has been on compressed air system optimization
Evaluation			
Major market barriers		High first-cost; lack of appreciation of compressed air system savings.	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Education programs	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase	EIA 1999; Xenergy 1998; Nadel, et al, 2000		
Basecase energy use	Nadel, et al, 2000		
New Measure energy savings	Nadel, et al, 2000		
Lifetime	Nadel, et al, 2000		
Feasible applications	Nadel, et al, 2000; Xenergy 1998		
Costs	Perry 2000		
Key non energy factors	Nadel, et al, 2000		
Principal contacts	Neal Elliott, ACEEE		
Additional notes and sources	melliott@aceee.org		

### **Compressed Air System Management (Motorsystems-3)**

Compressed air (CA) systems consume about 9 percent of industrial electricity (Xenergy 1998). They are made up of an assemblage of components including the motor and drive, the air compressor itself, controls, air treatment equipment, piping, and, often, storage. Typical compressed air system wire-to-air efficiencies are around 10 percent (DOE 1998).

Achieving peak compressed air system performance requires addressing the performance of individual components, analyzing the supply and demand sides of the system, and assessing the interaction between the components and the system. This “systems approach” moves the focus away from components to total system performance. System opportunities have been shown to be the area of greatest efficiency opportunity. At the system level, savings opportunities can be grouped into three general categories: leaks, inappropriate uses of CA, and system pressure level. The goal of a management plan is to minimize all three.

Leaks can be a significant source of wasted energy, often accounting for 20-30 percent of compressor output. They can also contribute to other production problems. A drop in system pressure can adversely affect equipment performance and efficiency, and the increased compressor runtime needed to satisfy the leak will lead to increased equipment maintenance and unscheduled downtime. Leak detection and repair is a critical element of a compressed air system maintenance program. Typically, the worst leaks are in remote areas of the plant, such as abandoned equipment and roofs. Some leaks are inevitable, but a well-maintained system can keep them under 10 percent. Unfortunately, even when leaks are identified and repaired, the job is not over. New leaks will develop over time. The best strategy to avoid further problems is to set up a prevention program that monitors the system for new leaks and fixes them as they develop (DOE 1998).

Many leaks are intentional, because compressed air is clean and usually readily available. Many people choose it for applications without comparing it to more economical energy sources. Alternatives are available and should be considered for many CA applications. Examples include circuit box and personal cooling that could be done with a blower, or an open pipe that is used to remove dust from a product, when a mechanical brush would accomplish the same function with lower noise (DOE 1998).

A system’s pressure level should be set at the lowest pressure that meets all requirements of the facility. Lowering the compressed air header pressure by 10 psi reduces the air leak losses by approximately 5 percent and improves centrifugal compressor capacity by 2-5 percent. One element of this may be the application of controls, as is addressed in technology motorsys-2. Reducing system pressure also decreases stress on system components, lessening the likelihood of future leaks (DOE 1998).

The optimization process is an approach that addresses these opportunities in a systematic way. Because of the experience required, a CA expert usually offers this analysis as a service. These experts have found that after they implement the measures identified in a thorough review of the system, either one or more compressors can be shut down or a compressor can be downsized, with energy savings frequently exceeding 40 percent. While a survey by an expert can be an important step in establishing the plan, it is necessary to implement an ongoing maintenance program by plant staff, which requires both awareness and technical training (DOE 1998).

Reductions in wasted air due to inadequate maintenance, leaks, and inappropriate uses can save 20-30 percent of CA energy. Although costs will likely vary from near zero to more than 5 cents/kWh, depending on the measure and the facility, Suozzo and Nadel (1998) estimate an average cost of saved energy of 1.5 cents/kWh.

Most of the barriers to improved compressed result from lack of awareness of the opportunity. The staff reductions that have become common in United States industry and a hesitation to use pay for outside consultants compounds this problem.

The Compressed Air Challenge (CAC) has developed a CA management training program that is available for plant staff, and the Compressed Air and Gas Institute (CAGI) has developed a CA experts train

# Compressed Air System Management Data Table

	Units	Notes	
Compressed air system management			
Motorsys-3			
Implement a management plan to minimize system energy requirements and reduce leaks and inappropriate uses			
Market Information:			
Industries		Cross cutting	
End-use(s)		Motors and drives	
Energy types		Electricity	
Market segment		Retrofit	
2015 basecase	GWh	1,173,798	Compressed air is approximately 9% of industrial electricity
Reference technology			
Description		Assumes CA system using screw compressors	
Throughput or annual operating hours	cfm/hr	100	
Electricity use	kWh	1640	Based on average 22hp/cfm (DOE 1998)
Fuel use	MBtu	NA	
Primary Energy use	MBtu	13.989	
New Measure Information:			
Description		Survey eliminates 25% of CA demand by identification of leaks and inappropriate uses	
Electricity use	kWh	1230	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	10.492	
Current status		Commercial	
Date of commercialization		pre 1980	
Estimated average measure lifetime	Years	1.5	Measure requires regular reviews and resurveying as discussed in text
Savings Information:			
Electricity savings	kWh/%	410	25%
Fuel savings	MBtu/%	NA	
Primary energy savings	MBtu/%	3.497	25%
Penetration rate		medium	45% penetration in 2010
Feasible applications	%	23%	Feasible in 50% of compressed air system capacity
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	66,026	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	563	
Cost Effectiveness			
Investment cost	\$	0	No equipment purchases usually required
Type of cost		Full	
Change in annual costs (O&M/other benefits)	\$	6.15	Fee and staff time cost ~\$0.015 per kWh saved (Nadel et al 2000)
Cost of conserved energy (electricity)	\$/kWh	0.015	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	1.8	Discount rate for all CCE calculations is 15%
Simple payback period	Years	0.38	Based on increase in O&M cost
Internal rate of return	%	undefined	Since there is no capital cost, IRR undefined
Key non energy factors			
Productivity benefits		Significant	Improve system operation and increases pressure stability
Product quality benefits		Somewhat	More precise pressure control may allow for improved equipment performance
Environmental benefits		None	
Other benefits		Significant	May avoid need for addition compressor purchase or allow retirement of existing compressor with resulting reduced O&M and salvage value
Current promotional activity	H,M,L	Medium	CAC is providing training and limited trade marketing
Evaluation			
Major market barriers		Customer awareness and availability of trained CA system experts	
Likelihood of success	H,M,L	Medium	Significant problems have been encountered with conveying message
Recommended next steps			
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase		EIA 1999; Xenergy 1998; Nadel, et al, 2000	
Basecase energy use		DOE 1998	
New Measure energy savings		DOE 1998	
Lifetime		DOE 1998	
Feasible applications		Nadel, et al, 2000; Xenergy 1998, DOE 1998	
Costs		Nadel, et al, 2000	
Key non energy factors		DOE 1998	
Principal contacts		Bill Scales	516-248-9096
Additional notes and sources			



## **Motor Diagnostics (Motorsystems-4)**

Motors consume about two-thirds of industrial electricity. Once placed in service, a motor will operate for years and receive minimal attention before it fails. At that point the motor is likely to be repaired and placed back in service. Mean time between failures is seven to ten years, and motors are typically repaired three times in their life. During a motor's service life, many changes can take place that affect a motor's performance. The loads that the motor is servicing are likely to change, frequently resulting in a mismatch between the motor and its new load. The motor itself can also deteriorate mechanically and electrically. These changes can reduce the efficiency and reliability of the motor. The most common problem is bearing wear, which can ultimately lead to failure that usually damages the windings of the motor (Nadel et al. 2000).

A number of techniques have been used for many years to assess the performance of motors. These techniques have ranged from monitoring the temperature of bearings, monitoring vibration, and measuring the voltage and currents for the different phases, to extensive test bench evaluations for performance and efficiency. These tests can detect changes in motors that indicate that it should be resized for a changing load, repaired or replaced before it fails. However, in the past these test procedures have been labor intensive and expensive, often requiring that the motor be removed from service. As a result, these tests are infrequently used, and the motor is left in service until failure (Nadel et al. 2000).

Over the past decade, a number of new diagnostic devices have been introduced that make in-service testing much easier. These tests make use of advanced sensors and on-board computing to measure temperature, voltage, current, harmonics and flux density. These data allow for various analyses such as current signature that can assess performance and efficiency and detect problems before they lead to an in-service motor failure, allowing them to be repaired during normal service cycles (Nadel et al 2000). While there may be some secondary energy savings, it is unclear that this family of technologies offers any direct energy savings. The primary benefit is reduced downtime (Boteler 2000).

Some manufacturers have begun to offer built in diagnostics as an option on new motors. These motors are positioned for mission critical applications and are intended to be integrated into a plant-wide monitoring and control network. The network uses the motor data to provide "conditioned-based" monitoring of critical components. Conditioned-based is the successor to predictive maintenance, allowing for improved reliability, availability and continuous system optimization through monitoring of system conditions. Integrated retrofit modules are also available for some newer motors. Current cost per motor for these advanced motor diagnostic packages is about \$1000, though with volume it is projected that the cost could fall to the \$750 range (Boteler 2000).

Conditioned-based monitoring of motors offers a number of significant non-energy benefits. By identifying motors prior to failure, additional damage resulting from the failure can be avoided, thus reducing repair costs and avoiding potential permanent damage to the motors (Nadel et al 2000). By preventing most in-service failures, system availability is significantly increased, thus increasing annual throughput. This additional production capability can avoid the need to make capital investments to expand production (Boteler 2000).

The major barriers to the adoption of motor diagnostics are the first cost of the equipment and the need to implement management practices necessary to realize the benefits. Case studies and education of end-users on the benefits are the most important actions to encourage more rapid adoption of the technology. Several programs, such as those offered by Sacramento Municipal Utility District and the Northwest Energy Efficiency Alliance have already begun to develop programs to build customer awareness of this technology (Nadel, et al., 2000).

**Motor Diagnostics Data Table**

	Units	Notes	
Motor diagnostics			
Motorsys-4			
Use of external or internal sensor and monitoring system to assess the operational status of motors			
Market Information:			
Industries		Cross cutting	
End-use(s)		motors and drives	
Energy types		electricity	
Market segment		new, OEM, replacement	
2015 basecase	GWh	7,825,322	Motor systems are approximately 60% of industrial electricity
Reference technology			
Description	EPAct TEFC 100 HP induction motor		
Throughput or annual operating hours	hrs	6000	Assumes 7 day per week/16 hour per day
Electricity use	kWh	89.4	Assumes average 60% load, 94.1% efficiency
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.762	
New Measure Information:			
Description			
Electricity use	kWh	89.4	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.762	
Current status		Commercial	
Date of commercialization		1999	
Estimated average measure lifetime	Years	15	
Savings Information:			
Electricity savings	kWh/%	0.0	0%
Fuel savings	MBtu/%	NA	NA
Primary energy savings	MBtu/%	0.000	0%
Penetration rate		medium	45% likely penetration
Feasible applications	%	11%	Justified in 25% of motors
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	0	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	0	
Cost Effectiveness			
Investment cost	\$	750	Cost per motor, independent of size, in 2015
Type of cost		Incremental	
Change in annual costs (O&M/other benefits)	\$	-1500	Wide range of benefits based on specific application
Cost of conserved energy (electricity)	\$/kWh	NA	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	NA	Discount rate for all CCE calculations is 15%
Simple payback period	Years	immediate	
Internal rate of return	%	200%	
Key non energy factors			
Productivity benefits		Compelling	Can increase uptime which results in increased annual production
Product quality benefits		Somewhat	Increased uptime reduce product fluctuations
Environmental benefits		None	No direct benefits, though indirect benefits may be significant
Other benefits		Somewhat	May be able to avoid plant capital expansions due to increased production
Current promotional activity	H,M,L	Low	Vendors just beginning to promote and some regional programs offering
Evaluation			
Major market barriers	First cost and lack of management infrastructure necessary to realize benefits		
Likelihood of success	H,M,L	High	Non-energy benefits are compelling
Recommended next steps	Demonstration and education		
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase	EIA 1999, Nadel, et al 2000; Xenergy, 1998		
Basecase energy use	Nadel, et al 2000		
New Measure energy savings	Boteler 2000		
Lifetime	Boteler 2000		
Feasible applications	Elliott 2000		
Costs	Boteler 2000		
Key non energy factors	Boteler 2000, Nadel et al 2000		
Principal contacts	Rob Boteler, USEM 314-553-1179		
Additional notes and sources			

## Motor System Optimization (Motorsystems-5)

Motor systems are made up of a range of components centered around a motor-driven device such as a pump or fan. Systems performance optimization focuses on optimizing the flows in motor-driven systems, principally fan and pump systems, to meet end-use requirements. The opportunity derives from the physical fact that the power consumption of fans and pumps varies as the cube of the speed, while output varies linearly. As a result, small changes in motor speed can yield large energy savings, so it is important to closely match output to end-use requirements. This concept is referred to as “the systems approach.”

Because accomplishing this goal requires specialized analytical and design skills, the concept has been deployed as a service. The Performance Optimization Service (POS) is built on Canadian utilities’ Performance Optimization program, which focused on identifying applications for adjustable speed drives (ASDs). ASDs represent one means of matching motor speed when the end-use requirements vary. Field experience has shown that most loads do not vary significantly, and speed can be varied by changing fan pulleys or trimming pump impellers (Nadel et al. 2000).

The Energy Center of Wisconsin (ECW) ran a POS program from 1994 to 1998. In the ECW POS program, customer service representatives identified candidate projects. A POS engineer then offered the customer a quick, free engineering “walk through” analysis of their systems. If substantial savings were projected, a feasibility-study proposal was prepared to determine what needed to be done to improve efficiency and performance, and how much it would save the customer. Once a proposal was accepted, a POS engineer collected system-load and operating data, and prepared a feasibility study report, which recommended a design strategy and details on the technical and economic impacts of the project (Nadel et al. 2000). In another program, DOE, EASA, PG&E, California Energy Commission (CEC) and local motor distributors deployed a POS program targeted at water and wastewater pumping, based on several previous demonstration projects. They organized O&M pumping workshops for Northern California American Water Works Association (AWWA) members. The workshops focused on how to choose motors and pumps, maintenance and operation practices, and motor and pump repair (Oliver 1999).

The POS programs have evolved over time, and have come to focus on providing information and convenience for the customer. POS now gives customers a comprehensive proposal right after the initial walkthrough, outlining what needs to be done and what it will cost and save. This immediate feedback keeps up momentum and motivation. POS also provides technical expertise to customers throughout the process, which is a key factor in building customer confidence in the program. POS success is attributed to identifying opportunities throughout the process, which is facilitated by training customers. Credibility is enhanced by the objectivity of the service provider (Wroblewski 1996).

Based on the ECW program experience, typical energy savings from fan, pump, or blower-system upgrades are estimated at 20 to 50 percent for systems identified as good candidates for POS. To be conservative, we have chosen the bottom of the range for our calculations. Based on known and estimated costs and energy savings for sites that are proceeding toward implementation, the average payback is 1.2 years. These estimates do not account for productivity gains known to exist at many of the sites (Hanson 1997).

Experience with POS has found that it is difficult to promote for a number of reasons. First, the concept is complex and difficult to explain even to a technical audience. This barrier is more difficult with smaller companies, where the customer is less technically-versed than in larger industries. Engineering fees account for most of a project’s cost, and customers have shown a reluctance to approve these expenditures. Since limited customer demand has been evidenced for these services, the engineering design community has been reluctant to develop the required specialized skills (Nadel et al 2000).

While POS offers significant energy and cost savings and performance enhancements, customer awareness and demand for the service must be developed. Possible strategies include case studies, training and seminars, and partnering with the design engineering community to help them market this service to candidate customers.

**Motor System Optimization Data Table**

	Units	Notes	
Motor system optimization			
motorsys-5			
Survey of operating conditions for an existing pump or fan system, with the goal of matching output to process demand			
Market Information:			
Industries		Cross cutting	
End-use(s)		Motors and drives	
Energy types		Electricity	
Market segment		Retrofit	
2015 basecase	GWh	7,825,322	Motor systems are approximately 60% of industrial electricity
Reference technology			
Description		Existing 20 HP exhaust fan system with damper controls	
Throughput or annual operating hours	hrs	6000	
Electricity use	kWh	5.8	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.050	
New Measure Information:			
Description		Reduce motor speed to match flow requirements by changing belts and pulleys	
Electricity use	kWh	4.7	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.040	
Current status		Commercial	
Date of commercialization		~1980	Application of standard engineering practice, formalized in early 1980s
Estimated average measure lifetime	Years	10	Systems tend to fall out of optimization due to facility changes
Savings Information:			
Electricity savings	kWh/%	1.2	20% Savings are not dependent upon existing equipment efficiencies
Fuel savings	MBtu/%	NA	NA
Primary energy savings	MBtu/%	0.010	20%
Penetration rate		Medium	45% penetration in 2010
Feasible applications	%	11%	Feasible in 25% of industrial motor loads
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	176,070	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	1,502	
Cost Effectiveness			
Investment cost	\$	410	Cost of replacing belts and pulleys, plus two hours of engineering at \$100/hour
Type of cost		Full	
Change in annual costs (O&M/other benefits)	\$	0	If fan speed is reduced, bearing life my be extended
Cost of conserved energy (electricity)	\$/kWh	0.0117	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	1.368	Discount rate for all CCE calculations is 15%
Simple payback period	Years	1.50	
Internal rate of return	%	67%	
Key non energy factors			
Productivity benefits		Significant	Better matching of motor driven equipment to demand can improve process throughput, and may allow free up capacity for expansion.
Product quality benefits		Significant	Better matching of motor driven equipment to demand can improve process control
Environmental benefits		Somewhat	Reduced fan speed can reduce environmental noise
Other benefits		Significant	Reduced fan speed can reduce worker noise exposure
Current promotional activity	H,M,L	Low	
Evaluation			
Major market barriers		Lack of knowledge, reluctance to pay engineering fees, lack of skilled providers	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Expanded end-user education, development of engineering training	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase		EIA 1999, Nadel et al 2000, Xenergy 1998	
Basecase energy use		Nadel et al 2000, Xenergy 1998	
New Measure energy savings		Nadel et al 2000, Wroblewski 1996, Martin 1999, Hanson 1997	
Lifetime		Nadel et al 2000, Wroblewski 1996, Martin 1999	
Feasible applications		Nadel et al 2000, Martin 1999	
Costs		Nadel et al 2000	
Key non energy factors		Nadel et al 2000	
Principal contacts		Vern Martin, Flow Care	519-740-8733
Additional notes and sources			

## Pump System Efficiency Improvements (Motorsystems-6)

Pumps consume approximately 20 percent of industrial electricity. The selection of a pump for a given application requires the consideration of the flow requirements, required delivered pressure, and the system effects. While most engineers are trained to select pumps to meet requirements as specified in a design, many motor selection decisions are based upon estimates of operating conditions that may not be close to the true operating conditions. Once a system is placed in operation, the conditions may change further, moving the pump into a range of operation that is not only inefficient, but potentially even destructive. These changes result from changes in application, such as increases, or more frequently, decreases in the flow requirements. System resistance can increase as a result of fouling and/or scaling, and the pump impeller can erode, changing its effective system curve. Many of these changes are gradual and so may not be evident (Nadel et al 2000).

To bring a pump system back into acceptable operation, an engineer needs to first assess what the process requirements are. This task can be as simple as taking some measurements, or as complex as performing a systems optimization analysis as described in **Motorsys-5**. Once the pumping requirements are determined, the existing equipment must be assessed. An analysis needs to be performed to determine if the existing pump can meet the current operating characteristics. Among the options available are slowing the pump, trimming or replacing the impeller, and replacing the pump. Frequently, the initial reaction is to slow the pump. This may not be a good choice if the pump is significantly oversized. If the pump is slowed dramatically from its design speed, its system curve will change and may have a very limited range of operation. In many cases it may be much better to select another pump (Nadel et al. 2000, Hovstadius 2000, DOE 1999d).

The savings from right-sizing a pump can be dramatic. The 17 percent savings in the example used in the Data Table is reflective of the savings that are achievable (DOE 1999d). The system analysis is perhaps the most difficult and costly portion of a project. However, payback periods of 3 years are typical (Nadel et al 2000, Hovstadius 2000, DOE 1999d).

Because large pumps frequently require the largest motors at a facility, downsizing the pump can frequently also achieve significant electricity demand savings, thus reducing demand charges paid by the facility. In addition to the electricity savings, right-sizing pumps can lead to more stable system operation. Pulsation and flow variations that often result from pumps operated outside of their system curve can disrupt processes. Correction of these problems can improve product quality, and in some cases increase the capacity of systems that depend upon the pump. Sometimes the downsizing of a pump can free up space that can offer additional options for process improvements. Frequently, these benefits will be the driving motivation for project implementation (Nadel et al. 2000, Hovstadius 2000).

While the engineering associated with pump systems is well understood, many engineers are not experienced in conducting these analyses. Software tools, such as the pump system assessment tool developed by DOE and the Hydraulic Institute (DOE-OIT 2000b), provide a means of addressing this issue. Engineers need to be made aware of this and similar tools, and receive training in its application. Unfortunately a trained and equipped consulting community does not create demand for the service by users. The end-user community must be made aware of the opportunity and must be encouraged to seek out these services. However, there is a delicate balance between creating market demand, and developing the capability to deliver services in the marketplace. Both demand and supply need to grow in parallel.

**Pump Efficiency Improvement Data Table**

	Units	Notes	
Pump efficiency improvement			
Motorsys-6			
Appropriate selection of pump system components to optimize system operation and minimize system losses			
Market Information:			
Industries		Cross cutting	
End-use(s)		Motors and drives	
Energy types		Electric	
Market segment		Retrofit	
2015 basecase	GWh	1,541,589	pump systems are 20% of industrial motor electricity
Reference technology			
Description	200HP pump rated at 4650gpm at 114 ft of head, but operating at 3612 gpm with 107 ft of head		
Throughput or annual operating hours		4000	
Electricity use	kWh	128	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	1.096	
New Measure Information:			
Description	Replaced with smaller pump optimized to process requirements and new 200hp motor		
Electricity use	kWh	107	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.910	
Current status		Commercial	
Date of commercialization		~1980	Application of standard engineering practice, formalized in early 1980s
Estimated average measure lifetime	Years	10	Systems tend to fall out of optimization due to facility changes
Savings Information:			
Electricity savings	kWh/%	21.8	17%
Fuel savings	MBtu/%	NA	NA
Primary energy savings	MBtu/%	0.186	17%
Penetration rate		Medium	45% penetration in 2010
Feasible applications	%	23%	Feasible in all half of pump systems
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	58,860	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	502	
Cost Effectiveness			
Investment cost	\$	15,693	
Type of cost		Full	
Change in annual costs (O&M/other benefits)	\$	-1,800	Electric demand savings
Cost of conserved energy (electricity)	\$/kWh	0.010	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	1.19	Discount rate for all CCE calculations is 15%
Simple payback period	Years	3.0	
Internal rate of return	%	33%	
Key non energy factors			
Productivity benefits		Significant	More stable system operation
Product quality benefits		Significant	More consistent flow, allows for more stable process operation
Environmental benefits		None	
Other benefits		Somewhat	Ability to downsize equipment and free up space
Current promotional activity	H,M,L	Moderate	DOE has distributed a design program, and has been working with the Hydraulic Institute to deploy an educational program
Evaluation			
Major market barriers		Lack of knowledge, reluctance to pay engineering fees, lack of skilled providers	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Expanded end-user education, development of engineering training	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase		EIA 1999, Nadel et al 2000, Xenergy 1998	
Basecase energy use		DOE 1999d	
New Measure energy savings		DOE 1999d	
Lifetime		Nadel et al 2000, Martin 1999	
Feasible applications		Nadel et al 2000, Martin 1999	
Costs		DOE 1999d	
Key non energy factors		Nadel et al 2000	
principal contacts		Vern Martin, Flow Care	519-740-8733
Additional notes and sources			

## Switched Reluctance Drives (Motorsystems-7)

Motors consume about 60 percent of industrial electricity, and a number of types of motors are available to meet specific application needs in industry. Most applications make use of a constant-speed motor, while some applications require some degree of speed control. The most common motor type is the NEMA-standard poly-phase induction motor. For operations that require speed control, these motors are coupled with an adjustable speed drive (ASD). These motor/drive combinations are now reliable and cost-effective for many applications.

The switched reluctance motor is an old concept for designing a variable speed motor that has advanced recently with progress in solid-state electronics and software. The switched reluctance (SR) drive itself is a compact, brushless, electronically-commutated AC motor with high efficiency and torque, and simple construction. Available in virtually any size, the SR motor offers the advantage of variable speed capability (very low to very high) and precision control. As for its design, the motor comes as a package integrated with a controller. This setup enables some models to operate at speeds as low as 50-rpm and as high as 100,000-rpm (Howe et al. 1999). The rugged rotor of a SR motor is much simpler than that of other motors, since it has no field coils or embedded magnetic materials. However, the coils and magnets attached to the rotor can be subjected to very high stresses (Albers 1998). Both torque and efficiency are, in general, higher in SR drives (motor and controls) than in induction motors with ASDs. The current generation of SR drives have relatively flat efficiency curves with maximum efficiencies around 93 percent in integral-hp models and the low- to mid-80 percent range in fractional-hp units (Albers 1998).

Because of its simplicity, the SR motor in mass production should theoretically cost no more than, and perhaps less than, mass-produced induction motor/ASD packages of comparable size. But at this time, automating the manufacturing of integral horsepower and larger fractional horsepower SR motors is proving difficult and it is uncertain whether the hoped-for price reductions will materialize (Wallace 1998, Albers 1998, Boteler 1999).

Currently, an SR motor and its associated controls, starter, and enclosure cost 50 percent more than comparably sized and equipped induction motors with variable speed controls (Wallace 1998, Albers 1998, Means 1997). This amounts to about a \$2,000 premium for a 20-hp installation. For this analysis we assume that the price premium will be cut in half, to 25 percent (or \$1,000 for a 20-hp motor), once SR motors are more widely adopted.

Because of their precise and wide range of speed control and their ruggedness of design, SR motors are attractive in a broad range of commercial and industrial applications. Most SR research and application in the U.S. is in fractional-hp printer, copier, precision motion tasks and appliances. SR motors are now also being used in residential and commercial washing machines. Industrial applications include manufacturing equipment, process fans and pumps, and machine (servo) control (Wallace 1998). In addition, SR motors with control systems are competing to supplant induction motors with variable speed drives in a number of applications. For example, SR motors are most attractive in new and OEM (original equipment manufacturer) installations where the full benefits of their speed control can be realized.

In the future, there may be some retrofit applications for both general-purpose applications and as replacements for DC drives in process equipment, but the availability and understanding of how to use these motors has not yet progressed to the point that this is feasible. SR motors could potentially replace 20 to 50 percent of the existing general-purpose motors in service today (Albers 1998, Motor Challenge Clearinghouse 1998). We assume the middle of this range (35 percent) as the level of feasible applications once the technology matures.

The primary technical challenge facing SR motor technology is the fact that while the motor is simple conceptually, it is complex to engineer and manufacture (Wallace 1998). Unless the cost premium can be reduced, it will limit SR motors to applications that require the unique features of this motor. Noise has been an issue in some designs. The development and commercialization effort is primarily through manufacturers, OEMs, and EPRI-funded R&D. The motor's recent introduction in the Maytag horizontal-axis clothes washer should help speed the SR motor's market development (Nadel et al. 2000).

**Switched Reluctance Drives Data Table**

	Units		Notes	
Switched reluctance motor				
motorsys-7				
Use of a switched reluctance motor with integral control package in place of an induction motor with adjustable speed drive				
Market Information:				
Industries		Cross cutting		
End-use(s)		Motors and drives		
Energy types		Electricity		
Market segment		New, OEM		Some retrofit applications may occur in the future
2015 basecase	GWh	7,825,322		Motor systems consume approximately 60% of industrial electricity
Reference technology				
Description		20 hp induction motor with adjustable speed drive		
Throughput or annual operating hours	hrs	6,000		Assumes 7 day per week/16 hour per day
Electricity use	kWh	18		Operating at 60% load with 90% efficiency including 1% penalty for losses in the ASD
Fuel use	MBtu	NA		
Primary Energy use	MBtu	0.152		
New Measure Information:				
Description		20 hp switch reluctance motor with controls		
Electricity use	kWh	17		SR motor at 93% efficiency operating at 60% load
Fuel use	MBtu	NA		
Primary Energy use	MBtu	0.148		
Current status		Commercial		Commercial is some sizes
Date of commercialization		1994		
Estimated average measure lifetime	Years	15		
Savings Information:				
Electricity savings	kWh/%	0.6	3%	
Fuel savings	MBtu/%	NA		
Primary energy savings	MBtu/%	0.005	3%	
Penetration rate		Low		25% penetration in 2010
Feasible applications	%	9%		Feasible in 35% of applications
Other key assumptions for savings				
Electricity savings potential in 2015	GWh	6,626		Assumes 25% of motor applications become eligible, 30% of those use SR
Fuel savings potential in 2015	TBtu	NA		
Primary energy savings potential in 2015	TBtu	2.3		
Cost Effectiveness				
Investment cost	\$	1000		
Type of cost		Incremental		
Change in annual costs (O&M/other benefits)	\$	0		
Cost of conserved energy (electricity)	\$/kWh	0.049		
Cost of conserved energy (fuel)	\$/MBtu	NA		
Cost of conserved energy (primary energy)	\$/MBtu	5.8		Discount rate for all CCE calculations is 15%
Simple payback period	Years	7.41		
Internal rate of return	%	12%		
Key non energy factors				
Productivity benefits		Somewhat		Precise speed control may allow for increased output for equipment
Product quality benefits		Significant		More precise speed control may allow for reduced defect rate
Environmental benefits		None		
Other benefits		None		
Current promotional activity	H,M,L	Medium		R&D, demonstrations
Evaluation				
Major market barriers		Manufacturing difficulties, price premium, noise		
Likelihood of success	H,M,L	Medium		
Recommended next steps		continued R&D focusing on cost reductions		
Data quality assessment	E,G,F,P	Good		
Sources:				
2015 basecase		EIA 1999, Nadel, et al 2000; Xenergy, 1998		
Basecase energy use		Nadel, et al 2000		
New Measure energy savings		Nadel, et al 1998, Howe, et al, 1999		
Lifetime		Nadel, et al 1998, Howe, et al, 1999		
Feasible applications		Nadel, et al 1998, Howe, et al, 1999		
Costs		Nadel, et al 1998, Howe, et al, 1999		
Key non energy factors		Nadel, et al 1998, Howe, et al, 1999		
principal contacts		Neal Elliott, ACEEE		melliott@aceee.org
Additional notes and sources				



### **Premium Lubricants (Motorsys-8)**

Lubricants are a critical element of every motor-driven system, reducing the friction on equipment and minimizing component wear. Motor driven equipment accounts for about 60 percent of the electricity consumed by industry (Xenergy 1998). Traditionally, petroleum derivatives have been used for most applications. These lubricants trade off lubricating characteristics with increased resistance due to higher viscosity. This selection is complicated by the fact that the lubricant characteristics can vary widely over the range of operating temperatures that a piece of equipment experiences from startup to sustained operation. In addition, the characteristics of these lubricants tend to deteriorate with use, requiring frequent replacement.

Replacing conventional petroleum-based oils and greases with synthetic, engineered lubricants can reduce energy consumption and equipment wear while extending lubricant life. Synthetic lubricants, introduced beginning in the 1970s, use modern chemical-manufacturing processes to build organic polymers tailored to the specific lubricating requirements of various applications. Because synthetic lubricants are optimized for their application, friction can be reduced significantly. While friction is a relatively small loss in motors themselves, friction can represent a large loss in mechanical equipment like compressors, pumps, and gear drives. Savings of 2 to 30 percent have been realized in gear reducers, compressors, pumps, and motors while using synthetic lubricants (Howe et al. 1999).

While these lubricants cost between 1.5 and 3 times more than conventional products, they retain their lubricating properties longer, allowing the relubrication interval to be extended two to five times. This life extension results in both lubricant cost and maintenance labor savings. Extended service intervals are extremely important, especially in view of reduction in maintenance staff size in many industries. In addition, improved lubrication can reduce equipment wear, further decreasing operating and maintenance costs while improving equipment reliability. In many cases, the additional cost of the synthetics can be more than justified by longer lubricant life alone (Howe et al 1999).

Synthetic lubricants have been slow to be adopted because of their higher initial cost and limited awareness by end-users. In addition, because of specificity of the different synthetic lubricants, customers may find correct selection intimidating. Penetration has been higher in industrial than in commercial applications, in part because of the greater proportion of technically-oriented staff in industry. While information on lubrication has been included in many electric utility motor-system programs, it has not been a major focus (Elliott and Pye 1997).

Further documentation of the benefits of synthetic lubricants, and guidance on selection and use, may help to overcome the barriers to this product and expand its use. In fact, a new level of product guidance, “lubrication services”, represents an emerging trend in the lubrication industry. In out-sourced lubrication services, a provider, often affiliated with lubrication distributors, performs normal lubrication services for a facility. This value added service can be combined with other monitoring, such as predictive maintenance. This new service channel is well positioned, as well as motivated, to increase diffusion of this technology into the market (Nadel, et al. 2000).

**Advanced Lubricants Data Table**

	Units	Notes	
Advanced lubricants			
Motorsys-8			
Replace conventional petroleum lubricants with advanced synthetic lubricants			
Market Information:			
Industries		Cross cutting	
End-use(s)		Motors and drives	
Energy types		Electricity	
Market segment		New, Retrofit	
2015 basecase	GWh	7,825,322	Motor systems use about 60% of industrial electricity
Reference technology			
Description	Conventional compressor oil used in a 350 HP air compressor		
Throughput or annual operating hours	hrs	6,000	Assumes 7 day per week/16 hour per day
Electricity use	kWh	383	Hourly consumption at an average 80% load
Fuel use	MBtu	NA	
Primary Energy use	MBtu	3.27	
New Measure Information:			
Description	Substitution of an engineered, synthetic lubricant		
Electricity use	kWh	373	Based on case study in E Source 1999
Fuel use	MBtu	NA	
Primary Energy use	MBtu	3.18	
Current status		commercial	
Date of commercialization		1978	
Estimated average measure lifetime	Years	0.5	
Savings Information:			
Electricity savings	kWh/%	10	3%
Fuel savings	MBtu/%	NA	
Primary energy savings	MBtu/%	0.1	3%
Penetration rate		medium	45% penetration rate in 2010
Feasible applications	%	23%	About half of industrial motors use is eligible for customer lubrication since many smaller motors use sealed bearing which are not user serviceable
Other key assumptions for savings			
Electricity savings potential in 2015	GWh	45,931	
Fuel savings potential in 2015	TBtu	NA	
Primary energy savings potential in 2015	TBtu	15.7	
Cost Effectiveness			
Investment cost	\$	300	Cost is 1.5-2.5 x of conventional lubricant, but last 3-4 times as long
Type of cost		Incremental	Because lubrication is assumed to be a maintenance measure, it will bear only incremental measure cost
Change in annual costs (O&M/other benefits)	\$	(3,162)	Maintenance savings from extended lubricant life
Cost of conserved energy (electricity)	\$/kWh	<0	
Cost of conserved energy (fuel)	\$/MBtu	NA	
Cost of conserved energy (primary energy)	\$/MBtu	<0	Discount rate for all CCE calculations is 15%
Simple payback period	Years	0.05	
Internal rate of return	%	917%	
Key non energy factors			
Productivity benefits		Significant	Reduced equipment wear and extended service internals with labor and downtime savings.
Product quality benefits		Somewhat	Greater equipment reliability
Environmental benefits		Significant	Reduced volume of spent lubricant to be disposed of
Other benefits		None	
Current promotional activity	H,M,L	Low	
Evaluation			
Major market barriers		First cost, lack of market knowledge	
Likelihood of success	H,M,L	Medium	Economics attractive if barriers can be overcome
Recommended next steps		Market education and encourage development of lubrication service companies	
Data quality assessment	E,G,F,P	Good	
Sources:			
2015 basecase	Xenergy 1998		
Basecase energy use	EIA 1999		
New Measure energy savings	Howe et al. 1999		
Lifetime	Howe et al. 1999		
Feasible applications	Nadel, et al 1998		
Costs	Howe et al. 1999		
Key non energy factors	Howe et al. 1999		
Principal contacts	Bill Howe, E-Source	720-548-5000	
Additional notes and sources			

## **Advanced CHP Turbines (Utilities-1)**

Combined heat and power systems generate electricity (and/or mechanical energy) and thermal energy in a single, integrated system. This contrasts with the more common practice where electricity is generated at a central power plant, and on-site heating and cooling equipment is used to meet non-electric energy requirements. Because CHP captures the heat that would otherwise be rejected in traditional separate generation of electric or mechanical energy, the total efficiency of these integrated systems is much greater than from separate systems.

CHP is not a specific technology, but rather an application of technologies to meet end-user needs for heating and/or cooling, and mechanical and/or electric power. Steam turbines, gas turbines, combined cycles, and reciprocating engines are the major current technologies used for power generation and CHP (Elliott and Spurr, 1999). Collaborative research by government and industry has contributed significantly to the new generations of turbines and engines.

Conventional electricity generation is inherently inefficient, converting only about a third of a fuel's potential energy into usable energy. The significant increase in efficiency with CHP results in lower fuel consumption and reduced emissions compared with separate generation of heat and power. CHP is an economically productive approach to reducing air pollutants through pollution prevention, whereas traditional pollution control achieved solely through flue gas treatment provides no profitable output and actually reduces efficiency and useful energy output.

The thermodynamic cycle associated with the majority of gas turbine systems is the Brayton cycle. In this cycle, atmospheric air is passed as the working fluid through the turbine. The thermodynamic steps of the Brayton cycle include compression of atmospheric air, introduction and ignition of fuel, and expansion of the heated combustion gases through the gas producing and power turbines. The developed power is used to drive the compressor and the electric generator.

Since there are two or more usable energy outputs from a CHP system, defining overall system efficiency is more complex than with simple systems. The system can be viewed as two subsystems – the power system and the heat recovery system. The efficiency of the overall system results from an interaction between the individual efficiencies of the power and heat recovery systems.

We have considered the example of a 5MW gas-fired CHP turbine operating with a 73 percent overall efficiency and a power-to-heat ratio of 0.607. This system is compared to the example of purchased grid electricity with an on-site gas boiler. The electric grid is estimated to have an efficiency of 33.4 percent and the gas boiler has an efficiency of 68 percent. Installed costs for a 5MW combustion turbine currently cost about \$1070/kW and are projected to cost \$950/kW by 2020 (Onsite Sycom 2000). Operating and maintenance costs are currently \$0.0059/kW and are expected to drop to \$0.0049/kW by 2020 (Onsite Sycom 2000).

The estimated technical potential for CHP at existing manufacturing facilities is approximately 132,000 MW (Onsite Sycom 2000). Approximately 44,000 MW of CHP capacity is already in place at existing manufacturing facilities, leaving a remaining CHP potential of 88,000 MW. Much of the remaining potential is found in those industries that have traditionally relied on CHP – paper, chemicals, food, primary metals, and petroleum refining. Most CHP development to date has focussed on large systems (20 MW or larger) and 55 percent of the remaining CHP potential is in systems of this size. However, small systems represent a largely untapped market for CHP. Thirty two percent of the remaining potential is in system sizes of 4 MW or less (Onsite Sycom 2000).

**Advanced CHP Turbines Data Table**

Advanced CHP Turbines Data Table		Units	Notes
Advanced CHP Turbines			
Utility-1			
Replace Grid Electricity combined with Natural Gas Boiler			
Market Information:			
Industries		Cross Cutting	
End-use(s)		Utilities	
Energy types		Natural gas	
Market segment		Retrofit	
2015 basecase	MWh	132,000	Estimated total industrial technical potential- Onsite Sycom, 2000
Reference technology			
Description	68% efficiency natural gas boiler plus 33.4% efficiency grid electricity		
Throughput or annual operating hours	hours	6000	Typical annual operating hours for a CHP system
Electricity use	kWh	1.000	Obtain 1 kwh from grid
Fuel use	MBtu	0.00562	Obtain 0.005 MBtu from boiler based on Power/Heat of 0.607
Primary Energy use	MBtu	0.01848	Energy required to produce the 1kwh of grid elec.and .005 MBtu of boiler steam
New Measure Information:			
Description	5 MWe CHP system operated at 80% load with 73% efficiency ; Power/Heat = 0.607		
Electricity use	kWh	0	
Fuel use	MBtu	0.012	Overall efficiency of 73%
Primary Energy use	MBtu	0.012	
Current status		Commercialized	
Date of commercialization		1998	
Estimated average measure lifetime	Years	10	A refit must be done after 10 years. Cost of refit is 20% of the initial capital cost
Savings Information:			
Electricity savings	kWh/%	1.000	100%
Fuel savings	MBtu/%	-0.007	-120%
Primary energy savings	MBtu/%	0.01	33%
Penetration rate		high	
Feasible applications	%	60%	
Other key assumptions for savings	Average 2015 grid electricity price is \$0.039/kWh and natural gas price \$3.38/Mbtu		
Electricity savings potential in 2015	kWh	79200	Decreased grid electricity
Fuel savings potential in 2015	Mbtu	-534.8	Increased fuel use
Primary energy savings potential in 2015	Mbtu	483.8	Net primary energy savings
Cost Effectiveness			
Investment cost	\$	1070	Onsite Sycom, 2000
Type of cost		full	
Change in annual costs (O&M/other benefits)	\$	-0.0096	\$45/kWyear for CHP, \$5/Mbtu for gas boiler
Cost of conserved energy (electricity)	\$/kWh	0.01	
Cost of conserved energy (fuel)	\$/Mbtu	(1.45)	
Cost of conserved energy (primary energy)	\$/Mbtu	1.60	
Simple payback period	Years	6.9	
Internal rate of return	%	9%	Includes refit cost of \$214 at year 11
Key non energy factors			
Productivity benefits		Significant	Fewer shutdowns due to grid outages
Product quality benefits		Significant	Greater reliability
Environmental benefits		Significant	Higher efficiencies mean better fuel utilization
Other benefits			
Current promotional activity	H,M,L	High	
Evaluation			
Major market barriers			
Likelihood of success	H,M,L	High	
Recommended next steps			Favorable tax policies
Data quality assessment	E,G,F,P	Excellent	
Sources:			
2015 basecase			EIA 1999
Basecase energy use			EIA 2000
New Measure energy savings			Onsite Sycom, 2000
Lifetime			Onsite Sycom, 2000
Feasible applications			Onsite Sycom, 2000
Costs			Onsite Sycom, 2000
Key non energy factors			
principal contacts			
Additional notes and sources			

## **Advanced Reciprocating Engines (Utilities-2)**

Reciprocating engines can be used to generate a portion of a plant's needs onsite, reduce demand during peak periods, or support premium power applications (e.g., microelectronics manufacturing) (Elliott and Spurr 1999). Most industrial facilities have some sort of on-site back-up power requirements that can be met by advanced generation technologies. Reciprocating engines are even more efficient when operated as part of a CHP system, which can meet some of the facility's thermal requirements as well. However, reciprocating engines will have to compete with microturbines and fuel cells to gain a stronghold in this market.

Reciprocating engines (e.g., diesel engines) are used to generate electricity. These internal combustion engines convert fuel to shaft power, which then spins a generator. Diesel generators have long been used to generate small amounts of electricity at industrial, commercial, and institutional sites, either for continuous use or for backup in case of utility power failure. Recent developments in engine design have increased power efficiency (now approaching 50 percent) and reliability, while dramatically reducing the emissions of these engines. These new designs can use a variety of liquid and gas fuels, including natural gas. For emissions reasons, natural gas-fired engines have become dominant for continuous operation applications (i.e., not emergency generators).

Advanced reciprocating engines compete against other distributed generation technologies, as well as grid-supplied electricity. However, conventional electricity generation is inherently inefficient, converting only about a third of a fuel's potential energy into usable energy. An advanced reciprocating engine can obtain an overall efficiency of 65 percent. A primary energy savings of 49 percent can be obtained with this technology.

Advanced reciprocating engines cost approximately \$350/kW. At this price, they are not competitive with purchase grid electricity. However, for high-value and niche applications they may be more cost-effective. Reciprocating engines are the dominant independent generation technology for small installations, accounting for 47 percent of sites but only 2 percent of the power generation. In the industrial sector in 1995, reciprocating systems generated less than 1 percent of total cogenerated electricity but accounted for 5 percent of the installed systems with an average installed size of less than 1 MW<sub>e</sub>. This type of system is most commonly found in the food products industry (SIC 20) (EIA 1997).

A number of market barriers exist in installing distributed generation technologies in addition to the technical issues. These barriers will need to be removed for this technology to achieve its full market potential. (Alderfer, Eldridge and Starrs 2000). Efforts are underway at both the national and state levels to address these barriers. While our analysis did not compete the various electricity generating technologies against each other, it is worth noting that advanced reciprocating engines are currently being installed in larger quantity than fuel cells or microturbines. Reciprocating engines can be manufactured, delivered, and installed very quickly (usually within a few months). The waits for microturbines and fuel cells can be as much as 18 months. To put this length of time into perspective, consider the product cycle of a microchip manufacturer. New product lines for microchips are installed approximately every 18 months. The wait for delivery of other types of on-site generation may be an entire product cycle for these manufacturers, which is simply too long.

# Advanced Reciprocating Engines Data Table

	Units	Notes	
Advanced Reciprocating Engines			
Utility-2			
Replace grid-supplied electricity			
Market Information:			
Industries		Cross Cutting	
End-use(s)		Utilities	
Energy types		Natural gas	
Market segment		Retrofit, new	
2015 basecase	GWh	1,304,220	All industrial electricity, AEO 2000 forecast
Reference technology			
Description	Grid supplied electricity at 33.4% delivered efficiency		
Throughput or annual operating hours	hours	6000	
Electricity use	kWh	1	
Fuel use	MBtu	0	
Primary Energy use	MBtu	0.0102	
New Measure Information:			
Description	800 kW reciprocating engine operated 6000 hours per year at 85% load with 65% efficiency		
Electricity use	kWh	0	
Fuel use	MBtu	0.0052	
Primary Energy use	MBtu	0.0052	
Current status		Commercial	
Date of commercialization		2000	
Estimated average measure lifetime	Years	7	A refit after 7 years. Cost of refit is 50% of the initial capital cost
Savings Information:			
Electricity savings	kWh/%	1.000	100%
Fuel savings	MBtu/%	-0.005	-
Primary energy savings	MBtu/%	0.0050	49%
Penetration rate		low	
Feasible applications	%	12%	Assumes 20% of electric power demand classified as premium
Other key assumptions for savings	Average 2015 grid electricity price is \$0.039/kWh and natural gas price \$3.38/Mbtu		
Electricity savings potential in 2015	kWh	156506	Decreased grid electricity
Fuel savings potential in 2015	Mbtu	-821.5	Increased fuel use
Primary energy savings potential in 2015	Mbtu	777.3	Net primary energy savings
Cost Effectiveness			
Investment cost	\$	350	Onsite Sycom, 2000
Type of cost		Full	Competes against capital cost embedded grid price
Change in annual costs (O&M/other benefits)	\$	0.0142	\$85.20/kWyear - Onsite Sycom, 2000
Cost of conserved energy (electricity)	\$/kWh	0.01	
Cost of conserved energy (fuel)	\$/Mbtu	(1.33)	
Cost of conserved energy (primary energy)	\$/Mbtu	1.40	
Simple payback period	Years	8.3	
Internal rate of return	%	4%	Includes a 50% of original capital cost refit charge at years 8 and 16
Key non energy factors			
Productivity benefits		Significant	Improved reliability can offer increase up-time
Product quality benefits		Significant	Improve power quality can improve product quality in sensitive applications
Environmental benefits		Limited	Increases on-site emissions and it is unclear whether is cleaner than grid supplied electricity
Other benefits		Somewhat	Can allow expansions without needing to upgrade utility service, and can allow for peak load shaving
Current promotional activity	H,M,L	High	Both manufacturer and government R&D and demonstration
Evaluation			
Major market barriers		Market barriers to distributed generation	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Continued R&D and demonstrations	
Data quality assessment	E,G,F,P	Excellent	
Sources:			
2015 basecase		EIA 1999	
Basecase energy use		EIA 1999	
New Measure energy savings		Onsite Syscom Energy 2000	
Lifetime		Onsite Syscom Energy 2000, EIA 1999	
Feasible applications		Onsite Syscom Energy 2000	
Costs		Onsite Syscom Energy 2000, Bautista 2000	
Key non energy factors		Elliott and Spurr 1999	
Principal contacts			
Additional notes and sources			

### **Fuel Cells (Utilities-3)**

A fuel cell generates direct current electricity and heat by combining fuel and oxygen in an electrochemical reaction. This technology is an advancement in power generation that avoids the intermediate combustion step and boiling water associated with Rankine cycle technologies (e.g. steam turbines), or efficiency losses associated with gas turbine technologies. Fuel to electricity conversion efficiencies can theoretically reach 80-83 percent for low temperature fuel cell stacks and 73-78 percent for high temperature stacks. In practice, efficiencies of 50-60 percent are achieved with hydrogen fuel cells while efficiencies of 42 percent-65 percent are achievable with natural gas as a fuel (Blok et al. 1996).

A fuel cell consists of two electrodes separated by an electrolyte. Electrochemical reactions in the cell release electrons from one electrode and take up electrons at the other electrode. When these electrodes are connected to an external circuit, they produce useful electrical work (Blok et al. 1996). The five main types of fuel cells are alkaline (AFC), polymer electrolyte membrane (PEMFC), phosphoric acid (PAFC), molten carbonate (MCFC), and solid oxide (SOFC). For industrial sector combined heat and power applications, the most promising types of cells are the PAFC, MCFC, and the SOFC.

Of these, the PAFC is the most developed (there are over 200 operating worldwide), but only has fuel electricity conversion efficiencies of 5 percent better than the most recent combined cycle technologies (Hydrogen Fuel Cell Investor 2000, Blok et al. 1996). We therefore focus on the MCFC and SOFC in this write up.

MCFC, due to their high temperatures of operation, are good candidates for small scale CHP. While the MCFCs have slightly better heat rates than PAFC, their high material costs and high parasitic loads (they operate in a pressurized system) detract from the technology's long term potential. A small scale 2 MW MCFC technology demonstration project started in 1996 for the city of Santa Clara, California achieved a conversion efficiency of 44 percent (Hydrogen Fuel Cell Investor 2000). SOFC, while a less developed technology, has also progressed. Siemens Westinghouse Power Corporation announced the first demonstration of a tubular solid oxide fuel cell (SOFC) power generation technology fueled by natural gas in Norway (Fuel Cells 2000). Other demonstrations and proof of concepts are planned for 2001 and 2002, with commercial orders available after that point (Siemens 2000). Because of their lower materials cost, SOFC may be a better candidate technology than MCFC for high temperature applications in the long term (Freeman 2000).

A particular variant of fuel cell technology that also offers promise in an industrial context is the family of fuel cell/microturbine technologies, or so-called "hybrid" technologies. Combining fuel cells and microturbines can further boost efficiency by utilizing waste heat to further generate power. The first SOFC fuel cell/gas turbine hybrid power system (220-kW capacity) is being readied for shipment, installation and operation at the National Fuel Cell Research Center at the University of California, Irvine. The microturbine is said to add an additional 12 percent efficiency with the turbine system (Fuel Cells 2000, DOE 2000). This year Fuel Cell Energy was selected by the Department of Energy for a \$3.1 million program, including 20 percent cost sharing, to support the design of an ultra-high efficiency, fuel cell/turbine hybrid power plant. The system proposes an innovative combination of FuelCell Energy's Direct FuelCell™ with a turbine without requiring any combustion in the turbine, or pressurization of the fuel cell (DOE 2000).

In our analysis we compare fuel cells to a base case of average purchased electricity from the grid of 34 percent. While fuel cell efficiencies can vary from 40-65 percent, we assume that technologies entering the industrial market achieve conversion efficiencies of 60 percent based on improvements to existing fuel cell technologies but not including hybrid systems. While high temperature fuel cells do offer a significant potential for the production of both heat and electricity for useful purposes, we assume that in the near to medium term, initial fuel cell markets will not be attractive for combined heat and power. We anticipate that these initial markets will primarily value the high quality electricity.

## Fuel Cells Data Table

	Units	Notes	
<b>Fuel cells</b>			
<b>Utilities-3</b>			
<b>Replace grid-supplied electricity</b>			
<i>Market Information:</i>			
Industries		Cross cutting	
End-use(s)		Utilities	
Energy types		Fuels, other	
Market segment		New, retrofit	
2015 basecase use	Mill kwh	1,304,220	All industrial electricity, EIA 1999 forecast
<i>Reference technology</i>			
Description	Grid supplied electricity at 33.4% delivered efficiency		
Throughput or annual op. hrs.		6000	
Electricity use	kWh	1	Assume a 200 kW load application
Fuel use	MBtu	0.0	Electricity purchased from the grid. no fuel inputs on site
Primary energy use	MBtu	0.0102	
<i>New Measure Information:</i>			
Description	Install fuel cells for industrial use		
Electricity use	kWh	0	
Fuel use	MBtu	0.007	Assume a 50% electricity conversion efficiency
Primary Energy use	MBtu	0.007	
Current status		Pre-commercial	
Date of commercialization		2005	Both MCFC and SOFC models. PAFC already commercial
Est. avg. measure life	Years	7	Estimated economic life. A refit must be done after 7 years. Cost of refit is 50% of the initial capital cost
<i>Savings Information:</i>			
Electricity savings	kWh/%	1.000	100%
Fuel savings	MBtu/%	-0.007	0%
Primary energy savings	MBtu/%	0.003	33%
Penetration rate		low	
Feasible applications	%	5%	Niche applications in the industrial sector
Other key assumptions			
Elec svgs potential in 2015	GWh	65211	
Fuel svgs potential in 2015	Tbtu	-2	
Primary energy svgs potential in 2015	Tbtu	185	
<i>Cost Effectiveness</i>			
Investment cost	\$	1500	MCFC costs run roughly \$5000/kW; \$1,500/kw after long term production.
Type of cost		Incremental	
Change in other costs	\$	0.012	We assume \$70/kwyear based on Onsite Sycom, 2000
Cost of saved energy (elec)	\$/kWh	0.06	
Cost of saved energy (fuel)	\$/Mbtu	(8.18)	
Cost of saved energy (primary)	\$/Mbtu	16.46	Discount rate for all CCE calculations is 15%
Simple payback period	Years	58.6	
Internal rate of return	%	-14%	
<i>Key non energy factors</i>			
Productivity benefits		Somewhat	Increased reliability could lead to cost savings
Product quality benefits		Somewhat	Higher power quality
Environmental benefits		Significant	Little to no NOx emissions
Other benefits			
Current promotional activity	H,M,L	High	Several fuel cell promotion organizations (see text)
<i>Evaluation</i>			
Major market barriers		Technical, cost	
Likelihood of success	H,M,L	Medium	At first in niche markets
Recommended next steps			
Data quality assessment	E,G,F,P	Good	Cost data projected for full scale production
<i>Sources:</i>			
2015 basecase			EIA 1999
Basecase energy use			EIA 1997
New measure energy savings			See text
Lifetime			Blok et al. 1996
Feasible applications			EIA, 1997; judgement
Costs			See text
Key non energy factors			
Principal contacts			
Additional notes and sources			



In addition to the improvements in energy conversion, fuel cells provide improved power quality and reliability, and have the flexibility to be scaled according to a variety of industrial processes. In the near term fuel cells will be particularly attractive for those industries which value an non-interruptible supply of high quality power, (such electronics manufacturing) especially in non-attainment areas that are facing tough air quality regulation.

While fuel cells definitely have significant potential, particularly in niche end-uses in the industrial sector, production costs are still high due to the lack of large scale production lines. MCFC installation costs for recent projects are running about \$5,000/kW (FuelCell Energy 2000). Siemens plans on achieving an installation cost of \$1,300-1,500/kW for their SOFC model after achieving mass production, but initial costs are much higher (Forbes 2000). Eventual electricity delivery costs are estimated to be less than \$0.05/kWh (Hydrogen and Fuel Cell Investor, U.S. DOE 2000, Forbes 2000). We assume an increase in O&M costs of \$70/kw-year based on (Onsite-Sycom 2000). Given the progress in mobile and small-scale stationary applications, it is more likely that these applications may first reach levels of mass production with medium temperature fuel cells with some of the technology know-how spinning off to larger scale, high-temperature industrial cell applications.

There is a high level of activity surrounding the promotion of fuel cell technologies given their potential application in all end-use sectors<sup>19</sup>. While PAFC are already commercialized, SOFC and MCFC are in the demonstration stage under cost-shared arrangements between the U.S. government. The key U.S. manufacturer of SOFC is Siemens-Westinghouse, and of MCFC is FuelCell Energy, Inc. ([www.fce.com](http://www.fce.com)). Other international companies are also involved in MCFC and SOFC fuel cell development in Canada, Europe, and Japan (see <http://www.h2eco.org/links.htm>, and [www.h2fc.com](http://www.h2fc.com)). Full commercialization expected before 2005. Given the higher costs of new fuel cell systems, we assume that penetration will be limited in the near term to niche applications (e.g. electronics manufacturing) where power quality and reliability are at a premium.

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<sup>19</sup> Some of the main U.S. bodies include: the National Hydrogen Association (<http://www.ttcorg.com/nha/>), the U.S. Department of Energy and Department of Defense, fuel cell research programs operated by the Federal Energy Technology Center ([www.fetc.doe.gov](http://www.fetc.doe.gov)), the Fuel Cell Commercialization group (<http://www.ttcorg.com/fccg/>), the American Hydrogen Association (<http://www.clean-air.org/>), and the U.S. Fuel Cell council (<http://www.usfcc.com/>), the Hydrogen and Fuel Cell Investor (<http://www.h2fc.com/>) and others.

## Microturbines (Utilities-4)

As discussed in the introduction, a number of technologies are available to generate electricity on site, and compete against grid supplied electricity for both energy and reliability. Microturbines are a new class of small combustion turbine engines, ranging in size from 25 kW to 500 kW of electric generating capacity (DOE 1999a). Like the current class of industrial turbines, which were developed using jet engines as a model, these devices have derived from several types of turbo-machinery, including aircraft auxiliary power units (APU) and industrial gas compressors. Like their larger siblings, microturbines can run on a variety of liquid and gaseous fuels, with natural gas projected to be the most common.

Microturbines are high-speed devices, usually rotating at over 40,000 rpm. They come in several physical configurations, which represent tradeoffs in cost and performance. The engine can be a single-shaft machine, which reduces cost, or a split-shaft machine, which is more complex but allows for direct drive of a generator, thus avoiding the need for an inverter. Another design consideration is choice of bearings. Air bearings, which have emerged as the technology of choice, reduce the cost of the microturbine, but oil bearings offer longer life and are more rugged. One configuration of microturbines, the simple-cycle machine, is less expensive, but is also less efficient than a recuperated and/or intercooled machine. Simple-cycle microturbines are projected to have an efficiency of 26-30 percent (DOE 1999a). When heat recovery is implemented, the efficiency could approach 40 percent (DOE 1999b). When used in a cogeneration or combined heat and power (CHP) system, the fuel conversion efficiency can approach 80 percent (DOE 1999a). The first cost premium for CHP is approximately 40 percent compared to a simple cycle configuration (Bautista 2000).

Four domestic manufacturers are currently in the microturbine market: Honeywell (2000) (formally AlliedSignal), Capstone (2000), Elliott (2000) and Ingersoll-Rand (2000) (formerly Northern Research and Engineering Company). Most units are at the commercial demonstration stage and should not be considered a fully commercial technology. A number of large companies, such as GE (2000) and ABB (van Trigt 1998) are exploring entering the market either through an acquisition or the introduction of a new unit.

Thus far, the marketing of microturbines has focused on the commercial marketplace. However, these devices can address important needs in manufacturing as well, because the standard manufacturing establishment has an average electricity demand of just under 400 kW (Census 1996). Microturbines can be used to generate a portion of a plant's needs onsite, reduce demand during peak periods, or support premium power applications (e.g., microelectronics manufacturing) (Elliott and Spurr 1999). Microturbines are even more efficient when operated as part of a CHP system, which can meet some of the facility's thermal requirements as well. However, microturbines will have to compete with reciprocating engines and fuel cells to gain a stronghold in this market.

While the first cost of microturbines appear attractive compared to fuel cells, they are less attractive when compared with reciprocating engines. A recent analysis for the Energy Information Administration (EIA) has estimated the current installed costs in CHP mode to be \$1,970 per kW, dropping to \$915 by 2010. This is compared with \$1,390 per kW installed today and \$990 per kW in 2020 for a comparable reciprocating gas engine. It is projected that the first costs would become competitive during this study's time frame (Onsite 2000). These microturbine cost estimates appear higher than current prices that manufacturers are quoting (GE 2000, Honeywell 2000, and Tanner 2000). As the Onsite (2000) study notes, these cost quotes frequently do not include all equipment necessary for a functional install (GE 2000). Also, as a recent new analysis points out, many manufacturers appear to be selling below cost to build market share (Kaplan 2000).

One of the promises of microturbines is greater reliability and a lower operating cost than reciprocating engines. However, field experience with microturbines has been limited, and because the technology is evolving very rapidly, reliable information about performance is not readily available. Another area in need of improvement is environmental emissions, in particular NO<sub>x</sub>. While manufacturers have raised hopes that microturbine emissions would be much lower than emissions from other technologies, current rates are similar to those for low-emissions gas engines (Greene and Hammerschlag 2000). The

## Microturbines Data Table

	Units	Notes	
<b>Microturbines</b>			
<b>Utilities-4</b>			
<b>Replace grid-supplied electricity</b>			
<i>Market Information:</i>			
Industries		Cross Cutting	
End-use(s)		Utilities	
Energy types		Natural gas	
Market segment		Retrofit, new	
2015 basecase	GWh	1,304,220	All industrial electricity
<i>Reference technology</i>			
Description	Grid supplied electricity at 33.4% delivered efficiency		
Throughput or annual operating hours	hours	6000	
Electricity use	kWh	1	
Fuel use	MBtu	NA	
Primary Energy use	MBtu	0.0102	
<i>New Measure Information:</i>			
Description	100 kW microturbine operated 6000 hours per year at 85% load with 40% efficiency		
Electricity use	kWh	N/A	
Fuel use	MBtu	0.0085	
Primary Energy use	MBtu	0.0085	
Current status	Commercial demonstration		
Date of commercialization	2001		
Estimated average measure lifetime	Years	7	Estimated economic life. A refit must be done after 7 years. Cost of refit is 50% of the initial capital cost.
<i>Savings Information:</i>			
Electricity savings	kWh/%	1	
Fuel savings	MBtu/%	-0.00001	
Primary energy savings	MBtu/%	0.002	17%
Penetration rate		Low	
Feasible applications	%	5%	Assumes that 20% of electric power demand can be classified as premium, penetration rate 25% in 2010
Other key assumptions for savings		Average 2015 grid electricity price is \$0.039/kWh and natural gas price \$3.38/Mbtu	
Electricity savings potential in 2015	GWh	39,900	Decreased grid electricity
Fuel savings potential in 2015	Tbtu	-0.3	Increased fuel use
Primary energy savings potential in 2015	Tbtu	67	Net primary energy savings
<i>Cost Effectiveness</i>			
Investment cost	\$	641	Bautista 2000.
Type of cost		Full	Competes against capital cost imbedded grid price
Change in annual costs (O&M/other benefits)	\$	0.0125	
Cost of conserved energy (electricity)	\$/kWh	(0.00)	
Cost of conserved energy (fuel)	\$/Mbtu	95.18	
Cost of conserved energy (primary energy)	\$/Mbtu	(0.48)	Discount rate for all CCE calculations is 15%
Simple payback period	Years	N/A	Not cost effective against grid electricity
Internal rate of return	%	Undefined	
<i>Key non energy factors</i>			
Productivity benefits		Significant	Improved reliability can offer increase up-time
Product quality benefits		Significant	Power quality can improve quality in sensitive apps
Environmental benefits		Somewhat	Increases on-site emissions and it is unclear whether is cleaner than grid supplied electricity
Other benefits		Somewhat	Allows expansion without util. upgrade and peak shaving
Current promotional activity	H,M,L	High	Both manufacturer and government R&D and demo
<i>Evaluation</i>			
Major market barriers		High first cost, lack of proven reliability, and market barriers to DG	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Continued R&D and demonstrations	
Data quality assessment	E,G,F,P	Good	
<i>Sources:</i>			
2015 basecase	EIA 1999		
Basecase energy use	EIA 1999		
New Measure energy savings	Onsite Syscom Energy 2000		
Lifetime	Onsite Syscom Energy 2000, DOE 1999c		
Feasible applications	Onsite Syscom Energy 2000		
Costs	Onsite Syscom Energy 2000, Bautista 2000		
Key non energy factors	Elliott and Spurr 1999		
Principal contacts	Bruce Hedman, Onsite Sycom bhedman@onsitesyscom.com		
Additional notes and sources			

Department of Energy has identified this as another important area for development, with the application of low emissions technologies developed as part of the advanced turbine system program (DOE 1999c).

In addition to the technical issues, a number of market barriers exist in installing distributed generation technologies, which will need to be removed for this technology to achieve its full market potential (Alderfer, Eldridge and Starrs 2000). Efforts are underway at both the national and state levels to address these barriers.

Current projections for operating costs are for \$90 per kWyear falling to \$75 by 2020 (Onsite 2000). These compare favorably with reciprocating engines today and appear even more attractive in the future. Realizing these performance goals require further product development with deployment of advanced materials and operating experience (DOE 1999c).

In the configuration of electric generation only, microturbines appear unable to compete against the average industrial energy price for grid supplied electricity. In CHP mode the economics appears somewhat more efficient, but they are still not competitive. These assessments do not take into account variations in energy prices or valuation of ancillary services such as reliability. If a combination of these were to increase to twice the EIA 2015 estimate for electricity of \$0.0039/kWh, the payback would fall to 2.9 years with an IRR of 34 percent in simple cycle mode and 3.4 year with an IRR of 29 percent in CHP mode. An ancillary benefit of \$0.039 per kWh is perhaps at the low end for premium-power applications such as are currently seen in pharmaceutical and semiconductor applications (Elliott and Spurr 1999). The systems can offer high reliability and power quality as well as low noise. This analysis would indicate that the market for microturbines would likely be limited to premium power applications.

## Advanced Lighting Technologies (Lighting-1)

Lighting accounts for approximately 6.5 percent of industrial sector electricity demand. In 1994, more than 58,600 GWh of electricity was consumed by lighting in industrial facilities (EIA 1997). High-bay lighting, required to provide overall ambient lighting throughout manufacturing and storage spaces, is typically provided by high-intensity discharge (HID) sources, including metal halide, high-pressure sodium and mercury vapor lamps. HID accounts for approximately 60 percent of industrial lighting energy consumption (Johnson 1997). Supplementary lighting is used to provide low-bay and task-specific lighting for inspection, equipment operation, and fine assembly activities. Fluorescent, compact fluorescent and incandescent light sources are commonly used for task lighting needs and together account for approximately 40 percent of industrial lighting energy.

A range of advanced lamp, ballast, fixture, and light pipe technologies can significantly reduce lighting energy consumption in industrial facilities. Electrodeless light sources, such as the induction lamps offered by Philips, Osram Sylvania, and GE, combine high quality light with high efficacy, long-lived lamps. These systems offer energy and maintenance cost reductions, particularly in spaces where lighting is hard to access and maintain. Remote-source lighting technologies, including fiber optics systems and light pipes using a variety of light sources such as sulfur lamps, LEDs, and hybrid artificial-natural lighting, offer numerous advantages in industrial settings. Benefits of remote-source lighting include: minimized heat gain in lit areas resulting in a lower cooling load; improved safety from elimination of lighting-related electrical wiring and equipment in wet or explosive areas; allowance for the use of more efficient and powerful light sources; more targeted and esthetically-pleasing light; and reduced installation and maintenance costs (Krepchin 1999).

Another example is the replacement of HID lighting with high-intensity fluorescent lighting in high-bay applications. New high-intensity fluorescent lighting systems incorporate high-efficiency twin-tube or linear T5 fluorescent lamps, advanced electronic ballasts, and high-efficacy fixtures that maximize light output to the work plane. Each of the system components confers advantages over traditional HID fixtures. Advantages include: lower energy consumption; lower lumen depreciation over the lifetime of the lamp; better dimming options; faster start-up and restrike (virtually “instant-on” capability); better color rendition; higher pupil lumens ratings (translating into improved worker productivity and performance); and less glare (given fixture design and the more diffuse nature of the fluorescent light source) (Rogers and Krepchin 2000).

Under similar operating conditions, high-intensity fluorescent replacements yield 50 percent electricity savings over standard metal halide HID. The use of dimming or on/off controls, which are impractical with most HID systems, can increase savings substantially (see “Advanced lighting design”). The first high-intensity fluorescent systems suitable for high-bay industrial applications were introduced in 1996. Since that time, the number of fixture manufacturers has grown to more than a dozen and prices have dropped dramatically. In new facilities, high-intensity fluorescent and HID systems are comparable in cost. In retrofit applications, investment costs are approximately \$185 per fixture (\$150 fixture and \$35 installation cost); the lamp costs are equal to HID (Rogers 2000, EBN 2000). Case studies have also found reduced maintenance costs resulting from the use of multi-lamp fixtures – unlike HID fixtures, the fluorescent fixture continues to provide sufficient light in most applications even when one lamp fails. As a result, lamp replacement can be delayed until several lamps fail at which time the entire fixture (i.e., 4-6 lamps) is changed out (Rogers 2000).

To date, promotional efforts have been focused predominately on commercial sector applications including large retail and warehouse spaces. The lack of readily available information targeted to industrial end-users and a lack of interest in upgrading facility lighting has prevented acceptance of the technology in the industrial sector. Furthermore, there has been reluctance on the part of contractors to share information on the technology and its benefits with their competitors. However, the potential for widespread application and large-scale energy savings in manufacturing facilities is beginning to spark an interest in greater promotion of the technology by utilities. Utilities in the Northeast are offering incentives in the form of custom rebates, but there has been some conflict with recent rebate programs for HID retrofits (Rogers and

## Advanced Lighting Technologies Data Table

	Units	Notes	
Advanced lighting technologies			
Lighting-1			
High-intensity fluorescent replacements for high bay HID			
Market Information:			
Industries		Cross-cutting	
End-use(s)		Lighting	
Energy types		Electricity	
Market segment		New, retrofit	
2015 basecase use	GWh	91,000	Lighting electric is 7% of industrial electricity consumption
Reference technology			
Description	400W metal halide lamp, ballast, bell-shaped spun-aluminum fixture		
Throughput or annual op. hrs.	hours	5000	Rogers and Krepchin 2000
Electricity use	kWh/yr	2325	Rogers and Krepchin 2000; EBN 2000
Fuel use	MBtu	N/A	
Primary energy use	MBtu	19.8	
New Measure Information:			
Description	High-intensity fixture w/4 T-5 lamps and electronic ballast		
Electricity use	kWh	1170	Rogers and Krepchin 2000; EBN 2000
Fuel use	MBtu	N/A	
Primary Energy use	MBtu	9.9	
Current status		Commercialized	
Date of commercialization		1996	Rogers 2000
Est. avg. measure life	Years	4	20,0000 hours at 5,000 hours/year
Savings Information:			
Electricity savings	kWh/%	1155	50%
Fuel savings	MBtu/%	N/A	N/A
Primary energy savings	MBtu/%	9.8	50%
Penetration rate		High	
Feasible applications	%	60%	100% of industrial HID
Other key assumptions			
Elec svgs potential in 2015	GWh	27,124	
Fuel svgs potential in 2015	Tbtu	N/A	
Primary energy svgs potential in 2015	Tbtu	231	30% primary energy savings. Lighting primary energy totals 773.5 Tbtu in 2015
Cost Effectiveness			
Investment cost	\$	185	Fixture cost \$150; lamp costs equals HID; \$35 install cost
Type of cost		Full cost	
Change in other costs	\$	-25	Reduced maintenance cost
Cost of saved energy (elec)	\$/kWh	0.03	
Cost of saved energy (fuel)	\$/Mbtu	N/A	
Cost of saved energy (primary)	\$/Mbtu	4.05	Discount rate for all CCE calculations is 15%
Simple payback period	Years	1.3	Based on \$11.43/Mbtu average cost for electricity
Internal rate of return	%	64%	
Key non energy factors			
Productivity benefits		Somewhat	Dimming capability/improved lighting quality increase worker performance
Product quality benefits		Somewhat	Less glare/better color rendition improve lighting quality for product inspection
Environmental benefits		None	
Other benefits		Significant	Added savings with controls and sensors; faster start-up
Current promotional activity	H,M,L	High	Demonstrations, incentives, supplier marketing, research
Evaluation			
Major market barriers		Lack of info/user interest	Some conflict with recent incentive programs for HID retrofits
Likelihood of success	H,M,L	High	
Recommended next steps		Info dissemination; demos	Rebates/incentives for retrofits
Data quality assessment	E,G,F,P	Excellent	Substantial literature from industry and independent sources, field data
Sources:			
2015 basecase			EIA 1999
Basecase energy use			Rogers and Krepchin 2000; EBN 2000; E Source 1997
New measure energy savings			Rogers and Krepchin 2000; EBN 2000
Lifetime			Rogers and Krepchin 2000; EBN 2000; E Source 1997
Feasible applications			Rogers 2000
Costs			Rogers 2000; EBN 2000; E Source 1997
Key non energy factors			Rogers and Krepchin 2000; EBN 2000
Principal contacts			Jim Rogers 978/256-1345; Nancy Clanton, Clanton & Associates 303/530-7229
Additional notes and sources			

Krepchin 2000). In the Midwest, utilities are educating account representatives and customers about the products (Rogers 2000). and in California, several manufacturers and distributors of high-intensity fluorescent lighting products are expanding their marketing efforts and working with Southern California Edison to incorporate the technology into their new construction programs (Rogers 2000). Additional information dissemination, a broader range of demonstrations and case studies, and continued utility incentives and support would create further demand for the technology.

## Advanced Lighting Design (Lighting-2)

Advanced lighting design techniques that incorporate daylighting, lighting controls, and task lighting can substantially reduce lighting energy consumption in industrial facilities. Daylighting of facilities through the use of daylighting devices such as skylights, light shelves, and reflectors is most easily justified for new facilities. Existing facilities can take advantage of daylighting methods such as glazed windows and daylight pipes, which are installed through the roof and utilize a series of reflectors and a diffuser to direct sunlight to the interior space. Lighting sensors and controls adjust electric light levels to account for the level of natural light entering the space. Task lighting directs light to specific tasks being performed and to individual workers' needs, thereby allowing for reduced ambient light levels throughout the facility.

In order to reap the benefits of improved lighting design, the design must be integrated with compatible lighting technologies. For example, current lighting practice in the majority of manufacturing facilities relies on high-intensity discharge (HID) sources to provide overall ambient lighting. Dimming controls are impractical for use with most HID lamps because the long restart and warm-up times required for HID sources make on/off controls impractical. Additionally, unlike fluorescent sources, reductions in light output and energy consumption are not linear and overall energy savings can be quite small. Developments in HID lamp, ballast, and luminaire technology may help address these concerns, but it remains unclear whether HID technology will ever match the fast start and restrike, low lumen depreciation rates, and lighting quality achievable with fluorescent sources (Rogers and Krepchin 2000). Replacing low-bay fluorescent lighting with compact fluorescent task lighting specifically designed for the needs of individual workers and work stations can further improve lighting quality while reducing energy costs.

One example of advanced lighting design for existing facilities that incorporates many of the energy-saving features discussed above is the replacement of HID light sources with high-output fluorescent lighting and installation of daylight pipes. (For more information on high-output fluorescent lighting, see "Advanced lighting technologies.") High-intensity fluorescent lighting typically achieves a 50 percent reduction in lighting electricity compared to metal halide HID sources without the use of dimming or other control strategies. By incorporating dimming controls – high intensity fluorescent lamps have full dimming capability – and introducing daylight through the use of daylight pipes, overall lighting energy consumption can be reduced by approximately 80 percent. This system could effectively replace the majority of both HID and conventional fluorescent lighting found in most industrial facilities (Rogers 2000).

The costs of such a system vary depending on the level of ambient light required and whether full daylighting (i.e., elimination of all electric lighting during daylight hours) is desired. For full daylighting of 300 to 400 square feet of floor space, replacement of two conventional 400W HID fixtures would cost approximately \$1070 installed. This configuration would require two high-intensity fluorescent fixtures at \$370 (\$150 for each fixture and \$35 installation cost per fixture), dimming controls including photosensors and control interface at \$100, and a 21-inch diameter daylight pipe at \$600 installed (Rogers 2000, EBN 2000, Miller 2000). Although the diffuser dome within the daylight pipe must be cleaned once or twice a year depending on the levels of dust generated in the facility, maintenance costs are expected to remain constant because of fewer lamp replacements. Additional benefits of the system include reduced HVAC loads resulting from lower lighting-related heat input and improved worker performance and productivity due to better lighting quality.

More than a dozen manufacturers offer high-intensity fluorescent lighting systems (Rogers 2000). At least ten manufacturers produce daylight pipes (Krepchin 1999). This product was originally developed for residential use, but the manufacturers are increasing their focus on commercial and industrial applications. Demonstrations, utility incentives, and supplier marketing efforts are being employed to increase demand for these systems. To date, efforts have been more focused and more successful in the commercial sector, but interest among the industrial sector is growing. However, a number of remaining barriers including the high first cost for daylight pipes and a lack of detailed information on the costs and benefits continue to hinder acceptance of the technology. Detailed case studies to verify savings and benefits in industrial applications, broader promotion and incentives, and coordination among manufacturers of the system components could



improve the long-term market viability of these systems. In addition, studies on the impacts of daylighting on worker productivity are needed. The results of such studies in schools appear to have significantly increased interest in daylighting of school facilities and could have a similar effect in the industrial sector.

### Advanced Lighting Design Data Table

	Units		Notes	
Advanced lighting design				
Lighting-2				
Daylighting with dimmable fluorescent replacement for HID				
Market Information:				
Industries		Cross-cutting		
End-use(s)		Lighting		
Energy types		Electricity		
Market segment		New, retrofit		
2015 basecase use		91,000		Lighting electric use is 7% of industrial electricity consumption
Reference technology				
Description	400W metal halide lamp/ballast/bell-shaped spun-aluminum fixture; 2 fixtures per zone			
Throughput or annual op. hrs.	Hours	5000		
Electricity use	kWh/yr	4650		
Fuel use	MBtu	N/A		
Primary energy use	MBtu	39.5		
New Measure Information:				
Description	High-intensity fluorescent fixture w/4-T5 lamps/electronic ballast (2 fixtures per zone); dimming controls; daylight pipe			
Electricity use	kWh	936		2000 hours 100% dimming; 2000 hours 50% dimming; 1000 hours no dimming
Fuel use	MBtu	N/A		
Primary Energy use	MBtu	8.0		
Current status		Commercialized		
Date of commercialization		1996		
Est. avg. measure life	Years	20		Fixtures; controls; light pipe
Savings Information:				
Electricity savings	kWh/%	3714	80%	
Fuel savings	MBtu/%	N/A	N/A	
Primary energy savings	MBtu/%	31.6	80%	
Penetration rate		Medium		
Feasible applications	%	66%		70% of industrial HID; 60% of industrial fluorescent
Other key assumptions				
Elec svgs potential in 2015	GWh	47,971		
Fuel svgs potential in 2015	Tbtu	N/A		
Primary energy svgs potential in 2015	Tbtu	408		53% primary savings. Lighting 2015 primary energy 773.5 Tbtu.
Cost Effectiveness				
Investment cost	\$	1070		\$370 for 2 fixtures w/installation; \$100 controls; \$600 light pipe w/installation
Type of cost		Full cost		
Change in other costs	\$	0		
Cost of saved energy (elec)	\$/kWh	0.05		
Cost of saved energy (fuel)	\$/Mbtu	N/A		
Cost of saved energy (primary)	\$/Mbtu	5		Discount rate for all CCE calculations is 15%
Simple payback period	Years	2.97		Based on \$11.43/Mbtu average cost for electricity
Internal rate of return	%	34%		
Key non energy factors				
Productivity benefits		Somewhat		Dimming capability/improved lighting quality increase worker performance
Product quality benefits		Somewhat		Less glare/better color rendition improve product inspection
Environmental benefits		None		
Other benefits		Significant		Added savings w/ task lighting; reduced HVAC load; faster start-up
Current promotional activity	H,M,L	High		Demonstrations, utility incentives, supplier marketing, research
Evaluation				
Major market barriers		Lack of info; first cost		Cost of daylight pipe particularly high
Likelihood of success	H,M,L	Medium		Cost of daylighting must come down
Recommended next steps		Info dissemination; demos		Rebates/incentives for new construction and retrofits
Data quality assessment	E,G,F,P	Good		Substantial industry and independent literature, limited field data
Sources:				
2015 basecase				EIA 1999
Basecase energy use				Rogers and Krepchin 2000; EBN 2000; E Source 1997
New measure energy savings				Rogers and Krepchin 2000; Krepchin 1999; Miller 2000
Lifetime				Rogers and Krepchin 2000; Krepchin 1999; Miller 2000
Feasible applications				Rogers 2000; Miller 2000
Costs				Rogers 2000; EBN 2000; E Source 1997; Krepchin 1999; Miller 2000
Key non energy factors				Rogers and Krepchin 2000; EBN 2000; Krepchin 1999; Miller 2000
Principal contacts				Jim Rogers 978/256-1345; Greg Miller, Sun Pipe, 847/272-6977
Additional notes and sources				

## High Tech Facilities HVAC Improvements (HVAC-1)

Within the manufacturing sector, a variety of high tech facilities such as laboratories and cleanrooms use a significant amount of energy to operate heating, ventilation, and air-conditioning equipment (HVAC). Much of this energy is used to ensure that production facilities are free from high levels of pollutants that could damage products. These facilities have energy intensities that can range from 5 to 50 (or more) times higher than typical commercial buildings, and HVAC loads account in some cases for 40-50 percent of total energy use (Tschudi 2000, Mills et al. 1996)

High-tech facilities have grown dramatically, and are expected to continue to grow significantly. In the manufacturing sector, high-tech facilities are most commonly associated with the production of semiconductor-based integrated circuits and other electronic components, and with pharmaceutical and biotechnology derived products. Together these two industries account for 70 percent of the clean room square footage in the U.S. (Mills et al. 1996). Other industrial sectors that use cleanroom space include automotive, flat panel manufacturing, food, hospitals, medical devices, and other electronics. Research by McIlvane and Co. has identified a total space use of 14 million square feet (msf) in 1995, growing to 25 msf in 2000, a growth of over 10 percent annually (McIlvane Co. 1996). In California, which houses over 10 percent of the US cleanroom space, electronics- and computer- manufacturing sectors are the fastest growing energy users (Tschudi and Sartor 1999).

There are no reported energy use estimates for high-technology facilities. Electricity intensities can range from 150-950 kWh/ft<sup>2</sup> depending on the level of cleanliness required in the manufacturing environment. Based on detailed analysis undertaken of high-tech facilities in California, we estimate a primary energy consumption in 1995 of 60 TBtu (63 PJ), based on an average weighted energy intensity of 480 kWh/ft<sup>2</sup>. This represents about 0.3 percent of total 1994 manufacturing energy use.

There are several HVAC technologies that have emerged recently which when combined, can achieve significant energy savings. Currently a large amount of energy is expended in heating, cooling, and filtering air that is then exhausted to the atmosphere. Minimizing exhaust flow reduces the amount of make up air that needs to be reconditioned. *Ultra low fume hoods*, a technology developed at Lawrence Berkeley National Laboratory, require 25 percent of normal exhaust flow. This technology is now being piloted in field trials (Tschudi 2000). Air re-circulation is another large HVAC energy user. If occupancy is reduced, then less airflow is required to maintain required cleanliness levels. *Sensors* and the use of *laser-based particle counters* are both technologies that can be applied to more efficiently moderate air flow. Additionally, *more efficient air flow equipment* that is near commercial (e.g. low face velocity fans, efficient duct systems, more efficient filter units) could be combined to further reduce recirculation requirements. Finally, new *immersing filter* technologies (HEPA/ULPA filters) offers the opportunity to significantly reduce filter energy use by reducing filter pressure drops (Tschudi 2000). While not emerging, there are several existing practices that can also be applied in conjunction with the above mentioned technologies that can further enhance energy savings, including “right-sizing” of exhaust systems, improved design guidance for ducting and other systems, and limiting the floor area that requires clean air flow to a smaller “micro” environment.

Combined, these clean room HVAC technologies have the potential to reduce electricity consumption of the average clean-room facility by 25-30 percent, or an average of 145 kWh/ft<sup>2</sup>. Additionally, they are accompanied by several additional non-energy benefits including improved productivity and a reduction in emissions without sacrificing any product quality.

When combined in a carefully optimized fashion, these measures can usually have a payback of 4 years or less, or an incremental cost of roughly \$30 per square foot. More case studies are needed in order to improve the evaluation of costs and payback.

## Hi-Tech Facilities HVAC Data Table

	Units		Notes
<b>Hi-tech facilities HVAC</b>			
<b>HVAC-1</b>			
<b>Improve HVAC systems in hi-tech industries</b>			
<i>Market information:</i>			
Industries		Cross cutting	
End-use(s)		HVAC	
Energy types		Electricity, gas	
Market segment		New	
2015 basecase use	msf	37.9	Estimate of laboratory facility square footage in 2010
<i>Reference technology</i>			
Description	Existing hi-tech facility HVAC systems		
Throughput or annual op. hrs.	1		Normalize on a square foot basis for reference and new technologies
Electricity use	kWh	480	Weighted average based on US cleanroom distribution
Fuel use	MBtu	0.9	
Primary energy use	MBtu	5.0	
<i>New Measure Information:</i>			
Description	Efficient HVAC in hi-tech facilities		
Electricity use	kWh	336	Tschudi and Sartor, 2000
Fuel use	MBtu	0.9	
Primary Energy use	MBtu	3.8	
Current status		Commercialized	Some technologies also near commercial
Date of commercialization			
Est. avg. measure life	Years	20	
<i>Savings Information:</i>			
Electricity savings	kWh/%	144	30%
Fuel savings	MBtu/%	0.0	0%
Primary energy savings	MBtu/%	1.2	25%
Penetration rate		Medium	
Feasible applications	%	30%	High feasibility for new buildings
Other key assumptions			
Elec svgs potential in 2015	GWh	1637	
Fuel svgs potential in 2015	Tbtu	0	
Primary energy svgs potential in 2015	Tbtu	13.9	
<i>Cost Effectiveness</i>			
Investment cost	\$	20	Based on Singapore wafer fab case study (Tschudi, 2000)
Type of cost		Incremental	
Change in other costs	\$	0	
Cost of saved energy (elec)	\$/kWh	0.02	
Cost of saved energy (fuel)	\$/Mbtu	#DIV/0!	
Cost of saved energy (primary)	\$/Mbtu	2.61	Discount rate for all CCE calculations is 15%
Simple payback period	Years	4.0	
Internal rate of return	%	0%	
<i>Key non energy factors</i>			
Productivity benefits		Somewhat	
Product quality benefits		None	
Environmental benefits		None	
Other benefits		Somewhat	Improved worker safety with improved fume hoods
Current promotional activity	H,M,L	Medium	
<i>Evaluation</i>			
Major market barriers		Information	High perceived risk
Likelihood of success	H,M,L	Medium	
Recommended next steps		Consortiums, roadmap	
Data quality assessment	E,G,F,P	Fair	
<i>Sources:</i>			
2015 basecase			McIlvane, 1996
Basecase energy use			Mills et al., 1996
New measure energy savings			Tschudi and Sartor, 2000
Lifetime			Tschudi and Sartor, 2000
Feasible applications			Tschudi and Sartor, 2000
Costs			Tschudi and Sartor, 2000
Key non energy factors			Tschudi and Sartor, 2000
Principal contacts			William Tschudi, LBNL (WFTschudi@lbl.gov)
Additional notes and sources			

There are marketing obstacles to the promotion of this technology. These obstacles primarily are geared toward the need for better information to cleanroom designers, builders, and operators on HVAC efficiency opportunities through increased information and education, and the lowering of perceived risk given what would be a higher first cost. LBNL and other research institutions have taken an early role in attempting to promote collaborations with key hi-tech industry associations, but this work is still in its early stages.

In addition to collaboration and engaging in a “roadmapping” process, other potential opportunities to encourage increased industry participation in HVAC efficiency include the development of a benchmarking tool to allow for inter-industry comparisons. We believe that in the absence of an existing consortium there is a medium likelihood of success of dramatically improving HVAC efficiency. A complicating factor is that the lifetime of cleanroom processes are significantly less than the lifetime of the buildings in which the measures are installed, so there is a possibility for increase in maintenance costs in the long term if HVAC equipment must be recalibrated. Next steps will require additional demonstration projects to improve acceptance by the industry.

## Anaerobic Wastewater Treatment (Other-1)

Industrial wastewater is typically treated by aerobic systems that remove contaminants prior to discharging the water. These aerobic systems have a number of disadvantages including high electricity use by the aeration blowers, production of large amounts of sludge, and reduction of dissolved oxygen in the wastewater which is detrimental to fish and other aquatic life (CADET 1993e, CADET 1996d). Anaerobic wastewater treatment is an alternative method for cleaning industrial wastewater which is based on the conversion of organic compounds in the wastewater into a biogas of methane, carbon dioxide, and hydrogen sulfide by bacteria in an oxygen-free environment (CADET 1993e).

The most widely used technology for anaerobic wastewater treatment is the Upflow Anaerobic Sludge Blanket (UASB) reactor which was developed in 1980 in The Netherlands (U.N. FAO 1997). Industrial wastewater is directed up through the UASB reactor, passing through a “blanket” that traps the sludge. Anaerobic bacteria break down the organic compounds in the sludge, producing methane in the process (CADET 1993e, CADET 1996d). This type of anaerobic wastewater treatment is currently used predominantly in the paper and food industries, but some industries such as chemical and pharmaceuticals have also used this technology and its use is growing for municipal wastewater treatment (Habets 2000, Motta 1998). Globally, there are approximately 1500 anaerobic wastewater treatment plants (80 percent are UASBs), of which approximately 150 are in the U.S. (Habets 2000).

Energy savings from the use of an UASB come from displaced electricity as well as from the use of the produced biogas. Depending upon the type and size of plant, an anaerobic wastewater treatment facility will displace roughly 6,570 MWh of electricity used annually in an aerobic plant (Habets 2000). In addition, the biogas that is generated can be used in the manufacturing process or can be used by a steam boiler (CADET 1993e, CADET 1996d). An anaerobic wastewater treatment facility at a whey processing plant in the Netherlands saves 1,100 MWh/year of electricity through the reduced demand for aeration, although electricity use of 727 MWh/year is still required for pumping and aeration to remove residual organic compounds in the water (CADET 1993e, Habets 2000). This same plant produces 344 m<sup>3</sup>/day of methane gas (CADET 1996d). We estimate a total savings of roughly 1000 kWh/day and an additional generation of 70 Mbtu/day (74 GJ/day) of biofuel.

The investment cost for the anaerobic wastewater treatment facility at the whey processing plant was \$1.8M, which represents an additional investment beyond an aerobic plant of \$274,000 (CADET 1996d). Annual electricity and fuel savings are \$167,000, savings from reduced sludge production are \$294,000, and savings from reduced consumption of chemical compounds is \$64,000. Costs of \$17,000 are incurred for additional personnel. Thus, the overall savings are \$508,000 per year, resulting in a payback period of less than 0.5 years for the incremental investment (CADET 1996d).<sup>20</sup> For use of this technology in a paper mill, the total capital cost of the anaerobic wastewater treatment facility was \$2.28M (1993\$). Savings from the production of natural gas are \$80,000 per year (based on fuel prices in the U.K), sludge sales are worth about \$50,000 per year, and savings of about \$1,400,000 per year result from reduced effluent discharge costs. Operating costs are an additional \$375,000 per year. Thus, total annual savings are over \$1.5M, resulting in a payback period of about 1.5 years (CADET 1993).

The UASB technology is used around the world and several hundred facilities have been installed by the two leading UASB companies, Paques and Biothane (Heijnen n.d.). Evaluations of anaerobic wastewater treatment facilities in the UK, Netherlands, Canada and U.S. show a wide range of costs and energy savings, with payback periods ranging from 1.4 years to 3.7 years (CADET 1993e, CADET 1996d, CADET 1997e, CADET 1997f, CADET 1997g, CADET 1998b, CADET 1999e). Currently, there are approximately 125 anaerobic wastewater treatment facilities in the U.S., which is about 0.5 plants per million residents. There is great potential to increase the number of anaerobic wastewater treatment plants; some countries have 3 to 5 plants per million people which implies that 750 to 1250 total plants could be installed in the U.S. (Habets 2000). For our analysis, we estimate that an additional 400 plants could be

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<sup>20</sup> These costs are calculated based on the cost of energy in The Netherlands. Using lower U.S. energy costs, the payback period is 0.8 years.

# Anaerobic Waste Water Treatment Data Table (Other-1)

	Units		Notes	
<b>Anaerobic wastewater treatment</b>				
<b>other-1</b>				
<b>Upflow anaerobic sludge blanket (UASB) wastewater treatment facility</b>				
<i>Market Information:</i>				
Industries		Cross-cutting		
End-use(s)		Other		
Energy types		Electricity		For pumping
Market segment		New		
2015 basecase use	TWh	338		Electricity consumption in 2015 for paper, food, bulk chemicals (AEO, 2000)
<i>Reference technology</i>				
Description		Conventional aerobic wastewater treatment plant		
Throughput or annual op. hrs.	m3/day	2500		8760 annual operating hours (Habets, 2000)
Electricity use	kWh/day	3019		For aeration
Fuel use	MBtu/day	0		
Primary energy use	MBtu/day	26		
<i>New Measure Information:</i>				
Description		Upflow anaerobic sludge blanket (UASB) wastewater treatment facility		
Electricity use	kWh/day	1992		Load of 5kw/day for pumping, 78kw/d for aeration (Habets, 2000)
Fuel use	MBtu/day	0		
Primary Energy use	MBtu/day	17		
Current status		Commercialized		
Date of commercialization				
Est. avg. measure life	Years	20		Habets 2000
<i>Savings Information:</i>				
Electricity savings	kWh/day	1027	34%	CADDET 1996d
Fuel savings	MBtu/day	70	N/A.	Generates a natural gas savings of 900,000 m3/year (CADDET 1996d)
Primary energy savings	MBtu/day	79	307%	
Penetration rate		Medium		Currentlv 5-10% of potential. should be able to triple bv 2015 (Habets 2000)
Feasible applications	%	33%		Weighted average for paper, food, and chemical industries
Other key assumptions				
Elec svgs potential in 2015	GWh	150		Est. 375-500 new anaerobic plants in US in 2015 (Habets 2000; Richards 2000)
Fuel svgs potential in 2015	Tbtu	10.2		
Primary energy svgs potential in 2015	Tbtu	11.5		
<i>Cost Effectiveness</i>				
Investment cost	\$	274000		CADDET 1996d (full cost for plant is \$1.8 million)
Type of cost		Incremental		
Change in other costs	\$	-341000		Reduced sludge handling & chemical consumption: added personnel costs
Cost of saved energy (elec)	\$/kWh	-0.79		
Cost of saved energy (fuel)	\$/Mbtu	-11.61		
Cost of saved energy (primary)	\$/Mbtu	-10.33		Discount rate for all CCE calculations is 15%
Simple payback period	Years	0.8		
Internal rate of return	%	125%		
<i>Key non energy factors</i>				
Productivity benefits		None		
Product quality benefits		None		
Environmental benefits		Significant		Reduced sludge production; in other applications, the biochemical oxygen demand (BOD) level can be significantly reduced (CADDET 1996d)
Other benefits		Somewhat		Compact design (reduces area needed), simple design (CADDET 1996d)
Current promotional activity	H,M,L	Low		Mainly promoted by companies that produce the technology; DOE held seminars on the practice, discontinued in the early 1980s (Richards 2000)
<i>Evaluation</i>				
Major market barriers				Low energy prices, high cost of technology, lack of knowledge among potential users (Richards 2000)
Likelihood of success	H,M,L	High		Depends on the cost of energy, the cost of waste disposal, and the dissemination of anaerobic technology information (Richards 2000)
Recommended next steps		Demonstration		Government (DOE) sponsored demonstration projects, on-going targeted publicity including data (Richards 2000)
Data quality assessment	E,G,F,P	Good+		
<i>Sources:</i>				
2015 basecase				Habets 2000
Basecase energy use				CADDET 1996
New measure energy savings				Habets 2000
Lifetime				Habets 2000
Feasible applications				Habets 2000
Costs				CADDET 1996
Key non energy factors				CADDET 1996
Principal contacts				Leo Habets, Paques, NL (L.Habets@paques.nl); Dr. E.A. Richards, P.E., 414-545-3629; fax 414-545-6094, (drer.execpc.com)
<b>Additional notes and sources</b>				

built by 2015. These plants can be used by a variety of industrial facilities, including papermaking, food processing, chemicals, pharmaceuticals, and distilleries. The market potential varies for these industries from 30 to 40 percent for the paper industry to 100 percent for processing of sugar, starch, and alcohol based on the size of the mills, types of mills, and their water consumption (Habets 2000). We estimate an average market potential of 33 percent of selected food, paper, and chemicals sectors based on a weighting of 1994 energy consumption.

Adoption of this technology depends on energy costs as well as effluent controls and disposal costs. This technology is being rapidly adopted in Brazil, Japan, China, Mexico, and Europe. Adoption in the U.S. has been slow, especially in the paper industry. In the past, the U.S. Department of Energy held a number of seminars promoting this technology, but these were discontinued in the early 1980s. Currently, the only promotion in the U.S. is through the large companies that produce this type of system such as Biothane Corporation in Camden, New Jersey (Richards 1996).

Market barriers include the low cost of energy, especially vis-à-vis the cost of the technology, as well as negative perceptions based on past experiences with less effective systems. Another barrier is the lack of information, including reliable data, available on this technology. Stricter effluent regulations combined with government-sponsored demonstration programs that provide real data on this technology, targeting marketing of this technology to potential users, and investment incentive programs could all help to promote increased adoption of anaerobic wastewater treatment (Richards 1996, Habets 2000).

## High-Efficiency/Low NO<sub>x</sub>-Burners (Other-2)

Recuperators and regenerators are the two major contributors to improved energy efficiency in combustion technology. These technologies preheat the combustion air. However, preheating leads to higher flame temperatures, which may lead to higher NO<sub>x</sub> emissions. Air quality regulation drives the demand for high efficiency but low emission (NO<sub>x</sub>, CO) emissions. Low NO<sub>x</sub> emissions can be achieved by reduce NO<sub>x</sub> formation in the combustion process or end-of-pipe catalytic removal. The costs of flue-gas removal are high. Integrated solutions in the combustion process are preferred due to the prohibitive costs of removal. NO<sub>x</sub> formation in the combustion process is reduced by reducing the amount of nitrogen in contact with oxygen at high flame temperatures. Available options are oxy-fuel combustion (e.g. in glass, metals industry), improved mixing of combustion air and fuel to maintain a stable temperature profile of the flame, and near stoichiometric conditions (reducing the amount of nitrogen in the flame) through staged combustion, as well as flue gas recirculation (FGR) (Berntsson et al. 1997). FGR is relatively expensive. Oxy-fuel burners were discussed for the steel and glass industry elsewhere. In this technology characterization we focus on high-efficiency low NO<sub>x</sub> burner designs using air as oxidant. We discuss burners for boilers, furnaces and direct heating. Note that the performance of a burner depends on the configuration of the boiler or furnace in which it is used. Hence, the savings may vary widely depending on the specific situation. In this description we try to separate the effects of improved burner design from furnace/boiler design.

**Boilers** are used throughout industry and consume about 6.05 Quads (6.38 EJ) of fuels, or 37 percent of total industrial fuel use (Einstein et al. 2000). Because of their widespread use air quality regulation has historically been aimed at boilers. Natural gas is the dominant boiler fuel (40 percent), followed by biomass/wastes (38 percent) and coal (14 percent). In this description we focus on natural gas burners. Solid fuels are normally burned in stoker-boilers. In stoker boilers NO<sub>x</sub> emissions can be reduced by Over-Fire-Air (OFA, introduction of air not at the burner) and gas reburning. In oil systems OFA and FGR are the main methods to reduce NO<sub>x</sub> emissions.

Research in Low NO<sub>x</sub>-burners is ongoing in many parts of the world. In the U.S. OIT is sponsoring a Crosscutting activity on combustion, while in many states research on low NO<sub>x</sub>-burners has been sponsored (e.g. in California and New York). The Vision (DOE-OIT 1998b) and Roadmap documents (DOE-OIT 1999a) aim at the development of low-NO<sub>x</sub> burners with increased efficiency. Efficiency goals are not determined for burners alone, but rather for the systems. For process heating systems the goal is and reduced fuel consumption of 20-50 percent, while reducing criteria pollutant emissions by 90 percent. Research to low NO<sub>x</sub>-combustion is done at research institutes (e.g. Gas Research Institute, Gas Technology Institute), national laboratories (e.g. Lawrence Berkeley National Laboratory) and universities (e.g. University of California at Irvine), as well as manufacturers. Most burner manufacturers also supply low NO<sub>x</sub>-burners, e.g. Alzeta, Bloom Engineering, COEN, Detroit Stoker, Hauck, and John Zink.

Heat distribution and flux are important design features of **furnaces** to improve the efficiency. Burner concepts are developed that aim at improving the heat distribution by impulse firing (for heat treatment and intermittent kilns) and high velocity burners (as discussed in the roller kiln for ceramic products). In furnaces recuperators and regenerators are used to improve efficiency. A recuperator is a heat exchanger that extracts heat from the furnace waste gases to pre-heat incoming combustion air. Compared to furnaces without air preheating energy savings of 30 percent can be reached (Flanagan 1993). Development is aimed at higher temperature ceramic recuperators and so-called self-recuperative burners, while minimizing NO<sub>x</sub> emissions. In self-recuperative burners the recuperator is an integral part of the burner, which decreases costs, and might make it easier to retrofit existing furnaces. Regenerative burners are operated in pairs. While one is used to burn the fuel, another burner uses a porous ceramic bed to store heat. After a short period (minutes) the process is reversed, and the heat stored in the ceramic bed is used to preheat the combustion air. In this way about 85 percent of the heat in the flue gases is recovered, and the combustion air can be pre-heated to temperatures of only 150°C less than the furnace operating temperature (Flanagan 1993). Compared with cold air burners, regenerative burners can achieve fuel savings in excess of 50 percent (Flanagan 1993). However, potential high NO<sub>x</sub>-emissions may limit preheat temperatures and hence energy savings. Also, the full benefit of the burners depends on the integration in the furnace. For low to medium-temperature applications, we concentrate on burner designs that achieve low-NO<sub>x</sub> (<20 ppm) while improving energy efficiency.



**High-Efficiency Low NO<sub>x</sub> Burners Data Table**

	Units	Notes	
High-Efficiency Low-NOx Burners other-2			
Low-NOx High Efficiency Burners			
Market Information:			
Industries		Cross-cutting	
End-use(s)		Boilers, Process Heating	
Energy types		Natural Gas	
Market segment		Retrofit	
2015 basecase use	Tbtu	6758	
Reference technology			
Description	Conventional burners in existing boilers or furnaces		
Throughput or annual op. hrs.		1	Boilers and furnaces are available in any size
Electricity use	kWh	0	
Fuel use	TBtu	6758	
Primary energy use	TBtu	6758.0	
New Measure Information:			
Description	Low-NOx High Efficiency Burners		
Electricity use	kWh	0	
Fuel use	TBtu	6543.6	
Primary Energy use	TBtu	6543.6	
Current status		Commercial	
Date of commercialization		1996	
Est. avg. measure life	Years	20	
Savings Information:			
Electricity savings	kWh/%	0	0%
Fuel savings	MBtu/%	214.4	3%
Primary energy savings	MBtu/%	214.4	3%
Penetration rate		Low	
Feasible applications	%	10%	
Other key assumptions		10% of industrial natural gas use is in non-attainment areas	
Elec svgs potential in 2015	GWh	0	
Fuel svgs potential in 2015	Tbtu	21	
Primary energy svgs potential in 2015	Tbtu	21.4	
Cost Effectiveness			
Investment cost	\$/MBtu	7	
Type of cost		Full	
Change in other costs	\$/MBtu	-0.1	
Cost of saved energy (elec)	\$/kWh	N/A	
Cost of saved energy (fuel)	\$/Mbtu	0.94	
Cost of saved energy (primary)	\$/Mbtu	0.94	Discount rate for all CCE calculations is 15%
Simple payback period	Years	3.1	
Internal rate of return	%	33%	
Key non energy factors			
Productivity benefits		Somewhat	Improved burner capacity could lead to higher throughput in specific cases
Product quality benefits		None	
Environmental benefits		Significant	Reduction of NOx emissions by 30 - 70%
Other benefits			
Current promotional activity	H,M,L	Medium	
Evaluation			
Major market barriers			
Likelihood of success	H,M,L	Medium	
Recommended next steps		Demonstration, Promotion	
Data quality assessment	E,G,F,P	Poor	Estimates based on few case-studies
Sources:			
2015 basecase		EIA 1999	
Basecase energy use		EIA 1999	
New measure energy savings		CADET 1997h, COEN 2000, Berntsson et al. 1997	
Lifetime		Author estimate	
Feasible applications		Author estimate	
Costs		CADET 1997h; Berntsson et al. 1997	
Key non energy factors		Author estimate	
Principal contacts		Steve Londerville, COEN Company (650) 697-0440	
Additional notes and sources			

For example, the Pyrocore ceramic burner marketed by Alzeta Corp. (after development with the Gas Research Institute, US EPA and Southern California Gas Company) is used for direct firing applications in the food industry (with extremely low emissions) (CADDET 2000c) and for process heaters in the oil industry (CADDET 1989). Energy savings were not specified in either application.

In natural gas boilers NO<sub>x</sub> is mainly generated through thermal processes. Advanced burner designs can reduce NO<sub>x</sub> emissions, while maintaining or improving efficiency. NO<sub>x</sub> emissions from standard industrial gas boilers can be between 60 and 200 ppm. Low NO<sub>x</sub> burners can reduce emissions to 20-30 ppm, while

ultra-low NO<sub>x</sub> burners (also used for direct heating applications) can reduce emissions to 5-9 ppm. COEN has installed low-NO<sub>x</sub> burners that comply with California air quality standards in the oil industry (Bakersfield, CA), textile plant (Vernon, CA), as well as heating plants (Sacramento, CA). In these plants NO<sub>x</sub> emissions between 9 and 26 ppm have been achieved, at high efficiencies. Efficiency gains are not always specified. In the case of a heating plant in Sacramento (CA), an efficiency gain of 3 percent was achieved (COEN 2000). We assume fuel savings of 2 percent for using high-efficiency (ultra) low-NO<sub>x</sub> burners. While the capital costs of the burner are comparable to those of standard burners, the total system costs would be lower, if SCR NO<sub>x</sub>-removal would need to be installed. Implementation of high-efficiency Low-NO<sub>x</sub> burners will be primarily driven by air regulation. We assume that implementation is limited to non-attainment areas. However, no industrial energy consumption data is readily available for non-attainment regions (STAPPA-ALAPCO 1999). In July 2000, 31 regions were non-attainment areas for ground level ozone (EPA 2000b). We estimate that 10 percent of all industrial boiler capacity is found in non-attainment areas, and would need NO<sub>x</sub>-reduction measures. Natural gas use for boilers in 2015 is estimated at 4118 TBtu (4344 PJ) (AEO 1999).

For high-temperature applications NO<sub>x</sub>-emission reductions are limited by the necessary high flame temperatures needed. Still, modern burners designed to mix the combustion air and fuel well, reduce NO<sub>x</sub>-emissions. The Gyro-Therm burner developed in Australia for the cement industry achieves reductions in NO<sub>x</sub>-emissions of 30 to 70 percent, while saving 5 percent on fuels in a clinker kiln in the cement industry. The stable flame reduced refractory wear. The technology has been applied in several cement plants around the world including the U.S. (e.g. Ash Grove, Durkee, OR). The payback period is around 2 years (CADDET 1997h). Stordy Combustion Engineering (United Kingdom) has developed a low-NO<sub>x</sub> regenerative burner that can achieve NO<sub>x</sub> emissions of 100-125 ppm at air-preheat temperatures of 1000°C (CADDET Newsletter 1999), resulting in fuel savings of 40 percent compared to conventional burners at near-stoichiometric conditions (Flanagan 1993). Potential applications are found in the metals industry, e.g. reheating furnaces, aluminum smelting, copper smelting.

For high temperature applications, we assume that new burners can save 5 percent on average for natural gas burners, while maintaining low NO<sub>x</sub>-emissions, across various process heating applications. As implementation is driven by air quality regulation, uptake of the technology will be highest in non-attainment areas. Due to the lack of data on industrial energy use for process heating applications in non-attainment areas we assume that the technology can be used in 10 percent of natural gas fired heating applications. We exclude natural gas use in the chemical industry (where most gaseous fuels are not necessarily natural gas), glass industry and specific natural gas applications in the steel industry. Hence, natural gas use for process heating in 2015 is estimated at 2640 TBtu (2785 PJ) (AEO 1999).

The costs will depend on the individual applications of the burners. The costs of low NO<sub>x</sub>-burners for large utility boilers is estimated at 10-20 \$/kW (Berntsson et al. 1997). The costs are different for the often smaller industrial applications. Based on the case-studies we assume a simple payback period of three years for retrofit-situations. The reduced use of FGR in existing boilers may lead to reduced operating costs, as may reductions in NO<sub>x</sub> emissions offsets. For example, the ARCO Refinery boiler project in Bakersfield (CA) with a capacity of 62.5 MBtu/hr (65.9 GJ/hr) can result in a reduction \$54,000 in reduced emission offsets (or 2.9 \$/kW), while reduced use of FGR resulted in an additional saving of \$40,000 at full capacity (COEN 2000). These cost-savings will be highly site-dependent.

The main driving force for Low NO<sub>x</sub>-burners is air quality regulation. The relative low cost compared to options like SCR or FGR makes them attractive options. However, in the design of Low NO<sub>x</sub> burners energy efficiency should be an integrated part of the design. Future steps include the dissemination of information on Low-NO<sub>x</sub> burner technology to potential users and air quality regulators, as well as demonstration of burners in different applications, especially with respect to furnace applications.

### **Membrane Technology Wastewater (Other-3)**

Water is used throughout industry for many applications. Daily industrial water use is estimated at 27,100 million gallons/day in 1995 (Solley et al. 1998), of which 85 percent is disposed after use. There is no information on water use by sector. Large water users are the food, paper, chemical and metal industries. Wastewater is produced in as many industries and may contain many different contaminants, ranging from bio-organic compounds to metal compounds. The water needs to be cleaned before it can be emitted or can be recovered for re-use in the plant. In 1995 only 110 million gallons/day were reclaimed and re-used by industry (Solley et al. 1998). Treatment with chemicals (sanitizing, flocculation), biological treatment, ozonation, ultraviolet treatment, gravity settling, flotation and screening are conventional methods used to clean water. The costs and energy use of wastewater treatment depends heavily on the facility, differences in flow, type of pollutants, as well as type of equipment used. For example, the wastewater treatment costs for printed wiring board manufacturers varied between 0.5\$/1000 gallons to 35\$/1000 gallons (EPA n.d.).

Membranes can also be used to remove dissolved or suspended solids, microbes. The membrane types mostly used in water treatment are ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), while MF is mainly used to stabilize (pre-filter) the water for RO-treatment. The differences between the used membrane methods are the separation capabilities due to size and molecular weight. Membranes have been used for desalting of water for some time now, and facilities using membranes can be found in 13 states in the United States, with most in California and Florida. Some recently constructed plants in Arizona, California, and Hawaii use wastewater as feed.

Membrane wastewater treatment plant design starts with the selection of the membrane. The type of membrane material used determines the contaminant rejection characteristics (i.e. chemicals removed from the water), durability and fouling characteristics (Jacangelo et al. 1998). Most membranes used today are polymer membranes, as these have lower costs. Ceramic membranes are more expensive, but can be used at higher pressures and with longer lifetimes (CADDET 1994e). Two membrane processes (e.g. MF and RO) can be combined to remove different contaminants. The main driver for membrane application is the cost of wastewater treatment, and not energy use, although membranes can reduce energy use when compared to evaporation. Koch Membrane Systems estimates the operating costs of an UF-system at 7.5\$/1000 gallons compared to 22\$/1000 gallons for chemical treatment (KMS 2000) for treatment of 5400 gallons/day of oily wastewater.

Membranes have been used in many industries to clean wastewater before disposal and to recover water for internal re-use. Examples can be found in e.g. the metal industries, metal plating, food, paper, chemicals, and electronics. Tri-Valley Growers in Madera, CA installed an UF/RO-membrane system, with help of PG&E and DOE, to reduce wastewater discharge of an olive-oil plant. The system allowed the operation of the plant with zero discharges. The system reduced capital costs and energy costs compared to a biological wastewater treatment system. Gas use was reduced by 55 percent and electricity use by 30 percent, reusing up to 800,000 gallons of water per day (Fok and Moore 1999). The project was a technical success. Unfortunately, the olive oil plant closed recently in response to market changes in the olive oil industry.

Replacement of polymer membranes by ceramic membranes in an UF-system to clean wastewater from an enameling plant reduced power consumption by 66 percent, due to the reduced silting of the system (CADDET 1994e). Reduced power and maintenance costs resulted in a simple payback period of 6-7 years, due to the high costs of the ceramic membrane.

Barriers to implementation include the lack of information, relative high capital costs, as well as the need for specific membranes of specific applications. Major suppliers are APV (Denmark), Koch Membrane Systems (US), Osmonics (US), U.S. Filter (US). Research aims at new membrane materials and applications, more efficient and longer lasting membranes, and cost reduction of membrane costs. Federal research programs (e.g. ATP) support development of membrane technology, as well as development of specific applications (e.g. DOE, EPA, USDA).

# Membrane Technology Wastewater Data Table

	Units		Notes
<b>Membranes for Wastewater Treatment and Recovery</b>			
<b>other-3</b>			
<b>Use of Membranes to Recover and Clean Industrial Wastewater</b>			
<b>Market Information:</b>			
Industries		Cross-Cutting	
End-use(s)		Other	Wastewater Treatment
Energy types		Fuel, Electricity	
Market segment		New, Retrofit	
2015 basecase use	kGd	23,035,000	1000 gallons/day, 1995 industrial water discharge
<b>Reference technology</b>			
Description		Evaporation, Clarification	
Throughput or annual op. hrs.		1	1000 gallons/day, 1995 industrial water discharge
Electricity use	kWh/kG	18	kWh/1000 gallons
Fuel use	Mbtu/kG	0.4	Mbtu/1000 gallons
Primary energy use	Mbtu/kG	0.6	Mbtu/1000 gallons
<b>New Measure Information:</b>			
Description		Use of Membranes to Recover and Clean Industrial Wastewater	
Electricity use	kWh/kG	45	kWh/1000 gallons
Fuel use	Mbtu/kG	0.0	Mbtu/1000 gallons
Primary Energy use	Mbtu/kG	0.4	Mbtu/1000 gallons
Current status		Commercial, Research	Many applications commercial; new membranes under development
Date of commercialization		1990	
Est. avg. measure life	Years	10	
<b>Savings Information:</b>			
Electricity savings	kWh/%	-27	-150% Actual savings depend on application
Fuel savings	MBtu/%	0.4	100% Actual savings depend on application
Primary energy savings	MBtu/%	0.2	31% Actual savings depend on application
Penetration rate		Medium	
Feasible applications	%	10%	Rough estimate, current use small
Other key assumptions			
Elec svgs potential in 2015	TWh	-19	Assuming daily use for 300 days/year
Fuel svgs potential in 2015	Tbtu	276	Assuming daily use for 300 days/year
Primary energy svgs potential in 2015	Tbtu	117.8	
<b>Cost Effectiveness</b>			
Investment cost	\$	30000	\$/1000 gallons-day
Type of cost		Full cost	
Change in other costs	\$	-6400	\$/1000 gallons-day
Cost of saved energy (elec)	\$/kWh	N/A	
Cost of saved energy (fuel)	\$/Mbtu	-1056.10	
Cost of saved energy (primary)	\$/Mbtu	-2477.64	Discount rate for all CCE calculations is 15%
Simple payback period	Years	4.7	
Internal rate of return	%	21%	
<b>Key non energy factors</b>			
Productivity benefits		Somewhat	Recover water and chemicals, reduced maintenance
Product quality benefits		None	
Environmental benefits		Somewhat	Reduced water use
Other benefits			
Current promotional activity	H,M,L	Medium	
<b>Evaluation</b>			
Major market barriers		Specificity, Unknown	
Likelihood of success	H,M,L	High	
Recommended next steps		Dissemination, R&D	
Data quality assessment	E,G,F,P	Fair, Poor	
<b>Sources:</b>			
2015 basecase			Solley et al. 1998
Basecase energy use			Rough assumption based on process energy use
New measure energy savings			Fok and Moore 1999
Lifetime			Wiesner and Chellam 1999
Feasible applications			Rough estimate
Costs			Koch Membrane Systems and current systems (Koch 2000; EPA n.d.)
Key non energy factors			Case-studies (CADET)
Principal contacts			
Additional notes and sources			

It is extremely difficult to estimate the potential energy savings from implementation of membranes for water treatment without a detailed study. For specific applications energy savings may be up to 40-55 percent of the energy needs for evaporation. Additional production savings are achieved through product quality, reduced water use, lower operation costs, which are site-specific.

Energy use for other treatment may be very low (coagulation, coarse filtration), or high (evaporation). Energy use for evaporation is very high (i.e. 100 MBtu/1000 gallons water evaporated (106 GJ/1000 gallons)). Mechanical vapor recompression would reduce the heat demand, but has still a high power demand of 25-50 kWh/1000 gallons (Fok and Moore 1999). However, most industrial wastewater is probably pre-treated with physical, chemical or biological means before being disposed to the public sewer system or surface water. Large industrial facilities may need to evaporate water for sludge disposal. We assume that 50 percent of wastewater is treated using biological and chemical technologies (consuming 0.8 Mbtu/1000 gallons (0.8 GJ/1000 gallons) and 30 kWh/1000 gallons, derived from Fok and Moore (1999)), and 50 percent uses only coagulation and mechanical treatment (using 4 kWh/1000 gallons).

Energy use for a membrane system is estimated at 15-40 kWh/1000 gallons (Fok and Moore 1999). We assume a two-step UF/RO-process with an average consumption of 45 kWh/1000 gallons.

The investment and operating costs depend heavily on specific application, and are site-specific. However, for the purposes of this study we make a general estimate, noting that the costs may vary widely in practice. The capital costs of membrane systems are relatively high, but may be lower than alternative processes, as shown by the example of Tri-Valley Growers, CA. Generally, capital costs are expressed per unit of surface area, while about half of the capital costs are for the system components (e.g. pumps, piping) (Wiesner and Chellam 1999). Investment costs are estimated for polymer membrane plants for oily wastewater streams are estimated at 30\$/gallon-day (Koch 2000), while annual operating costs are estimated at 5\$/gallon-day. Operating costs for a chemical treatment plant are estimated at \$10/gallon-day, and for evaporation at 16\$/gallon-day (Koch 2000). We assume average operating costs of 11\$/gallon-day for non-membrane equipment (EPA n.d.). Re-use of water will reduce the water purchase fees and discharge fees. The reduced costs are estimated at 0.4 cts/gallon-saved, although they may vary by location.

Membrane life of a properly operated facility may easily exceed 10 years (Wiesner and Chellam 1999). We assume a lifetime of 10 years.

The energy savings and cost estimates are rough. Given the large potential application area and potential energy savings, an in-depth study into membrane applications, energy savings, capital and operational cost benefits is warranted.

## Process Integration/Pinch Analysis (Other-4)

Process Integration (PI) refers to the exploitation of potential synergies that are inherent in any system that consists of multiple components working together. PI is the art of ensuring that the components are well suited and matched in terms of size, function and capability. Pinch Analysis is a tool for determining the optimum process integration strategy, generally applicable for manufacturing processes.

Pinch Analysis takes a systematic approach to identifying and correcting the performance limiting constraint (or pinch) in any manufacturing process (Kumana 2000a). It was developed originally in the late 1970s at the University of Manchester in England and other places (Linnhoff 1993) in response to the “energy crisis” of the 1970s, and the need to reduce steam and fuel consumption in oil refineries and chemical plants by optimizing the design of heat exchanger networks. Since then, the pinch approach has been extended to resource conservation in general, whether the resource is capital, time, labor, electrical power, water, or a specific chemical species such as hydrogen.

*Energy Optimization.* The critical innovation in applying pinch analysis was the development of “composite curves” for heating and cooling, which represent the overall thermal energy demand and availability profiles for the process as a whole. When these two curves are drawn on a temperature-enthalpy graph, they reveal the location of the process pinch (the point of closest temperature approach), and the minimum thermodynamic heating and cooling requirements. These are called the energy targets. The methodology involves first identifying the targets, and then following a systematic procedure for designing heat exchanger networks to achieve these targets. The optimum approach temperature at the pinch is determined by balancing the capital-energy tradeoffs to achieve the desired payback. The procedure applies equally well to new designs as well as retrofit of existing plants.

The analytical approach to this analysis has been well documented in the literature (Kumana 2000b, Smith 1995, Shenoy 1994). Energy savings potential using Pinch Analysis far exceed that from well-known conventional techniques such as heat recovery from boiler flue gas, insulation, and steam trap management. Results from pinch case studies sponsored by various government and industry institutes (DOE, EPRI, GRI) over the last 15 years on thermal pinch compiled by Kumana are reproduced below.

### Energy Savings Potential Using Pinch Analysis

Industry	No. of plants	Percent cost savings	Payback range (years)
Oil refining	9	10-40	0.6-2.8
Chemicals	17	15-40	0.9-4.3
Food and Beverage	18	7-45	0.7-3.9
Pulp and paper	9	10-35	0.8-2.4
Textiles	4	3-25	1.1-4.7
Iron and steel	2	11-50	0.9-1.5

Source: Kumana 2000b.

While opportunities for energy optimization still exist, even in the energy intensive process industries such as chemicals, petroleum refining, and pulp and paper sectors, the focus here is on emerging applications.

*Site-wide energy strategies or Total Site analysis.* In general, direct heat exchange between hot and cold process streams is practical only within an individual process unit. For large complexes, involving multiple process units, direct heat exchange is usually not feasible, but there can still be opportunity for significant energy savings through indirect thermal integration, through the plant utility (steam and power) system.

The technique applied here is to treat the residual heating and cooling requirements of each process unit (after all possible heat recovery has been accomplished within that unit) as if they were process streams, and then develop a set of heat source and sink curves representing the overall site. These curves reveal the optimum number and pressure for steam headers, and the optimum type and size of cogeneration projects. Savings in hot utility (i.e. using process heat to replace utility steam from boilers) of between 10 and 40 percent have been consistently demonstrated in over 70 projects (Eastwood and Kelfkens 1998).

## Process Integration/Pinch Analysis Data Table

	Units	Notes	
<b>Process Integration (pinch analysis)</b>			
<b>other-4</b>			
<b>Process integration emerging applications</b>			
<i>Market Information:</i>			
Industries		Cross cutting	
End-use(s)		Process heating, process cooling	
Energy types		Fuels, electricity	
Market segment		New and retrofit	
2015 basecase use	Tbtu	1871	AEO 2000. Based on EIA 1997 energy shares for specific industries
<i>Reference technology</i>			
Description	Current energy consumption in existing processes applied to steam use and compression use in refining		
Throughput or annual op. hrs.			
Electricity use	TWh	0.9	EIA, 1997; Xenergy, 1998; compression electricity use at refineries
Fuel use	Tbtu	932.2	EIA, 1997. Indirect fuel use for boilers from SIC: 20, 22, and 20% of SIC 28
Primary energy use	MBtu	939.5	EIA, 1997
<i>New Measure Information:</i>			
Description	Process integration-emerging technologies		
Electricity use	TWh	0.6	25% compressor savings in refining
Fuel use	Tbtu	839.0	10% savings in various emerging applications
Primary Energy use	Tbtu	844.4	
Current status		Comercial	Total site pinch, hydrogen pinch, batch processes
Date of commercialization			
Est. avg. measure life	Years	15	
<i>Savings Information:</i>			
Electricity savings	TWh/%	0.2	25%
Fuel savings	TBtu/%	93.2	10%
Primary energy savings	TBtu/%	95.0	10%
Penetration rate			
Feasible applications	%	40%	
<i>Other key assumptions</i>			
Elec svgs potential in 2015	TWh	0.1	
Fuel svgs potential in 2015	Tbtu	37.3	
Primary energy svgs potential in 2015	Tbtu	38.0	
<i>Cost Effectiveness</i>			
Investment cost	\$/Mbtu-s	5.0	
Type of cost		Incremental	
Change in other costs	\$	0	
Cost of saved energy (elec)	\$/kWh	0.86	
Cost of saved energy (fuel)	\$/Mbtu	0.86	
Cost of saved energy (primary)	\$/Mbtu	0.86	Discount rate for all CCE calculations is 15%
Simple payback period	Years	2.3	
Internal rate of return	%	43%	
<i>Key non energy factors</i>			
Productivity benefits		Somewhat	Can reduce bottlenecks in production lines
Product quality benefits		None	
Environmental benefits		Somewhat	
Other benefits			
Current promotional activity	H,M,L		
<i>Evaluation</i>			
Major market barriers		Information	
Likelihood of success	H,M,L	Medium	
Recommended next steps		Demonstration	
Data quality assessment	E,G,F,P	Fair	
<i>Sources:</i>			
2015 basecase			EIA 1999
Basecase energy use			EIA 1997
New measure energy savings			Kumana, J. 2000b; Linnhoff, B.; Tainsh, B.; Wasilewski, 1999
Lifetime			Author estimate from general pinch literature
Feasible applications			Author estimate
Costs			Kumana, J. 2000b; author estimate
Key non energy factors			Kumana, 2000b
Principal contacts			Kumana & Assoc.-- jkumana@aol.com/Linhoff March (www.linhoffmarch.com)
Additional notes and sources			

*Batch processes.* While the methodology for application of pinch analysis to batch processes is not new (Kemp and Deakin 1989, Obeng and Ashton 1988), the market has not caught on, and is nowhere close to reaching its full potential. Two R&D projects carried out under the auspices of the Best Practice program in the UK on batch process integration identified an energy savings of 8 percent and 40 percent respectively. In the first case, in a resin factory, a key savings was the use of condenser heat to pre-heat the reactor fuel and material feeds. These case studies demonstrate that energy savings are not necessarily limited to energy intensive industries, but could have significant applicability to food, pharmaceutical, fine chemicals and other industries where batch processes dominate (ETSU 1999). The major benefit here is not necessarily energy, but productivity of capital and labor. The resource being conserved is processing time, through better scheduling and proper matching of equipment functionality, which means one can get more output from the same plant, or save capital when building a new plant for a given production rate.

*Water Pinch.* While this application is not specifically geared toward energy savings we include it here because water conservation and wastewater minimization has a significant, albeit indirect, impact on energy, and in fact changes the optimum heat recovery strategy (Mann and Liu 1999). Only two companies – Aspen Technology, Inc. and Linnhoff March, Ltd. - currently offer commercial-grade software for modeling/reconciling the water balance, and development of reuse/recycle options for wastewater minimization based on pinch principles. Reported savings have ranged between 15 and 60 percent depending on the industry sector (Aspen Technology 2000, Dhole et al. 1996, Linnhoff March Online 2000a, Tripathi 1996, Kumana 1996). Part of the reason that savings are so high is that water conservation has not received the attention it deserves, and so there is a lot of potential savings “left on the table.”

*Hydrogen Pinch.* In certain process industries, (e.g. petroleum refining), high purity hydrogen gas is a critical (and very expensive) process raw material. During the process operation, the quality of hydrogen is degraded in terms of concentration and pressure. The impure hydrogen is unsuitable for reuse, and is typically burned as fuel. The goal of pinch analysis as applied to hydrogen management is to determine the optimum regeneration, reuse, and recycle strategy to minimize the total costs associated with capital investment in new hydrogen generation and upgrading facilities, and energy consumption (Linnhoff et al. 1999, Eastwood 2000). Reducing hydrogen demand/supply bottlenecks are particularly valued given the potential shortages that many refineries are facing. Using a pinch analysis approach for hydrogen systems has already demonstrated hydrogen feed savings of 25 percent and compression power savings of 35 percent (Linnhoff et al. 1999, Kumana 2000a). Some of the key measures include: the re-use of hydrogen rejected from one process directly in another process, the mixing hydrogen streams of different compositions to provide a stream suitable for re-use, compression and/or purification of reject hydrogen (e.g. using pressure swing adsorption), and process changes to improve hydrogen utilization (Linnhoff et al. 1999). Some of the early U.S. companies to explore the use of hydrogen pinch include Arco (recently purchased by BP Amoco) and Citgo/Lyondell (Kumana 2000a).

*Pollution Prevention.* Pinch Analysis also has applications in pollution prevention. When less energy is consumed, the emission of combustion byproducts (CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>) is reduced. When freshwater is conserved, the flow of wastewater effluent is reduced. In addition, methodologies are under development that optimize the selection and sizing of specific pollution control technologies (Kumana and Rossiter 1994, Rossiter 1995, El-Halwagi 1997). However, the commercial experience and success rate so far has been limited.

The strength of these new techniques is that they can be combined with existing thermal pinch analysis approaches to give particular process industries a broader array of analytical techniques to identify energy and capital savings. Whether in new plant designs or expansions, it is possible to reduce capital costs by 5-10 percent and to shorten the construction schedule when applying emerging techniques (Kumana 2000b). By comparison, the cost of undertaking a pinch study is relatively small (\$25-250K) with ongoing software support costs of \$15,000-25,000/year (Kumana 2000b).

Based on the existing experience in the market, it is clear that the application of emerging pinch analysis techniques has the potential to cost-effectively save energy. We estimate 25 percent savings in compression energy use for refineries and 10 percent savings for the application of total site analysis, and batch analysis techniques to the food, textile, and specialty chemicals industries.



As noted above, careful planning utilizing pinch analysis techniques can reduce new plant construction costs as well. Based on payback times of 1-4 years for most thermal pinch projects, we estimate an average investment cost of \$5 per MMBtu (\$5.3/GJ) of energy saved.

While traditional pinch analysis has been employed in certain industries, it is still underutilized. Kumana argues that this is primarily due to technical misconceptions by plant managers, who often believe that their processes are already optimized and that additional heat recovery projects will not be economical under today's fuel price regime (Kumana 2000b). The enabling technologies that accompany pinch projects are already available in the market. Further demonstration projects are necessary to better prove the feasibility of these techniques in the marketplace.

## Process Control and Sensors (Other-5)

Energy currently has a low priority in industrial management practices. Energy management comprises a large variety of measures such as recognizing the importance of energy management, planning, monitoring, and implementing optimal control strategies. Generally, no or low initial costs are involved with these measures. We focus on process monitoring and energy management technologies. It is stressed that training and motivation are important, if not essential, measures in energy management, and should be an integral part of industrial energy management, as well as introduction of new technologies. A variety of process control systems are available for virtually any industrial process. A wide body of literature is available assessing control systems in most industrial sectors such as aluminum, chemicals, pulp and paper, iron and steel. The table provides an overview of classes of process control systems.

### Classification Of Control Systems and Typical Energy Efficiency Improvement Potentials.

System	Characteristics	Typical energy savings (percent)
Monitoring and Targeting	Dedicated systems for various industries, well established in various countries and sectors	Typical savings 4-17%, average 8% , based on experiences in the UK
Computer Integrated Manufacturing (CIM)	Improvement of overall economics of process, e.g. stocks, productivity and energy	> 2%
Process control	Moisture, oxygen and temperature control, air flow control “Knowledge based, fuzzy logic”	Typically 2-18% savings

Note: The estimated savings are valid for the specific application (e.g. lighting energy use). The energy savings can not be added, due to overlap of the systems.

Sources: (Caffal 1995, WEC 1995).

Modern control systems are often not solely designed for energy efficiency, but rather at improving productivity, product quality and efficiency of a production line. Applications of advanced control and energy management systems are in varying development stages can be found in all industrial sectors. Control systems result in reduced downtime, reduced maintenance costs, reduced processing time, and increased resource and energy efficiency, as well as improved emissions control. For example, in cement kilns NO<sub>x</sub> emission reductions of 20 percent have been achieved through installing process controls (CADET 1997i). Many modern energy-efficient technologies depend heavily on precise control of process variables, e.g. strip casting in the steel industry and process integration in the chemical industries. Hence, in estimating the potential energy savings double-counting should be avoided. For this characterization we exclude building energy management systems, lighting controls, as well as adjustable speed drives (discussed elsewhere in this study). Application of process control systems is growing rapidly, and modern process control systems exist for virtually any industrial process. However, still large potentials exist to implement control systems, and more modern systems enter the market continuously. For example, the journal *Hydrocarbon Processing* produces a semi-annual overview of new advanced process control technologies for the chemical and oil refining industry.

Process control systems depend on information of many stages of the processes. A separate but important area is the development of sensors that are inexpensive to install, reliable, and analyze in real-time. Development aims at the use of optical, ultrasonic, acoustic, and microwave systems, that should be resistant to aggressive environments (e.g. oxidizing environments in furnace or chemicals in chemical processes) and withstand high temperatures. The information of the sensors is used in control systems to adapt the process conditions, based on mathematical (“rule”-based) or neural networks and “fuzzy logic” models of the industrial process.

## Process Controls and Sensors Data Table

	Units		Notes
Process Controls and Sensors			
other-5			
Modern process control systems using advanced sensors and knowledge-based or fuzzy logic control systems			
Market Information:			
Industries	Cross-Cutting		
End-use(s)	Processes, utilities, other	Excluding motor systems, lighting, HVAC	
Energy types	Fuels, electricity		
Market segment	Retrofit		
2015 basecase use	N/A		
Reference technology			
Description	Energy consumption for applicable process (excl. motors, building energy use)		
Throughput or annual op. hrs.			
Electricity use	TWh	337	337.1 TWh, based on MECS 1994 (or 31% of industrial power use)
Fuel use	TBtu	12291	12.291 Tbtu, based on MECS 1994 (or 89% industrial fuel use, excl. feedstocks)
Primary energy use	TBtu	15156.4	
New Measure Information:			
Description	Modern process control systems using advanced sensors and knowledge-based or fuzzy logic control systems		
Electricity use	TWh	327	
Fuel use	TBtu	11922	
Primary Energy use	TBtu	14701	
Current status	Commercialized, research		Depends on specific application
Date of commercialization	1995		
Est. avg. measure life	Years	10	
Savings Information:			
Electricity savings	TWh/%	10	3%
Fuel savings	TBtu/%	369.0	3%
Primary energy savings	TBtu/%	454.9	3%
Penetration rate		Low	
Feasible applications	%	30%	
Other key assumptions			
Elec svgs potential in 2015	TWh	3	
Fuel svgs potential in 2015	TBtu	110.7	
Primary energy svgs potential in 2015	TBtu	136.5	
Cost Effectiveness			
Investment cost	\$/Mbtu-s	6	Retrofit, costs are estimate of average costs, based on payback of 2 years
Type of cost		Full cost	
Change in other costs	\$	-1	Rough estimate value of average productivity benefits
Cost of saved energy (elec)	\$/kWh	0.001	
Cost of saved energy (fuel)	\$/Mbtu	0.20	
Cost of saved energy (primary)	\$/Mbtu	0.20	Discount rate for all CCE calculations is 15%
Simple payback period	Years	2.0	
Internal rate of return	%	50%	
Key non energy factors			
Productivity benefits		Significant	Reduced downtime and maintenance costs, improved yield
Product quality benefits		Significant	Less off-spec production
Environmental benefits		Somewhat	Reduced emissions, improved yield
Other benefits			
Current promotional activity	H,M,L	High	Process control is recognized as important measure
Evaluation			
Major market barriers		Technical	
Likelihood of success	H,M,L	Hqih	
Recommended next steps			
Data quality assessment	E,G,F,P	Fair	Own estimates based on literature survey
Sources:			
2015 basecase			EIA, 1999
Basecase energy use			EIA, 1997; Xenergy, 1998
New measure energy savings			Conservative average of many case-studies
Lifetime			
Feasible applications			
Costs			Average of many case-studies
Key non energy factors			
Principal contacts			Gensym Corp. (MA) (617) 547-2500
Additional notes and sources			

Neural network-based control systems have successfully been used in the cement (kilns), food (baking), non-ferrous metals (alumina, zinc), pulp and paper (paper stock, lime kiln), petroleum refineries (process, site), and steel industries (EAFs, rolling mills). New energy management systems that use artificial intelligence, fuzzy logic (neural network), or rule-based systems mimic the “best” controller, using monitoring data and learning from previous experiences. For example, improved process control using neural networks in electric arc furnaces in the steel industry can help to reduce electricity consumption beyond that achieved through classical control systems. Neural networks or “fuzzy logic” systems analyze data and emulate the best controller. For EAFs, the first “fuzzy logic” control systems have been developed using current, power factor and power use to control the electrodes in the bath (Staib and Bliss 1995). The average power savings are estimated to be up to 8 percent (or 38 kWh/t), with an average increase in productivity of 9-12 percent and reduced electrode consumption of 25 percent (Staib and Bliss 1995). The actual savings depend on the scrap used and the furnace operation. Furnace maintenance costs are reduced as well. In 1994, advanced control systems were installed at 16 furnaces in the U.S. (Kimmerling 1997), with a total capacity of 6.4 million tons (5.8 Mt) (equivalent to 9 percent of the U.S. EAF capacity in 1994). The capital and commissioning costs are estimated to be \$250,000 per furnace, with annual costs savings at roughly \$0.90/ton (\$1/t) (Kimmerling 1997). The capital costs are expected to be \$0.86/ton (\$0.95/t) (Worrell et al. 1999). The measure is assumed to be applicable to 90 percent of the U.S. EAF capacity. Similar applications are found in the cement industry, where energy savings of up to 8 percent have been found, with a payback period between 1 and 2 years (CADET 2000d).

Process knowledge based systems (KBS) have been used in design and diagnostics, but are hardly used in industrial processes. KBS incorporates scientific and process information applying a reasoning process and rules in the management strategy. A recent demonstration project in a sugar beet mill in the UK using model based predictive control system demonstrated a 1.2 percent reduction in energy costs, while increasing product yield by almost 1 percent and reducing off-spec product from 11 percent to 4 percent. This system had a simple payback period of 1.4 years (CADET 2000e).

Although, energy management systems are already widely disseminated in various industrial sectors, the performance of the systems can still be improved, reducing costs and increasing energy savings further. For example, total site energy monitoring and management systems (Kawano 1996) can increase the exchange of energy streams between plants on one site. Traditionally, only one plant or a limited number of energy streams were monitored and managed.

Research for advanced sensors and controls is ongoing in all sectors, both funded with public funds as private research. Several projects within DOE’s Industries of the Future try to develop more advanced control technologies, and sensors and controls are also represented in a Crosscutting OIT-program. Outside the U.S., Japan and Europe also give much attention to advanced controls. The main opportunities can be found in further development of advanced controls and sensors, as well as the marketing of existing advanced controls.

In our analysis we will assume ongoing development of energy management systems, resulting in improved performance through better control strategies and improved and real-time information as well as lower costs. We assume that on average energy efficiency savings of 3 percent are feasible. We exclude electricity use for motors and energy use for industrial buildings, as this is covered under other technologies (ASD, building management systems). By 2015 we assume that modern process control systems can be applied to an additional 30 percent of applicable industrial energy use. Estimating the specific costs of installing energy management systems is difficult. The pay back period of such systems is often not only influenced by energy savings, but more often by “non-energy” benefits which have a large impact (e.g. improved process throughput or product quality). Investment costs vary typically between 0.5 and 30\$/MBtu-(0.47 and \$28.40 per GJ) saved (ETSU 1994), with pay back periods mostly from 1 to 4 years (Caffal 1995) in industrial applications. We assume an average payback period of 2 years. The lifetime of EMS is dependent on the equipment for which it is used and progress in development of new controls. We estimate it to be 10 years on average for this study.

Future steps include further development of new sensors and control system, demonstration in commercial scale, as well as dissemination of the benefits of control systems in a wide variety of industrial applications.

### **Variable Mining Machine (Mining-1)**

The coal mining industry mined over 1.1 billion tons of coal in 1998, of which 63 percent in surface mines and 37 percent in underground mines. Because the variable mining machine can be used underground, we focus on underground coal mining. Underground coal mines use different technologies including conventional, continuous, shortwall and longwall mining. Conventional and continuous mining are slowly decreasing, due to their relatively lower productivity. Longwall mining is the most productive underground mining method.

In 1998, almost 200 million tons of coal were mined in longwall mines. Longwall mining has increased from 27 percent of 1983 production (EIA 1995) to 63 percent in 1998 of total underground production. Longwall mines can be found in Alabama, Colorado, Illinois, Kentucky, Maryland, Ohio, Pennsylvania, Utah, Virginia, West Virginia and Wyoming. These mines are operated by 24 companies, of which CONSOL Energy operates the largest number, followed by RAG American Coal Co., and Jim Walter Resources (Fiscor 2000). Fifty-nine longwall mining machines are operated in the U.S. mines, and it is expected that this will not change much in the near future. In the 1980s about 100 longwall installations were used in the U.S. (EIA 1995). The number has declined, but the average capacity has increased. Longwall mining has originally been developed in Europe to increase productivity of underground coal mines. Compared to conventional methods no pillars are needed, enabling to recover 25 percent more coal. In modern mechanized longwall operations, the coal is cut and loaded onto a face conveyor by continuous longwall miners called shearers or plows. The roof is supported by mechanized, self-advancing supports called longwall shields, which form a protective steel canopy under which the face conveyor, miners, and shearer operate. In combination with shields and conveyors, longwall shearers or plows create a continuous mining system with a huge production capacity. Two main longwall systems are widely practiced. The system described above, known as the retreating method, is the most commonly used in the United States (Britannica 2000). Longwall mining machines are marketed by various firms, e.g. DBT America (PA) and Longwall Associates (VA).

Coal mining consumed about 13.5 TWh electricity and 88 TBtu in fuels to mine and wash the coal (AEO 1999). By 2015 EIA expects the coal industry to consume 15.6 TWh and 103 TBtu (AEO 1999). There is no information on the energy use by surface and underground coal mining separately. Underground mining is more energy-intensive. The average horsepower on the shearer was 1180 hp (Fiscor 2000). Energy use in coal mines on the depth, size and type of coal. Hence, it is difficult to estimate specific energy consumption for coal mining. We roughly estimate the energy use for the cutting of a longwall miner at 0.75 kWh/ton of coal (Kelley 2000). More energy is used for transport and ventilation.

The variable wall mining machine is a variation on the longwall miner. It uses cutting heads that move vertically and sweep across the coal face. The important improvement is that the variable mining machine provides a separation between the coal face and the miners, providing a dual duct ventilation system. This would reduce the exposure of the miners to dust and methane, improve working conditions and safety considerably. The variable wall mining machine is developed by Kelastic Mine Beam Co., Greensburg, PA. The machine has been tested by the former U.S. Bureau of Mines and in a mine in Western Kentucky. The development has been supported by DOE's Inventions and Innovation Program in 1999.

We have only been able to find data on energy savings in the cutting of the coal. The developers estimate the energy savings at roughly 20 percent, depending on mine conditions, of the energy use of longwall mining machine (Kelley 2000). Additional savings may be possible in ventilation, but were not quantified. We estimate the energy savings at 0.15 kWh/ton of coal-mined.

Longwall miners are capital intensive machines, with a long lifetime. The longwall mining machine installed in 1994 in the Robinson Run Mine (West Virginia), owned by CONSOL Coal Group, consisted a 42 inch coal shearer and 172 hydraulic roof supports. The total capital costs were \$15 million (EIA 1995), with an estimated production of 4.8 Million tons/year (1997) (Consol Energy 2000).

# Variable Mining Machine Data Table

	Units	Notes
<b>Variable Wall Mining Machine</b>		
<b>Mining-1</b>		
<b>Variable Wall Mining Machine with Dual Duct Ventilation</b>		
<b>Market Information:</b>		
Industries	Coal Mining	
End-use(s)	Other	
Energy types	Electricity	
Market segment	New	
2015 basecase use	60	59 Longwall mining machines, total production 200 Million tons of coal
<b>Reference technology</b>		
Description	Modern Longwall Mining Machine (cutting only)	
Throughput or annual op. hrs.	tpy	3,400,000 Average size of longwall miners in US
Electricity use	kWh	2,540,000.0
Fuel use	MBtu	0
Primary energy use	MBtu	21590.0
<b>New Measure Information:</b>		
Description	Variable Wall Mining Machine with Dual Duct Ventilation	
Electricity use	kWh	2,030,000
Fuel use	MBtu	0.0
Primary Energy use	MBtu	17255.0
Current status	Prototype demonstration	
Date of commercialization		Currently no active development ongoing
Est. avg. measure life	Years	25
<b>Savings Information:</b>		
Electricity savings	kWh/%	510000 20%
Fuel savings	MBtu/%	0.0 N/A.
Primary energy savings	MBtu/%	4335.0 20%
Penetration rate		Low
Feasible applications	%	20%
Other key assumptions		
Elec svgs potential in 2015	GWh	6
Fuel svgs potential in 2015	Tbtu	0
Primary energy svgs potential in 2015	Tbtu	0.1
<b>Cost Effectiveness</b>		
Investment cost	\$	200000 Estimated costs of a new mining machine are \$10.6 Million
Type of cost		Incremental
Change in other costs	\$	-10000 Improved working conditions and safety, improved productivity
Cost of saved energy (elec)	\$/kWh	0.04
Cost of saved energy (fuel)	\$/Mbtu	N/A.
Cost of saved energy (primary)	\$/Mbtu	4.83 Discount rate for all CCE calculations is 15%
Simple payback period	Years	10.6
Internal rate of return	%	7%
<b>Key non energy factors</b>		
Productivity benefits		Somewhat Automated system may reduce costs compared to older longwall machine
Product quality benefits		None
Environmental benefits		None
Other benefits		Significant Improved working conditions and safety
Current promotional activity	H,M,L	Low
<b>Evaluation</b>		
Major market barriers		Structure Mining Industry
Likelihood of success	H,M,L	Low
Recommended next steps		Commercial Demonstration
Data quality assessment	E,G,F,P	Fair
<b>Sources:</b>		
2015 basecase		EIA 1999
Basecase energy use		EIA 1995a; EIA 1999; Kelley, 2000
New measure energy savings		Kelley 2000
Lifetime		Authors estimate
Feasible applications		Authors estimate
Costs		Authors estimate
Key non energy factors		Kelley 2000
Principal contacts		J.H. Kelley, Kelastic Mine Beam Co. (724) 832 8832
Additional notes and sources		Mike Plaha, RAG American Coal (410) 689-7500

The costs of a variable wall mining machine are likely to be similar or slightly higher to those of traditional longwall mining machines. The slightly higher costs may be due to the costs of the dual ventilation system. However, this may lead to operational cost savings. No specific cost data was available at the time of the study. We estimate the additional investments at \$200,000 per machine, compared to the costs of a modern longwall mining machine of \$10.6 million (EIA 1995). We assume reduction in annual costs due to improved automation and working environment safety.

Currently, no further development work is going on, and implementation of the technology has not happened, due to the limited number of new longwall/variable mining machines installed in the U.S., as well as further concentration of equipment manufacturers and users. Demonstration of the technology on a close to commercial scale in collaboration with the coal mining industry would be necessary to demonstrate the potential benefits of this technology.

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