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Emerging Energy-Efficient Technologies in Industry: Case Studies of Selected Technologies

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Environmental Energy Technologies Division

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Prepared for the
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Abstract

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. 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.

This report focuses on the long-term potential for energy-efficiency improvement in industry. In 2002, the industrial sector consumed 33% of the primary energy and was responsible for 30% of the energy-related greenhouse gas (GHG) emissions in the U.S. Due to the extremely diverse character of the industrial sector, it is not possible to provide an all-encompassing discussion of technology trends and potentials. Instead we focus on a number of key technology areas that illustrate the significant potential energy savings available to industry, given a sustained state, federal and private R&D effort. These include: near net shape casting, membranes, gasification, motor systems, and advanced cogeneration. The discussion of each of these technologies provides a detailed assessment of the potential for future contributions to energy efficiency improvement, economics and performance, as well as the potential development path, including promising areas for research, demonstration or other support. Some of these technologies have particular applications for a specific industry (e.g. near net shape casting in the metal producing sectors and black liquor gasification in the pulp and paper industry), while others can be found in many industries (e.g. advanced motor systems, membranes and advanced cogeneration applications).

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 foreseeable future. The five technology areas *alone* can potentially result in total primary energy savings of just over 2,600 TBtu by 2025, or nearly 6.5% of total industrial energy use by 2025. The savings are additional to energy savings found in the AEO 2004 reference case forecasts. The technical potential of these technologies in the long term is roughly three times larger, while additional technologies beyond the five covered in this report are currently available or under development.

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1. Introduction

Characterizing industry in the U.S. is difficult since it covers an extremely diverse range of activities. In 2002, the industrial sector consumed 33% of the primary energy and was responsible for 30% of the energy-related greenhouse gas (GHG) emissions in the U.S. (U.S. EIA, 2004a). Over half of this energy was used in energy-intensive industries producing commodities such as steel, cement, paper, and aluminum; the remainder was consumed by light manufacturing industries. Economic development patterns are leading to a shift away from these energy-intensive industries toward lighter, higher value-added industries, which will be responsible for more than half of all manufacturing energy use by 2050 (Interlaboratory Working Group, 2000).

Historically, industrial energy consumption in the U.S. showed an overall decline between 1973 and 1986 when energy prices were relatively high, but has grown annually since then. The U.S. Energy Information Administration's *Annual Energy Outlook* (AEO) for 2004 projects that energy consumption and GHG emissions for U.S. industry will continue to grow and, extrapolating current reference case growth rates, will double by 2050 (U.S. EIA, 2004b). Figure 1.1 and Figure 1.2 show the projected reference case industrial primary energy use by fuel and by sector, respectively, to 2025.

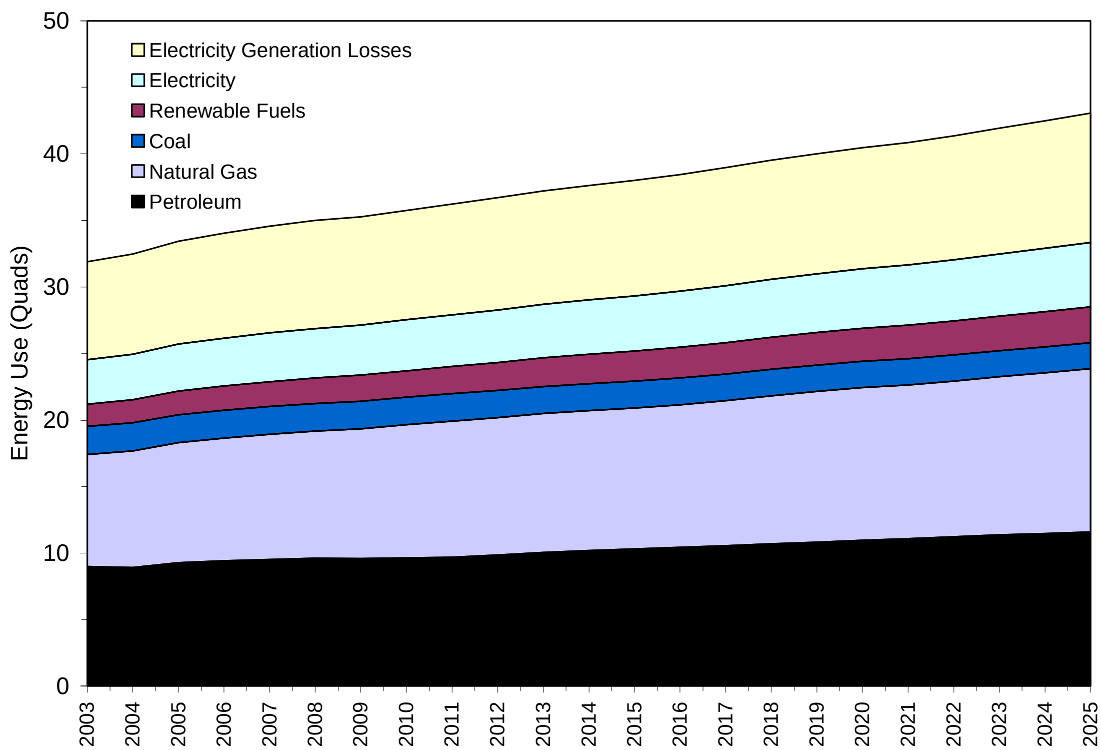

Figure 1.1. AEO2004 Industrial Primary Energy Use by Fuel. Source: U.S. EIA, 2004b.

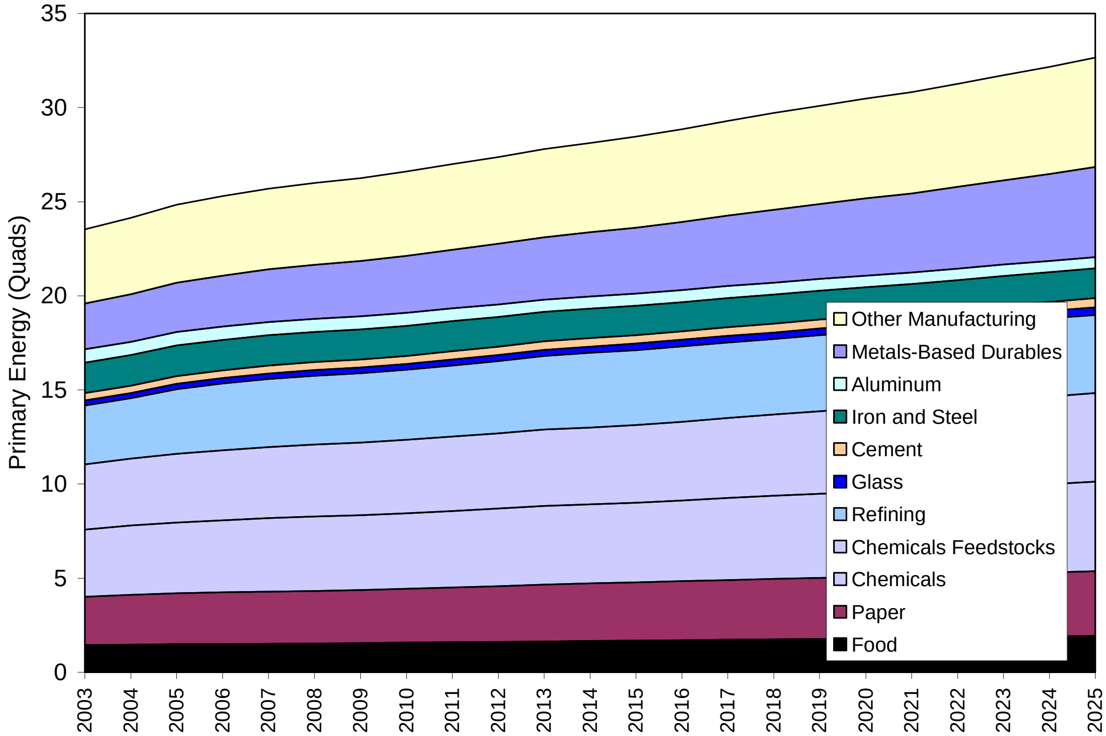

Figure 1.2. AEO2004 Industrial Primary Energy Use by Sector. Source: U.S. EIA, 2004b.

Currently many opportunities exist to improve industrial energy efficiency and there is large potential for future efficiency developments. Improving industrial energy efficiency and reducing energy-related GHG emissions can be accomplished through technological improvements as well as changes in the structure of the overall industrial sector (in response to economic and environmental drivers). In addition, further reductions in emissions due to energy use in industry can be realized through reduction of process-related emissions, fuel switching to lower carbon fuels, and integrated pollution prevention and material efficiency improvement. All of these opportunities are available in the near-term and many will continue to be available in the medium- and long-term.

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. Inappropriate characterization of technologies can lead to poor analysis and eventually less than optimal policy choices (Worrell et al., 2004).

This report focuses on the long-term potential for energy-efficiency improvement in industry. Due to the extremely diverse character of industry, it is not possible to provide an all-encompassing discussion of technology trends and potentials. Instead, we focus on a number of key technology areas. Martin et al. (2000) provided an in-depth discussion of a larger number of technologies. This report provides a detailed discussion of five major technology areas: near net shape casting, membranes, gasification, motor systems, and advanced cogeneration. Each section provides a detailed assessment on future contributions to energy efficiency improvement, economics and performance, as well as the potential development path, including potential areas for R&D needs Some of these technologies have particular applications for a specific industry (e.g. near net shape casting in the metal producing sectors and black liquor gasification in the pulp and paper industry), while others can be found in many industries (e.g. advanced motor systems, membranes and advanced cogeneration applications).

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2. Near Net Shape Casting/Strip Casting

2.1 Technology

2.1.1 Technology Description

Near net shape casting and strip casting are the most recent developments in metal shaping. Currently, metals are cast in ingots or slabs. The ingots and slabs need to be reheated after casting to roll them in the final shape. Near net shape/strip casting integrates the casting and hot rolling of steel into one process step, thereby reducing the need to reheat the steel before rolling it. Strip casting directly casts a strip of 1–10 mm. This technology leads to considerable capital cost savings and energy savings. It may also lead to indirect energy savings due to reduced material losses.

2.1.2 Specific End-Uses and Applications

Near net shape/strip casting can be used to cast and shape any metal. Since steel is the dominant metal produced in the U.S., this description will focus on steel. The iron and steel industry is one of the largest industrial energy consumers both in the U.S. and globally. 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). After reaching a peak production in the 1990's crude steel production in the U.S. declined to 10 million tons (92.2 million tonnes) in 2002, of which 49% was produced by integrated steel mils and 51% by electric arc furnaces in mini-mills.

Iron and steelmaking is still foremost a batch process. Today, in most steel mills the casting and rolling process is a multi-step process. The liquid steel is first cast continuously into blooms, billets, or slabs in the continuous casting process. About 97% of steel is cast continuously in the U.S., and only 3% is cast as ingots. In continuous casting, 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. Most steel slabs are reheated in reheating furnaces, and rolled into final shape in hot and cold rolling mills or finishing mills.

2.1.3 Current Status

Near net shape casting 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. 1998, Opalka 1999, Worrell et al., 1997). The steel is essentially cast and formed into its final shape without the reheating step.[1] Figure 1 provides a schematic presentation of a strip caster.

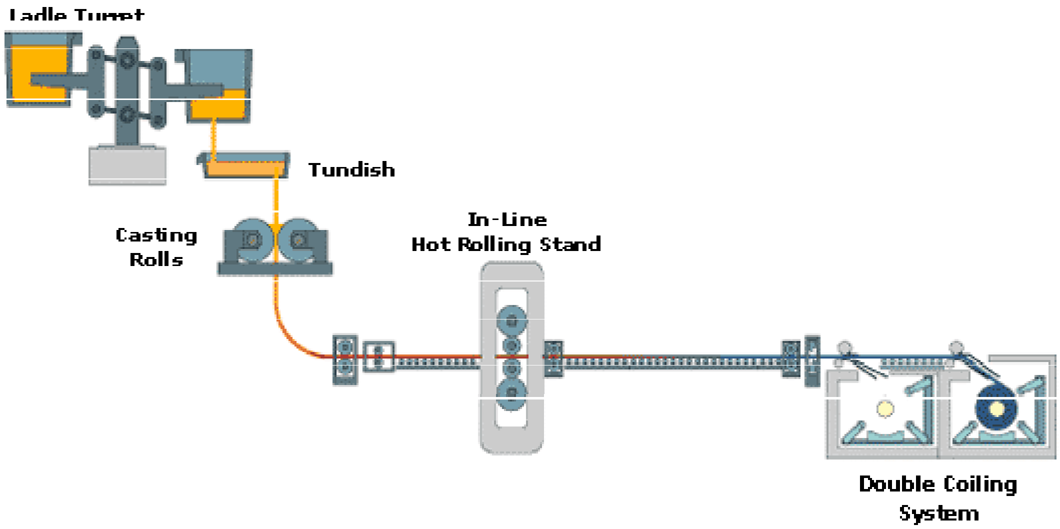

Figure 2.1. Schematic Representation of a Strip Caster. Source Eurostrip

The idea of strip casting was patented by Bessemer in 1856, but technical realization took almost 140 years. Earlier attempts at developing the technology were not successful. Starting in 1975, around 11 clusters of steel producers, technology suppliers, and research groups developing near net shape/strip casting emerged in Europe, Japan, Australia, United States and Canada (Luiten and Blok, 2003).

Since then, three commercial technologies have emerged. All three technologies are based on the same principle as proposed by Bessemer. The steel is cast between two water-cooled casting rolls. This results in very rapid cooling and high production speeds. The major advantage of strip casting is the large reduction in capital costs, due to the high productivity and integration of several production steps. The technology was first applied to stainless steel, and two plants have demonstrated strip casting of carbon steel. The first commercial technologies are:

- **Castrip.** Based on the technology developed by BHP (Australia) and IHI (Japan), the Castrip consortium was formed to commercialize the product. The third partner is Nucor (USA). Nucor is the largest steel producer in the U.S. and was the company to first introduce thin slab casting to the U.S. The first commercial strip caster was constructed at Nucor's Crawfordsville Indiana plant. The plant was commissioned in 2002 and production started in 2003. The plant has a capacity of 500,000 tonnes/year.
- **Eurostrip.** Eurostrip is a consortium of companies from Austria, France and Germany, which merged a number of projects and long-term experience in casting. A first pilot plant was operated in Terni (Italy). The pilot plant is now used to strip cast

[1] 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). Thin slab casting technology is already commercially applied in the U.S. and other countries.

carbon steel. The first commercial plant opened in 1999 in Krefeld (Germany). The technology is offered at a scale of 500,000 tonnes/year.

- **Nippon/Mitsubishi.** These two Japanese companies commercialized strip casting at Hikari Works of Nippon Steel Corporation (Japan). This is still a relatively small machine (35,000 tonnes per year).

The main challenges for the further development of this technology relate to the quality and usability of the product by steel processors and users, especially in the high-end markets of cold-rolled steels for automobile applications (AISI, 1998; Kuster, 1996). While there is no reason to assume that the quality is lower (Flick and Hohenbichler, 2002), different characteristics may affect processing options. It was feared that maintenance of the rollers would limit the productivity and cost savings, but the first plants in the U.S. and Europe demonstrated that this can be controlled. Furthermore, increased reliability, control and scaling (now limited to a relatively small scale of 500,000 tonnes/year) will benefit the wider application of the technology. Thin slab casters were initially developed at similar scales, but have been scaled up to over 1 million tonnes annual capacity and are used by integrated mills in Germany and The Netherlands.

In the U.S., near net shape casting has so far been applied to the production of 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). TXI/Chaparral Steel has developed a near net shape casting process for construction steel products like rebar and bar. The process is in use at TXI’s plants in Texas and Virginia.

Near net shape/strip casting technologies have been or are being developed for other metals. The most important are aluminum and copper. Steel, aluminum and copper together represent close to 95% of all metals produced in the United States. Together, these industries consume about 11% of all energy used in U.S. industry (1998).

Adoption of near net shape casting will be driven by retirement of existing casters and rolling mills and will be the technology of choice for new greenfield mini-mills.

2.1.4. Research & Development Needs

Further demonstration of the near net shape/strip casting technology at larger scales would make it more attractive to the integrated steel mills. There are three main areas for future R&D to increase the uptake of this technology in the metals industry:

- Improved control of the process and expansion of the capacity of the caster to improve the applicability to large integrated mills (the major producers of flat rolled steel).
- Improved understanding of the casting process to allow the application of the technology to cast different shapes, so to allow use of this technology for all metal products.

- Further development and design of the technology to non-ferrous metals, most importantly aluminum and copper, to directly produce thin film and various shaped castings.

2.2 Cost

2.2.1 Baseline and New Technology

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 (Flemming, 1995; Kuster, 1996; Eurostrip, 2004). Given that this technology is still new, we currently estimate a capital cost 20 percent below conventional continuous casting. However, through learning by doing and multiplication, this is likely to be reduced to 50% of the investments of a typical continuous casting and hot rolling mill.

A strip or near net shape caster is much more compact, reducing the space requirements to about 15-20% of a typical hot rolling mill. This contributes to the large reduction in capital costs (Eurostrip, 2004).

Operations and maintenance costs are also expected to drop by 20-25%, although these reductions will depend strongly on the lifetime of the refractory on the rollers used in the caster and local circumstances.

Baseline costs for construction of a continuous caster and rolling mill are estimated to be $200/ton annual capacity. The capital costs of the first-of-a-kind strip caster constructed at Nucor's Crawfordville's (Indiana) plant were about $180/ton. Given this, we estimate the specific capital costs of a strip caster/near net shape caster to be $160/ton (-20%) within the next 10 years. Eventually, this cost will be reduced to $110/ton (-45%).

2.2.2 Cost-Effectiveness

Given the lower investment costs of this technology compared to the current technology, the payback period is zero. The cost-effectiveness is driven by new casting and rolling mill construction. In the case of a new greenfield construction of a mini-mill, capacity expansion at an existing mill or replacement of an existing rolling mill, the introduction of a near net shape/strip caster is attractive. However, after the expansion of the steel industry in the 1990's new greenfield plant construction will likely be limited.

Most flat steel products are still produced in large integrated mills. These mills have larger capacities (for which the current capacity of a strip caster is too small) and are typically less innovative. Nucor and TXI are among the most innovative steel companies in the U.S. and have pioneered the commercial application of thin slab casting, and now near net shape/strip casting. Nucor and TXI use "mini-mills" of up to 2 million tons/year. Integrated mills in Europe and Japan, however, use thin slab casters. Further R&D can make this technology more attractive to large integrated mills.

2.3 Energy

2.3.1 Baseline and New Technology

In 1998 the iron and steel industry consumed 1426 TBtu in fuels and 158 TBtu electricity. Total primary energy consumption was equal to 1905 TBtu. Historically, the primary energy intensity of steelmaking has declined from 30.6 MBtu/ton in 1958 to 18.7 MBtu/ton (or 21.8 GJ/tonne) in 1998. This decline is due to a shift towards more secondary or recycled steel production, closing of inefficient plants, and improved energy efficiency, including reduction in material losses.

A study of the industry 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 2.6 MBtu/ton (3.0 GJ/t) of energy. Electricity consumption is estimated at 152 kWh/ton (0.67 MBtu/ton). We assume that this has not changed between 1994 and 1998.

Energy consumption of a near net shape/strip caster is significantly less than that for continuous casting. For the intermediate thin slab casting process, energy consumption is 0.8 MBtu/ton (0.9 GJ/tonne) fuel and 39 kWh/ton (43 kWh/tonne) electricity (Flemming 1995). Near net shape casting is expected to consume even less energy. A strip caster is estimated to consume 0.2 GJ/tonne of steel (Eurostrip, 2004). We estimate fuel use at 0.04 MBtu/ton (0.05 GJ/tonne) and electricity use at 39 kWh/ton (42 kWh/tonne).

2.3.2 Potential Energy Savings

The specific primary energy savings for this technology are estimated at 95% compared to the 1994 average energy intensity of casting and rolling. Compared to a state of the art casting and rolling facility, the specific energy savings are estimated at about 90%. Fuel savings are 98% compared to the 1994 average energy intensity and electricity savings are estimated at 74%.

The total energy savings will depend on the penetration rate of near net shape/strip casters into the market. Little new construction is expected in the U.S. steel industry, but the industry will need to re-organize to reduce over-capacity. This will likely happen most in the integrated segment of the industry. Near net shape/strip casters are expected to first penetrate the secondary steel or mini-mill market due to the limited capacity of the current equipment. Mini-mills currently produce 50% of all steel in the U.S.

A recent assessment of multiple emerging energy-efficient technologies assumed a 30% penetration rate by 2015 (Martin et al., 2000). The large benefits of this technology will make this technology an attractive alternative when the current caster and/or rolling mill needs to be replaced. Therefore, in this study we assume a slightly higher penetration rate by 2025. Assuming that by 2025, 40% of steel is cast using near net shape/strip casting technology, this would result in estimated primary energy savings of nearly 160 TBtu, or 10% of total projected primary energy use in the iron and steel industry.

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3. Membrane Technology

3.1. Technology

3.1.1 Technology Description

Membranes selectively separate one or more materials from a liquid or gas and can replace energy-intensive separation processes in a number of industrial sectors including the food processing, chemicals, paper, petroleum refining and metals industries. Membranes can be used to remove dissolved or suspended solids in the wastewater generated by large water-consuming industries. Membranes can also be used to purify product streams or separate gases. Energy savings, however, will depend on the specific application. Figure 3.1 gives a schematic presentation of a membrane unit.

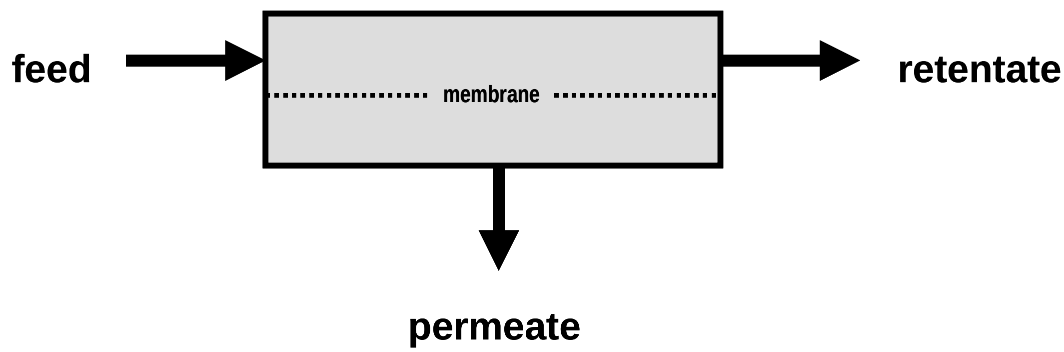

Figure 3.1. Schematic Representation of a Membrane Separation Unit

Membranes can be made from organic or inorganic materials, or can be a hybrid of both. Organic membranes can be used for processes with temperatures below 150°C. Inorganic membranes can be used in high temperature environments, ranging from 500-800ºC using metal membranes to over 1000ºC for many ceramic membranes. Hybrid membranes have organic molecules that allow water and dissolved substances to be filtered by the membrane, and inorganic molecules that provide stability.

Based on the separation principle and the state of feed and permeate streams, different membrane technology categories are distinguished. Typical membrane separation processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), electrodialysis (ED), gas separation, and pervaporation. Emerging membrane technologies include microporous membranes for gas separation; ion-exchange membranes for electrodialysis, diffusion dialysis, NF, membrane solvent extraction, and facilitated transport; pervaporation membranes for removing trace organics from water; proton exchange membrane fuel cells for converting chemical energy directly into electrical energy; encapsulating membranes for environmentally-sensitive materials; G-50 UF systems for oily waste streams; supported liquid membranes to selectively extract multiple elements or compounds from a mixed process stream; liquid membranes and emulsion liquid membranes for removal of trace impurities; and a variety of other membrane technologies (Srikanth, 2004).

3.1.2 Specific End-Uses and Applications

Membranes can be used in a wide variety of applications in the automobile, beverage, biopharmaceuticals, chemicals, dairy, electronic, fertilizer, food processing, metal finishing, mining, petroleum refining, pharmaceutical, and textile industries and for cleaning drinking water, cleaning wastewater, de-icing, de-watering, and desalinization. This reports on the food processing and chemicals industries as well as wastewater treatment applications across industries.

In the food processing industry, membranes are used to concentrate, fractionate and purify liquid products. Four types of membrane processes are important: MF, UF, NF, and RO. Gas separation is only used in the fruit and vegetable sector for packaging in a nitrogen atmosphere.

One of the most energy-intensive unit operations in the chemical industry is separation (U.S. DOE, OIT, 2000). Separation technologies include distillation, fractionation, and extraction. Gas membranes to separate organic mixtures and liquid membranes to separate both aqueous and organic mixtures offer an alternative to liquid-liquid extraction that uses much less energy. Membrane separation technology is increasingly being utilized in the chemicals industry for a wide range of applications such as removing water from organics. The membrane-based process of pervaporation is gaining importance and is now routinely used in the chemicals industry for splitting azeotropes.

Wastewater is produced in a variety of industries including the metal, metal plating, food, paper, chemicals, and electronics industries and may contain different contaminants ranging from bio-organic compounds to metal compounds. Such wastewater needs to be cleaned before it can be discharged or recovered for re-use in the plant. Treatment with chemicals (sanitizing, flocculation), biological treatment, ozonation, ultraviolet treatment, gravity settling, flotation and screening are conventional methods used to clean water. Membranes can also be used to remove dissolved or suspended solids, or microbes. The membrane types mostly used in wastewater treatment are UF, NF and RO, while MF is mainly used to stabilize (pre-filter) the water for RO-treatment.

3.1.3 Current Status

The U.S. membrane materials market was over $1 billion in 1997 (Wiesner and Chellam 1999) and forecast to grow to $2.1 billion by 2006 and to $3 billion by 2008 (Freedonia Group, 2004; Business Communications Company, Inc., 2003). In 1997, approximately 40% of the membrane sales were for water and wastewater treatment applications, another 40% was for food and beverage processing combined with pharmaceuticals and medical applications, with the remaining 20% in the area of chemical and industrial gas production (Wiesner and Chellam, 1999). The water and wastewater treatment market accounted for 55% of membrane demand in 2001 (Freedonia Group, 2004). Major suppliers are APV (Denmark) and APV Americas (U.S.), Koch Membrane Systems (U.S.), Osmonics (U.S.), PCI Membrane Systems (U.S.), U.S. Filter (U.S.). MF, UF, NF, and RO membranes account for more than 75% of 2003 sales in the U.S. (Business Communications Company, Inc., 2003).

In 2001, the vast majority of membrane materials were polymeric and these are projected to continue as market leaders because of their flexibility, permeability, and ability to be formed into a variety of membrane modules. By 2006, cellulose membranes are projected to account for over 50% of polymeric membranes. Rapid gains will also be made by non-polymeric materials, including ceramic, metal, and composite types, particularly in specialty uses, such as in extreme temperature or corrosive environments. By process, MF membranes accounted for approximately half of the market in 2001. These membranes are widely used for pretreatment before finer separation processes. Demand for RO membranes is projected to increase rapidly because of their ability to provide the highest level of purity which is a requirement in home water treatment, beverage processing, and wastewater treatment (Freedonia Group, 2004).

The dairy industry is the most important sector using membranes in the U.S. (Dziezak, 1990) and worldwide, and many thousands of m^2 membranes have been installed in this industry. Dairy is the sector with the longest history using membranes, which are used for the desalting of whey[2] and to separate lactose from salt and minerals (NF), the concentration of skim milk for ice cream and of soy proteins (UF), concentrating lactose or whey protein in the waste stream and reclaiming it as value-added concentrates or isolates for other processors (UF), the conversion of milk into cheese and soft cheese, and the preparation of egg white and egg yolk. RO is used to concentrate milk solids prior to evaporation in making concentrated milks and to remove water from whey concentrates, isolates, or lactose in cheese processing (Neff, 1999). Process water can also be recycled or used for boilers if cleaned with RO or can be prepared for discharge using NF (Neff, 1999). 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.

In the beverages industry, while MF is used sometimes for clarification of juices and water purification, UF is more frequently used because it removes a wider range of compounds and can selectively remove certain proteins or sugars. Membranes are used by Coca Cola (in Salina, KS) 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, although potential exists for further application and development. Water treatment is an important application of membranes in the beverages industry (Comb, 1995). Electrodialysis for stabilization of wines is a new application of membranes in the food processing industry (Amon and Mannapperuma, n.d.).

The market for liquid and gas membrane separators will encompass every portion of the chemical industry. The organic chemical industry is forecast to grow by 15 percent between the years 2000 and 2015. The market for membranes remains large because of

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[2] By the mid-1990s more than 10,000 m^2 of membranes for the desalting of whey had already been installed in the U.S. dairy industry (Maaskant et al. 1995).

the relatively few processes for which they are currently used for separation. Liquid membranes will first be used in the production of specialty chemicals in the pharmaceutical, agricultural, food, and biotechnology industries and for production of bulk commodity chemicals, processing industrial gases, industrial waste and wastewater (SRI, 1998). Membranes are also an attractive technology for hydrogen recovery in refineries. New membrane applications for the refinery and chemical industry are under development. Membranes for hydrogen recovery from ammonia plants were first demonstrated about 20 years ago (Baker et al., 2000), and are used in various state-of-the-art plant designs. Liquid membranes are highly specific with regards to the compounds that they can separate and therefore differing processes will require differing membranes.

Water is used throughout industry for many applications. Daily industrial water use is estimated at 20 billion gallons/day in 2000 (Hutson et al., 2004). 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. 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, 1994). Two membrane processes (e.g. MF and RO) can be combined to remove different contaminants.

3.1.4 Research and Development Needs

New membranes and membrane applications are under development, expanding the applications to many industries. Federal research programs (e.g. the National Institute for Standards and Technology's Advanced Technology Program) support development of membrane technology, as well as development of specific applications (e.g. DOE, EPA, USDA). Advances in membrane technologies will be driven by the increasing use of membranes in the water and wastewater treatment, and food and beverage processing industries.

One of the principal barriers facing liquid membranes is limited production. More research and development is needed to improve the performance of these technologies. Membranes with varying qualities are continuously being developed for the separation of specific gas mixtures. A large potential market for gas membrane separators is mobile and stationary fuel cells. One type of fuel cells that has promise for mobile applications is the proton exchange membrane (PEM) fuel cell. The U.S.DOE, along with the U.S.

Department of Transportation, has been conducting research and demonstration projects in this area. The U.S. DOE is currently sponsoring research to develop Ion Transport Membrane Technology (ITM) to produce hydrogen from natural gas and Oxygen Transport Membranes (OTM) for oxygen production. These technologies operate at high temperature, providing a higher level of thermal integration with the gasification process and will be increasingly important in the development of fuel cells as well as in the capture of carbon dioxide (Steigel, et al., 2003). An inorganic porous membrane for recovering hydrogen as a by-product of coal burning using Integrated Gasification Combined Cycle (IGCC) technology has recently been developed (U.S. DOE, OFE, 2001). One of the ways in which membranes could be improved is by increasing their lifetime and by decreasing their sensitivities to fouling. Sulfur-resistant membranes, for example, would be a great improvement for many processes in the petrochemical industries. For wastewater treatment, current research aims at new membrane materials and applications, more efficient and longer lasting membranes, and cost reduction.

Growing use of membranes is driven by increasingly strict environmental regulations enacted over the past several decades in addition to improvements in membrane technology, a more competitive market, a broader range of membrane processes, and new materials from which membranes can be fabricated (Freedonia Group, 2004; Wiesner and Chellam, 1999). Barriers to implementation include the lack of information, as well as the need for specific membranes in specific applications.

3.2 Costs: Baseline, New Technology, and Cost-Effectiveness

Economic assessment of membrane applications requires the evaluation of both the capital and operating costs associated with the application as well as the resulting benefits when compared to more traditional alternatives. The economic benefits in process applications include reduced operating costs relative to competitive technology, reduced product waste, recovery of by-products, and savings of water, energy, and chemicals. Economic benefits related to effluent reduction include savings in transport and disposal costs, as well as the ability to increase production in situations where effluent disposal limits are imposed.

Food Processing. In the food processing industry, traditional filtration, separation, and evaporation processes are typically used to separate, clarify, and purify foods and beverages. Membranes can be a cost-effective alternative, especially if they increase by-product recovery. For example, capital costs of $250,000 and annual operating costs of $82,000 for a membrane treatment system were seen at a Dole Raisin Plant, but annual savings of over $500,000 were realized due to recovery of sugar concentrate (Mannapperuma, et al., 1995). At Golden Town Apple Products in Canada, a combination of UF and RO was used for apple juice concentration. The payback period of the combined system is about 2.5 years (CADDET, 1996). Investment costs for a NF unit was installed for whey concentration at a dairy plant in The Netherlands, replacing a two-stage evaporation process were $9.3 ft^2 ($100/m^2). Energy savings, as well as reduced transport costs and emission charges, resulted in a payback period of 1.3 years (CADDET, 1998). Alcohol separation processes in breweries require an additional process step (as opposed to manipulated fermentation) and are done to improve taste. Estimates of utilities costs (energy and water) for RO membranes were \$2.40/barrel (\$2.04/hl) as compared to \$4.10/barrel (\$3.49/hl) for dialysis, while maintenance costs for RO systems are slightly lower than dialysis (\$0.6/barrel as compared to \$0.75/barrel) (Stein, 1993). The Heineken brewery at s'Hertogenbosch (the Netherlands) brewery produces 120,000 hl/year of non-alcoholic beer, by removing alcohol and water from ordinary beer, using a RO filter. In 1997, the filters were replaced by "spiral wound" units, where the filter membranes are shaped like tubes and are configured according to the cross-flow principle. The cost savings are on the order of \$50,000/year (NLG 101,000/year), and the payback period was about 4 years (CADDET, 1999; NOVEM, 1997). A recent study estimated that membranes for food processing cost approximately \$450/Mbtu-s with operating costs savings of \$55/Mbtu-s (varying greatly depending upon the application), resulting in a simple payback period of just over 2 years and an internal rate of return of 45%, given a 15% discount rate (Martin et al., 2000).

Chemicals. One of the most energy-intensive unit operations in the chemical industry is separation, which can account for over 50% of plant operating costs (Tham, 2003). 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. Improved gas separations involving oxygen (O_2), hydrogen (H_2), and carbon dioxide (CO_2) can lead to reduced capital and operating costs, as well as to improvements in thermal efficiency and superior environmental performance. DOE sponsored studies indicate that technologies now in the research and development phase will offer substantial cost reduction compared the cryogenic air separation methods now employed (Steigel, et al., 2003). Liquid and gas membranes for separation offer an alternative to liquid-liquid extraction that uses much less energy. Liquid membrane separators tend to cost about 10 percent less than traditional separation units (Martin et al., 2000). The annual operating costs of membranes tend to run a bit higher than other separators mainly because membranes foul easily and must be replaced rather frequently. In general, gas and liquid membrane applications currently have simple payback times around 10 years with low internal rates of return (Martin et al., 2000), but shorter payback times are seen in many applications.

Wastewater. Traditional wastewater treatment methods include the use of chemicals (coagulants) to remove impurities, flocculation, sedimentation, and fine particle (e.g. sand) filtration. 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. 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. Life-cycle costs of new, relatively small water treatment facilities (less than 20,000 m^3/day) using pressure-driven membrane processes should be less or comparable to those of new facilities using conventional processes for particle removal or reduction of dissolved organic materials (Wiesner and Chellam, 1999). A recent study estimated that membrane technologies for wastewater treatment average about \$30,000 in capital costs and save \$6,400 annually in operating costs, resulting in a simple payback period of just under 5 years and an internal rate of return of about 20% (Martin et al., 2000). In a number of applications, the annual operating cost savings from reductions in wastewater-related fees and associated labor costs lead to simple payback periods of 3 years or less (Nini and Gimenez-Mitsotakis, 1994; Pollution Engineering, 2002). Where the costs of the new membrane technology at a Hunt-Wesson tomato processing plant were greater than the direct benefits, the improved effluent treatment levels enabled the plant to increase production and the resulting increased income outweighed the membrane costs by a significant amount (Mannapperuma, et al., 1995).

3.3 Energy: Baseline, New Technology, and Potential Energy Savings

Food Processing. Primary energy use in the food and kindred products industry (SIC 20) in 1998 was 1573 TBtu (1659 PJ), equivalent to 6.5 percent of total manufacturing energy use in the U.S. Primary energy consumption for this industry in 2025 is estimated to be over 2100 TBtu (2215 PJ), growing at an average annual rate just slightly higher that the manufacturing sector as a whole (U.S. DOE, EIA, 2001; U.S. DOE, EIA, 2004). The main energy-consuming sub-sectors are corn milling, sugar, meat packing, soybean oils, beverages, and dairy. 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.

Net energy savings of 8.8 MBtu/ton (10.2 GJ/t) of water removed were realized when an NF unit was installed in place of a two-stage evaporation process for whey concentration at a dairy plant (CADDET, 1998). Energy savings of 66% were experienced when a combination of UF and RO were used for apple juice concentration when compared to an evaporation process (CADDET, 1996). Membrane microfiltration for sterilizing and filtration of beer typically uses approximately 0.15-0.25 kWh/gallon (PG&E, 2000). 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). Investigations into the use of oscillatory flow in crossflow microfiltration for beer clarification found energy savings ranging from 15-40% as compared to standard microfiltration due to reduced pumping requirements (Blanpain-Avet et al, 1998).[3] Electrodialysis for stabilizing wines can be used instead of conventional energy-intensive refrigeration, reducing electricity use by 80% (Amon and Mannapperuma, n.d.).

It is challenging 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% 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% of fuel using applications in the food industries (Eichhammer, 1995). A recent assessment found that overall primary energy savings (despite an increase in electricity use) using membrane technology instead of existing

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[3] Still, some manufacturers believe current cross flow membrane filtration systems may require as much extra energy as they save (Todd, 2001).

separation processes was about 30% and that these savings, when applied to the separation process portion of the food industry, would result in primary energy savings of 27 Tbtu in 2015 (Martin et al., 2000). Assuming increased penetration of membranes in the food industry overall, we estimate savings of about 50 TBtu in 2025.

Chemicals. The estimated total annual consumption of energy (fuels and electricity) and feedstocks by the U.S. chemical and allied products industry was estimated to be over 6500 TBtu in 2000; roughly 40% of that (2600 TBtu) is required for separation processes, including distillation, extraction, adsorption, crystallization, and membrane-based technologies (U.S. DOE, EIA, 2004; U.S. Climate Change Technology Program, 2003). Primary energy consumption (including feedstocks) for this industry in 2025 is estimated to be over 8500 TBtu (U.S. DOE, EIA, 2004). Any process facilitating such separations will result in enormous savings of both energy and waste (U.S. Climate Change Technology Program, 2003). Gas and 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. Membrane separation uses 60 percent less fuel than liquid-liquid extraction for separating a mixture of isopropyl alcohol and water. Separation processes account for one quarter of the process energy to produce isopropyl alcohol. A recent assessment found primary energy savings potentials of 20% and 53%, respectively, for specific applications of gas and liquid membranes as replacements in the production of methanol and isopropyl alcohol, respectively, resulting in potential savings of 0.08 TBtu and 0.81TBtu of primary energy in 2015 (Martin et al., 2000). Assuming increased penetration of membranes in these two applications as well as use of membranes in other applications in the chemicals industry, energy savings of about 95 TBtu will be realized in 2025, assuming membranes reduce about 2.5% of total projected chemical industry primary energy consumption.

Wastewater. Water and wastewater facilities operated by U.S. business, industrial, municipal water users, and others consume 75 billion kWh of electricity annually, or about 3% of the total U.S. electricity consumption (U.S. DOE, OIT, 2002a). Most industrial wastewater is 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.

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). 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, 1994).

A closed-loop zero-effluent discharge paper mill using pressurized ozone with dissolved air flotation and an ultrafiltration membrane in series allows total dissolved solids in process water to be readily converted to total suspended solids for efficient removal, saving energy through avoiding the cost to heat incoming fresh water. The reduced heating requirements will save an average mill producing 500 tons of paper a day approximately 75 billion Btu/year. Based on 15% market penetration by 2010, annual savings are estimated to be 8.2 trillion Btu. Market penetration of 35% by 2025 is estimated to save almost 20 trillion Btu (U.S. DOE, OIT, 2002b).

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% of the energy needs for evaporation. Additional production savings are achieved through product quality, reduced water use, lower operation costs, which are site-specific. A recent assessment estimated primary energy savings (accounting for fuel savings and increased electricity use) of about 30% and projected potential primary energy savings of almost 120 TBtu in 2015 for projects with a payback period of 4.7 years or less (Martin et al., 2000). Assuming wastewater energy consumption grows at a rate of 1.2% per year between 2015 and 2025 (slightly slower than the projected 1.4% average annual growth projected for the manufacturing sector as a whole during this period) and the availability of slightly greater savings of 35%, the projected primary energy savings in 2025 are estimated to be almost 160 TBtu.

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4. Gasification

4.1 Technology

4.1.1. Technology Description

Various energy-intensive industries produce low-grade fuels as a by-product of the production process. Currently, these low-grade fuels are combusted in boilers to generate steam or heat. Often, this results in relatively less efficient use of these fuels. Gasification offers opportunities to increase the efficiency of using low-grade fuels. In gasification, the hydrocarbon feedstock is heated in an environment with limited oxygen. The hydrocarbons react to form synthesis gas, a mixture of mainly carbon monoxide and hydrogen. The synthesis gas can be used in more efficient applications like gas turbine-based power generation or as a chemical feedstock. The technology not only allows the efficient use of by-products and wastes, it also allows low-cost gas cleanup (when compared to flue gas treatment). Various industries are pursuing the development of gasification technology, and are at different stages of development. Furthermore, gasification technology can also lead to more efficient and cleaner use of coal, biomass and wastes for power generation. A special gasifier-type is the molten iron bath gasifier, which is the basis for the smelt reduction process. However, this technology would warrant a separate description. This report focuses on industrial uses of gasification technology.

4.1.2 Specific End-Uses and Applications

In this description we highlight two main areas of current gasification development: the pulp and paper industry and petroleum refining. Both are energy-intensive industries that use a considerable amount of the total energy consumed in the U.S.

Pulp & Paper. 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 in which 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. Gasification allows not only the efficient use of black liquor, but also of other biomass fuels such as bark and felling rests to generate a synthesis gas that after cleaning is combusted in a gas turbine or combined cycle with a high electrical efficiency. This has the potential to increase the electricity production within the pulp mill. The technology is called black liquor gasification-combined cycle (BLGCC, see Figure 4.1). The black liquor gasifier technology produces a surplus of energy from the pulp process, creating the possibility to generate several different energy products for external use, i.e. electricity, heat and fuels. Alternatively, the synthesis gas can be used as a feedstock to produce chemicals, allowing the development of the “bio-refinery.” In Europe, policies focusing on an increasing share of biomass in transportation fuels have led to the increased interest of using black liquor gasifiers for the production of Dimethylether to replace diesel fuel.

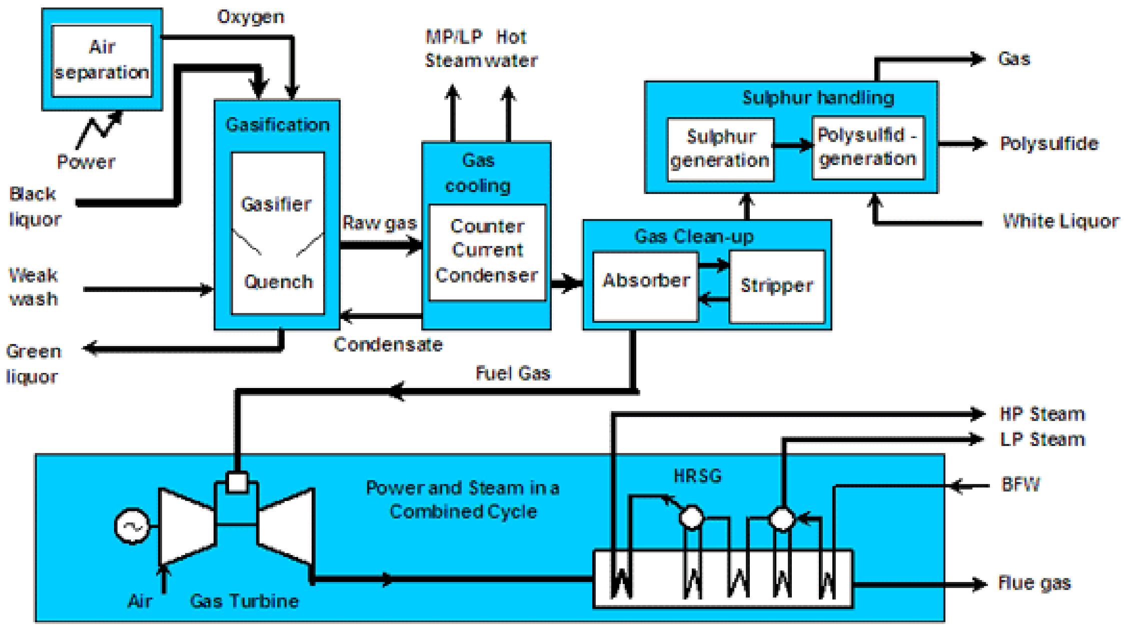

Figure 4.1. Schematic Representation of a Black Liquor Gasifier Integrated with a Combined Cycle (BLGCC). Source: Chemrec, Sweden

Gasifiers can use air or pure oxygen to provide the oxygen needed for the chemical conversions. The advantage of an air-blown gasifier is the reduction in investments. However, the disadvantage is the production of a synthesis gas with a lower heating value. The richer synthesis gas allows easier combustion in a gas turbine. The gas consists of hydrogen, carbon monoxide and hydrocarbons. After cleanup, the gas is well suited as a fuel for gas turbines. The black liquor gasification process can also be divided in different groups based on the form of sodium, i.e., in smelt or solid form. The smelt process is a high temperature process where the sodium is found as molten sodium sulfate and sodium carbonate. The process where the sodium is held in solid form is operated at a lower temperature compared to the smelt process. A natural separation of sulfur from sodium is provided through the gasification process, which allows opportunities for advanced pulping methods. This makes it possible to enhance pulping by modifying conventional pulping liquors (Larson et al., 2000).

Petroleum Refineries. Because of the growing demand for lighter products (e.g., gasoline) and increased use of conversion processes to process a “heavier” crude, refineries will have to manage an increasing stream of heavy bottoms and residues. Gasification of the heavy fractions and coke to produce synthesis gas can help to efficiently remove these by-products. The state-of-the-art gasification processes combine the heavy by-products with oxygen at high temperature in an entrained bed gasifier (see Figure 4.2). Due to the limited oxygen supply, the heavy fractions are gasified to a mixture of carbon monoxide and hydrogen. Sulfur can easily be removed in the form of

H_2S to produce elemental sulfur. The synthesis gas can be used as feedstock for chemical processes. However, the most attractive application seems to be the combination of hydrogen production and generation of power in an Integrated Gasifier Combined Cycle (IGCC). The increased use of conversion processes in the refinery will lead to an increased demand for hydrogen. Hydrogen is removed from the synthesis gas, and the remainder is combusted in a gas turbine (with an adapted combustion chamber to handle the low to medium-BTU gas) generating electricity. The hot flue gases are used to generate steam. The steam can be used onsite or used in a steam turbine to produce additional electricity (i.e. the combined cycle). Steam can also be used onsite when using a backpressure turbine. This technology will result in greater efficiencies in power generation, reduced air pollution (compared to conventional boilers) and reduced solid wastes.

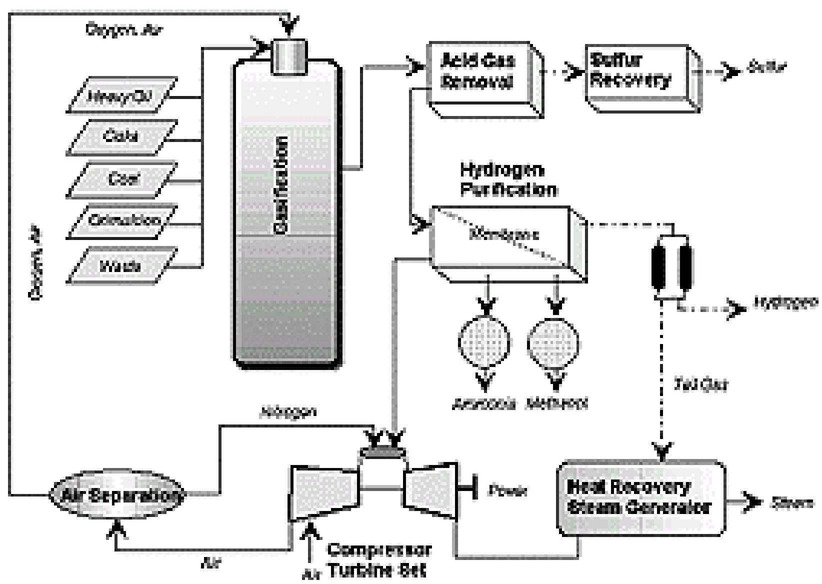

Figure 4.2 Schematic Representation of a Typical Gasification System in a Petroleum Refinery. Source: U.S. Energy Information Administration.

4.1.3 Current Status

In the **pulp and paper industry**, different gasification technologies are being demonstrated at commercial scales. Both air-blown and oxygen-blown gasifiers are being tested and demonstrated. A natural separation of sulfur from sodium is provided through the gasification process. This allows enhanced pulping by modifying conventional pulping liquors (Larson et al., 2000). An increased pulp yield of about 5-7% can be achieved (Larson et al., 2003).

The main developers of black liquor gasification can be found in the U.S. and Scandinavia (Sweden and Finland), and the teams collaborate in the development of the technology. In the U.S., development has focused on both the air and oxygen-based process. The air-based process was originally developed by MTCI, and has been investigated in a small-scale pilot plant at the Weyerhaeuser plant in New Bern (North

Carolina). Georgia-Pacific will build at the Big Island (Virginia) mill, while Boise Cascade also plans to demonstrate a gasifier. International Paper has selected two sites for high-pressure oxygen gasifiers. Weyerhaeuser is now collaborating with Chemrec (Sweden) to design and build an oxygen-based gasifier at its New Bern plant. Chemrec expects the first fully commercial application of its technology by 2006. Both for the low-temperature and high-temperature technologies, there are technical issues that need R&D attention to increase the reliability of the gasifier.

In **petroleum refining**, gasifiers are entering commercial use. Entrained bed IGCC technology was originally developed for refinery applications, but is also used for the gasification of coal. Hence, the major gasification technology developers were oil companies like Shell and Texaco. The technology was first applied by European refineries due to the characteristics of the operations in Europe (e.g., coke was often used onsite). IGCC is used by the Shell refinery in Pernis (The Netherlands) to treat residues from the hydrocracker and other residues to generate 110 MWe of power and 285 tonnes of hydrogen for the refinery. Also, the IPA Falconara refinery (Italy) uses IGCC to treat visbreaker residue to produce 241 MWe of power (Cabooter, 2001). Interest among U.S. refiners has increased, and 3 U.S. refineries currently operate gasifiers, i.e., Motiva (Delaware City, DE), Frontier (El Dorado, KS) and Farmland (Coffeyville, KS). New installations have been announced or are under construction for the Sannazzaro refinery (Agip, Italy), Lake Charles, (Citgo, Louisiana) and Bulwer Island (BP, Australia).

Gasifiers may also provide an attractive option for **food-processing** facilities that produce large amounts of waste, e.g. rice straw, bagasse (from cane-sugar production), shells and others. Regional facilities in areas with food processing plants may provide a cost-effective and energy-efficient way to process these by-products and wastes. However, we have not studied this in detail.

4.1.4 Research & Development Needs

While gasification in petroleum refineries is being implemented in more and more refineries worldwide, demonstration and further development of black liquor gasification is needed to make this technology commercially attractive. After successful commercial demonstration and cost reductions, implementation of BLGCC-technology will be driven by the retirement of current Tomlinson boilers, many of which will be retired over the next decades. However, R&D in oil residue gasification could make this technology more attractive. R&D focuses on improving the reliability, increasing the energetic efficiency, and reducing costs for materials used in the construction. Important areas for R&D are:

- Improved high-temperature gas cleanup systems to remove sulfur, alkali metals, and dust to increase the energetic efficiency of these systems considerably
- Demonstration of advanced pulping and black liquor gasification at near commercial scales to demonstrate the important benefits of integration.
- Improved materials to line the gasification reactor to increase operating hours between maintenance stops.
- Improved combustion turbines for operation on low to mid-calorific gases.

4.2 Cost

4.2.1 Baseline and New Technology

Gasifiers are an attractive way to use low-grade fuels to make a valuable by-product both at refineries and pulp and paper plants.

Larson et al. (2003) performed a cost-benefit analysis of **black liquor gasifier/combined cycle (BLGCC)** for a typical Kraft pulp and paper mill. Over the next 10-20 years, almost all recovery boilers will be retired, providing excellent opportunities to introduce advanced technology. The total capital costs of a BLGCC system are estimated to be about 60-90% higher than that of a standard Tomlinson boiler system. The high-temperature will have relatively lower capital costs than the low-temperature process. The capital costs for a plant with a capacity of 550,000 tons of pulp are estimated at $194 million, compared to $122 million for a Tomlinson system. Annual non-fuel O&M costs are estimated at $10.6 million. BLGCC can have positive macro-economic impacts due to reduced use of imported fossil fuels and maintained or increased regional development.

Petroleum Refining. Marano (2003) studied the efficiencies and costs of gasification processes at refineries. In this study, cost estimates were developed for different configurations. In the base case of the study it is assumed that a gasifier with a capacity of 2000 tons per day would cost $188 million, while the hydrogen plant would cost another $41 million and the combined cycle would cost $159 million (Marano, 2003). In this analysis we assume that the plant is used as an IGCC, with total costs of $347 million for a 178 MW facility. In a more advanced case, the cost of the technology would come down to $286 million. In the more advanced case the specific capital costs are estimated at $408/ton throughput. Gray and Tomlinson (2002) estimated that 40 refineries in the U.S. produce enough byproducts to justify the use of a gasifier. The largest 40 refineries in the U.S. represent over 60% of the refining capacity (O&G Journal, 2003). The baseline is assumed to be a conventional boiler to burn petroleum coke and heavy fuel oil. No cost estimates are available for such a boiler. However, it is likely considerably less than a gasifier system, dependent on the air quality standards to be met.

4.2.2 Cost-Effectiveness

Pulp & Paper. Black liquor gasification is a strategic investment. The IRR of an investment into a BLGCC is estimated at 16-17%, based on electricity sold at 4 cents/kWh. However, if a premium of 2.5 cents/kWh is added to the price of electricity produced from pulp and paper biowaste (as part of a renewable energy policy) the IRR may go up to 24-26% (Larson et al., 2003). The high rate of return is the result of increased pulp production and power sales to the grid, despite the increased capital costs.

Petroleum Refining. The simple payback period of a refinery integrated gasifier system is estimated to be 4 to 5 years (Gray and Tomlinson, 2002), depending on the price of natural gas and oil. Increasing use of gasification units will reduce the perceived risks and lead to further reductions in cost as investments in the technology increase.

4.3 Energy

Energy savings depend strongly on current technology baseline assumptions. We provide estimates of the typical energy savings, as well as an estimate of the technical potential in the U.S. for both applications. Additional energy savings may exist in other sectors or applications. Both applications may result in considerable potential for power production within the two industries. In 1998, industry purchased almost 890 TWh of electricity.

4.3.1 Baseline and New Technology

Pulp & Paper. Existing recovery boilers consume roughly 27 MBtu of black liquor and other biomass per short ton of air-dried pulp. Power production efficiencies using steam turbine systems in current Tomlinson boiler systems are estimated at 10 percent (Consonni et al. 1998, Larson et al. 1997), resulting in the generation of 790 kWh/ton of pulp, sufficient to cover part of the internal power demand in a pulp mill. In 2002 the U.S. pulp and paper industry produced 49.8 million short tons of chemical pulp, producing around 39.4 TWh of electricity from black liquor.

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 1740-1860 kWh/ton, and the performance of a typical Kraft-plant in the Southeastern U.S., a plant will be able to export 220-335 kWh/ton of pulp (Larson et al., 2003). At the 2002 production level of chemical pulp, the U.S. pulp and paper industry could produce around 89.6 TWh of electricity, or double that of the current Tomlinson boiler system, or 50.2 TWh additional to the current power production in the pulp and paper industry.

Petroleum Refining. In 1999, U.S. petroleum refineries produced 96,200 tons of coke per day, virtually all in the 40 largest refineries. A portion of this was burned off in the Fluid Catalytic Cracker to regenerate the catalyst. With increasing production of lighter products the coke production at refineries is expected to increase to 116,000 tons/day in 2010 (Gray and Tomlinson, 2000). Petroleum coke and heavy residues are currently combusted in a boiler or sold as fuel to cement kilns or disposed to a landfill. Currently, a large part of the coke is sold. To allow modeling of the technology, we assume that the petcoke and other heavy residues are combusted onsite. The generated steam is used for power production in a steam turbine. In reality, steam is most likely to be used for process heating. Assuming a power generation efficiency of 28% for a petcoke-fired boiler and steam turbine system, baseline energy use would be 84.4 TWh/year.

The net power production of a refinery based IGCC plant is estimated at 38-45%. Marano (2003) estimates net power production at 3,323 kWh/ton petroleum coke at an efficiency of 38.2%. The efficiency of an IGCC using heavy fuel oil is expected to be around 40% (Marano, 2003). In this assessment we assume that by 2025 the efficiency will increase to 45%, or a net power output of 3,914 kWh/ton petcoke. Based on the 1999 coke production, total power production can be 135.7 TWh/year, or 51 TWh over the baseline.

The above efficiencies are based on operation of the IGCC as a dedicated power production unit. However, the system can also be operated as a trigen-unit, generating electricity, steam and producing hydrogen. The overall system efficiency of such a system is higher, but harder to quantify, as it depends on the efficiency of the current steam reforming facility and of boilers. In practice, we expect the gasifiers to be run as a trigen-unit. However, for this analysis we focus on power production.

4.3.2 Potential Energy Savings

Pulp & Paper. Additional electricity production from black liquor and biomass is estimated at 50.2 TWh, or 1000 kWh/ton of chemical pulp. The primary energy savings (assuming an average efficiency of 32% for power generation) are estimated at 10.3 MBtu/ton of pulp.

Petroleum Refining. The potential energy savings are estimated at 51 TWh (assuming 1999 coke production) or 62.6 TWh in 2010. The specific energy savings are estimated at 1478 kWh/ton coke, equivalent to 18.5 kWh/barrel of oil processed.

For 2025, the combined technical potential in both sectors is estimated at 115 TWh/year. Assuming a penetration rate of 40% (based on stock turnover and age distribution of Tomlinson boilers, and the need for increased residue processing at refineries), we estimate the likely realized potential by 2025 at 45 TWh. This is equivalent to primary energy savings of 461 TBtu additional to the baseline scenario (AEO 2004).

4.4 References

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5. Motor Systems

5.1. Technology

5.1.1 Technology Description

Motor-driven equipment accounts for 64 percent of the electricity consumed in the U.S. industrial sector. Motor systems are made up of a range of components centered around a motor-driven device such as a compressor, pump or fan (see Figure 5.1).

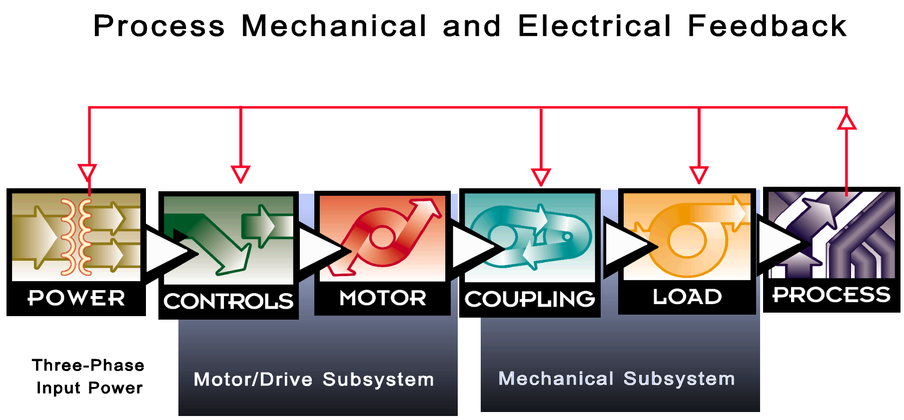

Figure 5.1 Schematic Representation of a Motor System. Source: U.S. Department of Energy

Motor systems performance optimization focuses on optimizing the flows in motor-driven systems to meet end-use requirements. The opportunity for energy savings derives from the fact that the power consumption of the end user 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. Many of these opportunities can be implemented today, but motor operators often fail to do so. However, in the long term new motor technologies may improve the energy efficiency further.

Emerging motor system improvements can be categorized into the following three areas of development opportunities:

1. Upgrades to the motors themselves, for example:
    - superconductive motors,
    - permanent magnet motors,
    - copper rotor motors,
    - switched reluctance (SR) drives,
    - written pole motors, and
    - very low loss magnetic steels; and

2. System design optimization and management, such as:
    - end use efficiency improvements,
    - use of premium lubricants, and
    - advanced system design and management tools; and

3. Controls on existing systems, for example:
    - multi-master controls on compressors,
    - sensor based controls, and
    - advanced adjustable speed drives with improvements like regenerative braking, active power factor correction, better torque/speed control.

New Motors. Superconductivity is the ability of certain materials, when cooled to extremely low temperatures, to conduct electrical current without resistance and with extremely low losses. High temperature superconductor (HTS) motors operate at temperatures between -280 to -320°F (-173 to -195°C), achievable through liquid nitrogen cooling. These motors are expected to exhibit longer operating life, greater safety, higher overload thresholds, reduction in friction, and reduced noise, size, volume and weight.

Permanent magnet (PM) motors either have replaced the stator winding on a motor with a permanent magnet or contain a stator with three windings producing a rotating field and a rotor with one or more permanent magnets that interact with the rotating field of the stator. By switching the direction of current through the stator windings, the polarity of their magnetic field is reversed causing the rotor to rotate. The most common type of PM motor is the electronically commutated permanent magnet motor (ECPMs), also known as the brushless DC motor (Nadel et al., 2002). ECPMs have a rotor with multiple permanent magnets and a stator with electrical windings creating the varying magnetic field. These motors can achieve varying speeds by varying the rate at which the magnetic fields are reversed (or commutated). ECPMs eliminate rotor resistive losses, brush friction, and maintenance associated with conventionally commutated motors. Other advantages include precise speed control, lower operating temperature and higher power factor than induction motors. High speed PM motors are also being developed for the commercial air conditioning market for increased efficiency.

Two new motors have been developed based on identifying the best materials to use in the casting process. Copper rotor motors and magnetic steel motors replace aluminum in the rotor "squirrel cage" structure of the motor since the electrical conductivity of these materials is up to 60% higher than aluminum and hence, produce a more energy-efficient induction motor. In addition, copper reacts with much more stability to changing loads, especially at low speeds and frequencies, operates cooler and has fewer repairs and re-windings, increasing motor life and decreasing maintenance costs (CDA & ICA, 2001).

Written pole (WP) motors are hybrids of induction motors during start-up, and synchronous motors upon reaching full operating speed. The single-phase motor combines the starting characteristics of a high-slip, high-power factor cage motor with the energy-efficiency of an AC permanent magnet motor without power electronics, reduced voltage starters or phase converters. The WP "writes" the number of poles and their locations electronically on the rotor, obtaining higher efficiency and a lower start-up inrush current. Written pole motors can now be used in applications for which only three-phase motors were available in the past.

Switched reluctance drives are simple, compact, brushless, electronically commutated AC motors that offer high efficiency and torque. The stator of the motor consists of steel poles each wound with a series of coils, connected in pairs, while the rotor is just a shape piece of steel or iron forming poles with no magnets or coil windings. Current is switched among the different-phased windings of the stator to rotate it. Their advantages include variable speed regulation and high efficiency in extremely high and low speed ranges (50 to 100,00-rpm), precision control, high vibration tolerance, high power density and simple construction. However, high pulsating magnetic flux cause acoustic noise and large vibrations; therefore, these motors require considerable control to properly switch current, and the specialized design that SR motors require is non-intuitive relative to traditional motors (Paula, 1998).

System Design Optimization and End Users. Designing a system that properly matches supply to demand is crucial to energy efficiency. All components of the motor system, including compressed air, pumps, fans and motors should be optimized to minimize demand and increase efficiency. Experts can be hired to manage the compressed air to minimize leaks, identify inappropriate uses of compressed air and determine proper system pressure level. Likewise, system optimization for pump systems and motors can be outsourced as a service as well, identifying system requirements and selecting the proper motor or end user. While the engineering associated with pump systems is well understood, many engineers are not experienced in conducting the energy efficiency analyses that their system requires (Martin et al, 2000). Pump systems may require slowing pumps, trimming the impellers, or replacing an existing pump. Free software tools are available that can identify system requirements for energy efficiency. One example is from the Motor Challenge Program at the Office of Industrial Technologies (U.S. DOE, OIT, 2004). In addition to system management for motors and motor systems, selecting a premium lubricant for the equipment can reduce friction losses, particularly in end-use equipment like compressors, pumps and gear drives, and increase system efficiency.

Controls. Many controls are available for motors and motors systems and they are continuously being updated. Today, more options are available to meet more system demands, and where one control does not work, another likely does. Still, all types of adjustable speed drives (ASDs) have only penetrated 9% of U.S. motor systems (Easton Consultants, 1999). A new class of ASDs - magnetically-coupled adjustable speed drives (MC-ASDs) offer a greater range of possibilities for ASDs; two particularly promising devices are the MagnaDrive and the PAYBACK drive. In the MagnaDrive, fixed rare earth magnets create an induced electromotive force to transfer torque. The physical connection between motors and loads is replaced with a gap of air, and the amount of torque transferred is controlled by varying the air gap distance between rotating plates in the assembly. The PAYBACK Drive is similar to the MagnaDrive but instead of rare earth magnets, an electromagnet is used to control the speed of the drive. Current is applied to the coil of the electromagnet rotor and speed is controlled by varying the strength of the magnetic field.

Compared to variable frequency drives (VFDs), MC-ASDs have many advantages in addition to greater energy efficiency, including:

- a greater tolerance for motor misalignment,
- little impact on power quality,
- the ability to be used with regular duty motors (instead of inverters),
- expected lower long term maintenance costs, and
- extended motor and equipment lives, due to elimination of vibration and wear on equipment (Chvála, 2002).

Other advanced ASDs include development of different inverter technologies, such as the snubbed inverter or the hybrid secondary uncluttered induction machine (HSU-I) both developed at Oak Ridge National Laboratory. HSU-I adds a section to an existing motor to make it adjustable with simple resistors and other low-cost components, rather than the typical adjustable frequency inverters. Three types of secondary circuits – variable resistance, inverter and magnetic switch can be used in varying combinations. The SR drive can also be used as an ASD (see above).

In addition to ASDs, system controls can be implemented on systems of motors or components to minimize energy consumption, to evenly distribute wear and tear on equipment and to allow for smooth operation of entire systems. For example, advanced compressor controls can handle multiple compressors that communicate with each other. One network boasts the ability to control up to 31 drives together at once (PML Flightlink, 2004). Sensor controls can monitor air quality or other end uses and feedback to the motor for adjustment.

5.1.2 Specific End-Uses and Applications

New Motors. Because of the variety of new motors emerging, many applications have efficient motor options; however, most new motors are best suited for a particular application, range of sizes or flexibilities. Below motors are categorized according to the sizes that are typically seen for each application. Most motors can be applied to a broader range of sizes, but those below are those seen most often (and most economical to manufacture).

Motors > 1000 HP.

Superconductor motors are being developed for a targeted size of 1000 HP and above. Though most motors are very small (1 HP or less), in terms of electricity, large motors of 1000 HP and above convert 30% of all electricity generated in the U.S., of which 70% are well suited to utilize high temperature superconductor technology (Lawrence and Cox, 2002). Xenergy (2000) estimates motors over 200 HP use 45% of the energy used by motors of all sizes (above 1 HP). Superconductor motors will be well suited for standard large motor applications like centrifugal compressors, boiler feed pumps, force draft fans and industrial scrubbers, blowers and belt drives.

Motors <600 HP.
ECPM motors are already in use in HVAC fans, drives and small appliances in the U.S., and can currently be used for applications of up to 600 HP in size (Saskatchewan, 2004). High speed PM motors are being developed for 25 ton or larger compressed air motors used for air conditioning (U.S. DOE, OIT, 2000).

Motors > 200 HP.
The copper rotor motor targets motors of 200 HP and above, although a few smaller specialty purpose motors have been produced when other factors, such as reliability, are more important than costs (Brush et al., 2002). However, if pressure-die casting can be extended to 20,000 shots per die, the economics of motor operation and manufacturing will favor copper in all classes of motors (Peters and Cowie, 1998).

Motors <75 HP.
Written pole motors are available in 15 to 75 HP sizes, and could potentially replace 4% of the integral-horsepower general-purpose motors in service today (Nadel et al., 2002).

All motor sizes.
Like the copper rotor motor, the switched reluctance drive is a good choice when high reliability is required (Paula, 1998). SR motors could potentially replace 20 to 50% of the existing general-purpose motors in service today (Martin et al., 2000).

System Design Optimization and End Users. Motor systems can be optimized for energy efficiency through experts, training programs or computer tools. Sometimes the only barriers to system optimization are a lack of awareness of opportunities or a lack of expertise available for assessment. Capabilities and market demand need to grow at the same rate for system optimization through performance services or experts to expand. We assume about 25 to 50% of the motors, pumps, and compressed air systems can be optimized when hiring experts, using self-assessment tools or completing management training programs to train staff for system optimization. About half of the motors used in industry are eligible for premium lubricants applied by the customer since many smaller motors use sealed bearings that are not user serviceable.

Controls. Today's ASDs are available to a wider range of applications than VFDs. MC-ASDs easily mount on the shaft of any AC motor and therefore can be applied to both new and retrofit motors. The MagnaDrive is well suited for direct-drive loads like fans, pumps and blowers for medium to large sized motors from 20 to 1000 HP. The PAYBACK Drive is best for belt-driven loads and, although in theory can service all motor sizes, today they are only available from 3 to 250 HP. We predict all applications requiring variable speed will have some form of advanced control drive available to them. In addition, we assume about half of the energy used in systems like large multicompressor systems can be optimized using advanced system controls like the multi-master compressor controls for compressed air.

5.1.3 Current Status

New Motors. Rockwell Automation, in partnership with DOE, has successfully demonstrated and tested a cryogenically cooled 1000 HP HTS motor. A prototype 5000 HP HTS motor has been developed by American Superconductor™ (AMSC) that utilizes an off the shelf cryogenic cooling system. The motor successfully passed full load testing at rated voltage, rated current and rated power, sustaining a maximum load of 7,000 HP at rated speed. The current barrier to marketability is costs, particularly wire costs (see below). HTS generators are currently being used in ship propulsion generators (AMSC, 2004).

Over 100,000 PM motors are in used in HVAC fans, drives and small appliances in the U.S. today. ECPMs are currently available from many manufacturers in sizes up to 60 HP. Powertec International and GE produce larger PM motors up to 600 HP in size. PM motors coupled with electronic speed controls are already being used in cordless power tools, residential AC, furnaces and heat pumps (Nadel et al., 2002).

The copper rotor motor is currently four to five years old, but the mold materials today require frequent replacement due to the thermal shock and fatigue experienced during casting. More research is needed on the materials and methods used in pressure-die casting of the copper rotors, their last major hurdle before they can compete in cost.

WP motors are limited to 15 to 75 HP and have been used in less than 100 commercial applications to date. WP motors are currently being used for irrigation pumps, conveyor motors, water pumps, food-processing air dryers and process stirring. At this time, however, only one manufacturer produces WP motors (Nadel et al, 2002).

Switched reluctance drives are currently used in military applications like generators for turbine engines and pump motors for jet fighters that require high reliability (Paula, 1998). However, initial publicity in the late 1990s was overly enthusiastic in its assessment of capabilities, which has hurt the market for SR motors since then (Bartos, 2003). Few engineers today are trained to construct the specialized design that the technology requires, and sensor control is costly (Paula, 1998). However, new high-speed digital signal processors specialized for motion control allows control without mechanical sensors, decreasing costs and increasing reliability (Fedigan and Cole, 1999).

System Design Optimization and End Users. Motor system management tools, experts, training programs are commercially available today. However, a lack of experts available for a particular application or assessment is possible given the overall lack of demand for services in the past. Capabilities and market demand need to grow at the same rate for system optimization through performance services or experts to expand. The only other barrier to system optimization is a lack of awareness of opportunities. Premium lubricants are commercially available to all motors eligible.

Controls. Currently all types of adjustable speed drives have only penetrated 9% of U.S. motor systems (Easton Consultants, 1999) and great potential exists for advanced ASDs. Today's ASDs are available to a wider range of applications than VFDs. MC-ASDs easily mount on the shaft of any AC motor and therefore can be applied to both new and retrofit motors. MC-ASDs are fairly new – less than 10 years old. The MagnaDrive is currently installed in pump, fan and blower installations in the pulp and paper, mining, food processing and raw materials processing industries, as well as in irrigation, power generation, water and wastewater treatment and HVAC systems. It is available in large systems from 20 to 1000 HP. The PAYBACK Drive is currently available from 3 to 250 HP and has been installed in a few applications. Multi-master compressor controls for compressed air are currently commercially available. First cost and lack of appreciation for compressed air inefficiencies are the major barriers.

5.1.4 Research & Development Needs

New Motors. The last hurdles for superconductor motors involve cost, and the drivers for cost are the costs of the wire and the refrigeration. Cryocoolers are used in some applications today but are not universal. More research is needed on the best cooling devices for superconductor motors, as well as ways to produce cheaper wires.

Currently PM motors are easy to manufacture and costs are comparable to conventional ASDs. Barriers that exist for PM motors are not of a research nature but will require information dissemination and demonstrations.

Research on pressure-die casting for the copper rotor motor will enable these motors to compete in costs in the future. Currently, commercialization is cost prohibitive only because of the expensive casting process. Mold materials need to be replaced often due to thermal shock and fatigue experienced during casting. More research on the materials or methods used in pressure-die casting of copper rotors is considered necessary for future cost competitiveness.

WP motors are currently easy to manufacture suffer only from a lack of production volume. Like PM motors, barriers for WP motors are not of a research nature but require information dissemination and demonstrations.

Switched reluctance drives currently require a specialized design and expensive sensor controls to implement. Shaft and bearing systems must be of higher quality than conventional motors, which drives up the price. Research is needed in these areas to develop SR motors that are more mainstream with simpler systems for implementation and control.

System Design Optimization and End Users. Continued research on system optimization will likely always improve efficiency of those systems. However, currently a lack of awareness is the biggest barrier to implementation of optimization techniques, not a lack of knowledge.

Controls. Similar to system optimization, lack of awareness restricts implementation of controls for motor systems. In addition, however, most systems are not evaluated on a life-cycle basis, where long term maintenance, reliability and other long-term costs will affect their cost effectiveness. Improved dissemination of life-cycle costing may help increase penetration of advanced controls whose first costs exceed those of conventional controls.

5.2 Cost

5.2.1 Baseline and New Technology

New Motors. Depending on the new motor, relative costs vary greatly, and each has its own barriers to mass production. Superconductor motors are eventually expected to have lower capital costs due to smaller sizes and compactness and reduced operating costs due to increased energy efficiency (AMSC, 2004). Cost drivers for superconductor motors are the refrigeration and wire costs. Cryocoolers, a mature, highly reliable and relatively low cost “off the shelf” technology, are expected to cool HTS devices (Cox and Hawsey, 2000). Predictions for wire prices at which superconductor motors will be profitable range from $4 to $50 per kA-m (Port, 2002; EIA, 2002; Lawrence and Cox, 2002). Projected wire costs for the near future (after a new production facility is in place) are $10 to $50 per kA-m, compared to copper wires that cost $4 per kA-m (Port, 2002) Several kilometers of wires made up the first 1000 HP HTS motor (Port, 2002).

PM motors are easy to manufacture and costs are comparable to conventional ASDs, about $200 – 400 per HP.

The copper rotor motor commercialization is currently cost prohibitive because of the expensive casting of the rotor. Once this barrier is overcome, potentially lower purchase prices could be achieved due to the motors’ reduced size. Operating costs for copper rotor motors are less than conventional aluminum motors. In addition, life expectancy of the motor itself is predicted to be 50% greater, increasing overall cost effectiveness of the motor.

WP motors are simple to manufacture, but costs are still high because of the lack of production volume (Nadel et al, 2002). The installation cost of a 20 HP WP motor and controller package is about 60% higher than for a conventional induction motor. Once the production volume reaches full production levels, the cost premium is expected to drop by 50%, bringing installation costs down to 30% higher.

Switched reluctance motors and their associated controls, starters and enclosures cost about 50% more than comparably sized and equipped induction motors with variable speed controls (Martin et al., 2000). This price is likely to drop to half (25%), if and when SR motors are more widely accepted and with new developments in controls. Currently shafts and bearing systems must be of higher quality than conventional motors, driving up the price.

System Design Optimization and End Users. There are generally no system optimization capital costs because no equipment needs to be purchased. Some fees for staff time or hiring an expert may be required. Many optimization tools are offered free of charge through DOE and require no investment costs. Premium lubricants cost 1.5 to 2.5 times more than conventional lubricants but last three to four times as long.

Controls. MC-ASDs installation costs are comparable to VFDs, when compared over a lifetime. The manufacturers of the MagnaDrive report costs of up to $600 per installed HP: $400 per HP for 25 to 100 HP and $300 per HP for 100 to 500 HP. Conventional ASDs cost between $200 and $400 per HP. However, the life expectancy of the MC-ASDs is longer – 30 years compared to 5 to 10 for conventional ASDs. Long-term maintenance costs are expected to be reduced, and MC-ASD motor systems can be downsized more easily than conventional ASD systems. Advanced ASD designs and advanced compressor controls will cost more up front than conventional ASDs or simpler controls but provide operational savings due to energy efficiency.

Table 5.1. Cost Estimates for Emerging Motor Technologies

Technology	Current Capital Costs	Capital Costs by 2025	O&M Costs	Payback by 2025	Notes
New Motors					
Superconductor	Higher	Lower	Lower	0-1 year	If wire costs decrease, payback will be short to none
Permanent Magnet	Roughly equal	Roughly equal	Lower	12-30 months	High speed PMs will have payback of 12-30 months
Copper Rotor	Higher	Potentially lower	Lower	0-1 year	If die casting costs decrease, payback will be short to none
Written Pole	60% higher	30% higher	Lower		
Switched Reluctance	50% higher	25% higher	Unclear		Controls are more complex but SRs are more efficient. Likely will be driven by reliability
System & End Use Improvements					
Optimization Experts	None	None	Higher initially, then lower	≤1 year	Cost of expert outweighed by energy efficiency savings
Optimization tools	None	None	Higher initially, then lower	≤1 year	Cost of time spent on tools outweighed by energy efficiency savings
Training programs	None	None	Higher initially, then lower	≤1 year	Cost of employee time (training) outweighed by energy efficiency savings
Premium lubricants	50-150% higher	50-150% higher	Lower	≤1 year	Premium lubricants last 3 to 4 times as long
Controls					
MagnaDrive	Higher	Higher	Significantly Lower	<4[4]	Initial capital costs are higher compared to non-ASDs, but more comparable to conventional ASDs
PAYBACK drive	Higher	Higher	Significantly Lower	≤1[4]	Initial capital costs are higher compared to non-ASDs, but more comparable to conventional ASDs
Advanced ASDs	Higher	Higher	Lower	Upon first avoided failure	Advanced ASDs that provide sag control pay for themselves upon first shutdown prevention.

[4] One study estimates payback periods currently at 4 to 5 years for MagnaDrive and 1 to 2 years for PAYBACK drive (Chvála et al, 2002). Costs and payback periods are decreasing for both technologies.

5.2.2 Cost-Effectiveness

Capital costs, operations and maintenance costs and predicted paybacks for particular motor applications are summarized in Table 5.1.

5.3. Energy

5.3.1 Baseline and New Technology

Motor systems are broad cross-cutting technologies that are used by every sector and every industry in the U.S. Motor-driven equipment accounts for 64 percent of the electricity consumed in the U.S. industrial sector, equal to about 6.4 quads (6,400 TBtu) (DOE, 2004). Total energy savings potential for upgrades in motors and motor systems has been estimated to be 15 to 25% (higher when emerging technologies are included) (Nadel et al., 2002). Below we address each of the areas discussed above for energy savings potential[5].

New Motors. Compared to conventional motors, superconductor motors are more efficient at all speeds greater than 5% partial speed up to fully loaded. According to U.S. DOE, current motor efficiency for conventional 500 HP motors is 95 to 96% (U.S. DOE, 1996). Superconductor motors are expected to have half the energy losses (NREL, 2001); at low speeds, AMSC predicts energy efficiency for HTS motors can be increased by 10%. Cryogenic cooling is used to cool the system, but accounts for less than 2% of the total losses in the machine (AMSC, 2004). Net operating efficiency including the cryogenic cooling system is 97.2% for the prototype 5000 HP motor, with expected efficiencies to reach 97.7% for this motor. At one-third to full speed, efficiencies are expected to reach 99%.

Typical induction motor/ASD drive combinations have a range of efficiencies between 85 and 90% at full load. The prototype of the high speed PM motor has an efficiency of 93 to 95% at full load; high speed PMs are predicted to save up to 10 to 15% savings over conventional motors (DOE, 2000). ECPMs are as high as 95% efficient at full load and can maintain their efficiencies better at part load (Nadel et al, 2002). Improved materials may increase efficiencies; a 50 HP PM with a 97% efficiency has been developed.

Copper rotor motors have been shown to reduce total motor losses by 10 to 15%, yielding energy savings of about 1.4% for a 15 HP motor (CDA, 2004), and 1 to 5% for a range of motor sizes from 4 HP to 270 HP (Peters et al., 2002). Energy savings of 1 to 3% are predicted for each motor implementing copper rotors instead of aluminum.

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[5] Energy savings comparisons for motors and motor systems should be considered from wire to shaft. Since direct comparisons incorporating wire to shaft efficiencies are not always possible for a *particular* motor based on available data, we have provided the information that is available in this section for each motor type. Conventional motor efficiencies are given where appropriate for a particular comparison.

Larger WP motors are more efficient than small WP motors – maximum efficiencies for motors 40 HP and below are 92%, while efficiencies for motors 60 HP or more are 93 to 94%, for loads of 70% or higher (Nadel et al., 2002). Precise Power Corporation, who manufactures WP motors, claim efficiencies from 92 to 95%, compared to 85% for single phase alternatives (Precise Power, 2004). Small (up to 40 HP) motors efficiencies vary from 72.5 to 93%, the higher efficiencies for larger motors (DOE, 1996). We assume efficiency improvements slightly higher than that of SR motors, about 3 to 4%.

SR motors have flat efficiency curves with maximum efficiencies around 93% in integral-HP models and the low to mid-80% range for fractional HP units (Nadel et al, 2002). If adopted, energy savings relative to conventional motors are estimated to be about 3% (Nadel et al., 2002).

System Design Optimization and End Users. Large savings in energy can result from system design optimization, and this should be the first step taken when evaluating energy efficiency of the motor system. Compressed air management can often yield savings of up to 25% or more. Leaks alone can account for 20 to 30% of compressor output. Pump systems optimization will likely yield slightly lower savings, about 17% are predicted (Martin et al., 2000). Savings of 2 to 30% have been realized in motors and end uses when switching to premium lubricants; however, we conservatively estimate savings to be about 3% on average.

Controls. Compared to non-adjustable speed drives, all ASDs can save large amounts of energy – up to 60% or more where motors are not constantly fully loaded. In some applications, MC-ASDs have shown slightly less efficiency than conventional ASDs, although cooling is no longer required for MC-ASDs at some torques, which will save additional energy[6]. In addition, MC-ASDs can operate at wider speed ranges and can easily be applied to retrofits where conventional ASDs cannot. The Northwest Energy Efficiency Alliance predicts that MC-ASDs will save at least 60% of the energy that typical VFDs save across a range of 50 to 100 HP drives (NEEA, 2004). Applications of the MagnaDrive provided energy savings of 25 to 66%. Advanced ASD designs will save even more energy than ASDs; about 2% is predicted (Nadel et al., 2002). Advanced compressor controls are predicted to save about 3.5% where applied (Nadel et al., 2002).

5.3.2 Potential Energy Savings

Primary specific energy savings for particular motor applications are summarized in Table 5.2. All savings are in electricity; no fuel is used in motor systems.

The total energy savings will depend on the penetration rate of new motors, controls and system improvements into the market. In turn, this rate depends on the success of R&D and the impact of market transformation and technology transfer programs. Depending on the application, some measures can be applied to retrofits of motors and motor systems

[6] Savings comparisons should be considered from wire to shaft. These studies are not available for comparisons of VFDs and MC-ASDs and therefore exact savings potential is not estimated here.

and some can only be applied to new motors (see above). Most systems can be adapted in some way for energy efficiency.

We estimated the total potential for energy savings on detailed assumptions for each individual technology. Assumptions are based on the market forecasts as included in the AEO 2004 and the NEMS motor-module, assumptions on typical energy savings and likely market penetration by 2025. The combined potential energy savings by 2025 are estimated at just below 12% of motor energy use. This is equivalent to additional electricity savings of 67 TWh or 686 TBtu of primary energy.

Table 5.2. Energy Efficiency Estimates for Emerging Motor Technologies

Technology	Energy Savings (%)	Notes
New Motors		
Superconductor	2 to 10	Higher efficiencies at partial load
Copper Rotor	1 to 3	5% has been reported
Switched Reluctance	3	
Permanent Magnet	5 to 10	
Written Pole	3 to 4	
System & End Use Improvements		
Systems Management	17 to 25	Compressed air efficiency improvements are likely greater than pumping systems or motors
Premium lubricants	3	
Controls		
MagnaDrive	Up to 60	Savings are great compared to non-ASDs. Compared to ASDs energy savings will be less.
PAYBACK drive	Up to 60	Savings are great compared to non-ASDs. Compared to ASDs energy savings will be less.
Advanced ASDs	2	Savings are compared to conventional ASDs

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6. Advanced Cogeneration

6.1 Technology

6.1.1 Technology Description

Combined heat and power systems (CHP, also called cogeneration) 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 for non-electric energy requirements. Conventional electricity generation is inherently inefficient, converting only about one third of a fuel's potential energy into usable energy. Because CHP captures the heat that would otherwise be rejected in traditional generation of electric or mechanical energy, the total efficiency of these integrated systems is much greater than from separate systems. 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 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. New technologies, such as fuel cells, are under development, while R&D also contributes to increased efficiencies and new applications of existing cogeneration in industry.

6.1.2 Specific End-Uses and Applications

Large scale (> 10 MW). Currently, most of the installed CHP plants have capacities over 20 MW. The future potential of large-scale conventional CHP systems is estimated at 48 GW (Onsite Sycom, 2000). An increase in turbine-inlet temperature has led to increasing efficiencies in gas turbines. Industrial-sized turbines are available with efficiencies of 40 to 42% (lower heating value, LHV). The current industry "standard" is the GE LM2500 turbine with an efficiency of 34 to 40%. It is expected that the efficiencies of aero-derivative and industrial turbines can increase to 45% by 2010.

The higher inlet temperature also allows a higher outlet temperature. The fluegas of the turbine can then be used to heat a chemical reactor, if the outlet and reactor temperatures can be matched. One option is the so-called *"re-powering"* option. In this option, the furnace is not modified, but the combustion air fans in the furnace are replaced by a gas turbine. The exhaust gases still contain a considerable amount of oxygen, and can thus be used as combustion air for the furnaces. The gas turbine can deliver up to 20% of the furnace heat. The re-powering option is used by a few plants around the world. For example, two of these installations, totaling 35 MW are installed at refineries in the Netherlands.

Another option, with a larger CHP potential and associated energy savings, is *"high-temperature CHP."* In this case, the flue gases of a CHP plant are used to heat the input of a furnace. Zollar (2002) discusses various applications in the chemical and refinery industries. The study found a total potential of 44 GW additional to the conventional CHP potential in these two sectors. The major candidate processes are atmospheric distillation, coking and hydrotreating in petroleum refineries and ethylene and ammonia manufacture in the chemical industry. In 1990, GE filed a patent for the integration of a gas turbine and a steam reformer (used in ammonia manufacture) (Reay, 2002). High-temperature CHP requires replacing the existing furnaces. This is due to the fact that the radiative heat transfer from gas turbine exhaust gases is much smaller than from combustion gases, due to their lower temperature. Two different types are distinguished. The main difference is that in the first type the process feed is directly heated by exhaust gases, where the second uses thermal oil as an intermediate, leading to larger flexibility. In the first type, the exhaust heat of a gas turbine is led to a waste recovery furnace in which the process feed is heated. In the second type the exhaust heat is led to a waste heat oil heater in which thermal oil is heated. The heat content of the oil is transferred to the process feed. The second type is more reliable, because a thermal oil buffer can be included. An installation of the first type is used in Fredericia, Denmark at a Shell refinery. Here, the low temperature remaining heat is used for district heating.

Within the timeframe of this study, large-scale applications of *fuel cells* are expected to consist of parallel smaller systems, which are discussed below. In the long term, integration of industrial processes, such as reforming in the chemical and petroleum refining industries, with high-temperature solid oxide fuel cells (SOFC) is believed to lead to revolutionary design changes and allow direct co-generation of power and chemicals. However, we do not expect SOFC-integrated processes to be commercially available by 2025.

Medium scale (< 20 MW). Both in the U.S. and Europe, research aims at developing medium-scale gas turbines with high efficiencies. In Europe, the development and demonstration of a 1.4 MW gas turbine with a single cycle efficiency of 43% (LHV) is being undertaken, as part of the CAME-GT program. Current turbines of this size have efficiencies of around 25% (LHV).

Steam-injected gas turbines (STIG, or Cheng cycle) can absorb excess steam, e.g. generated due to seasonal reduced heating needs, to boost power production by injecting the steam in the turbine. Steam injection boosts the power output of the turbine. The size of typical STIGs starts around 5 MWe. Currently, over 100 STIGs are found around the world, especially in Japan, as well as in Europe and the U.S. International Power Technology (CA), for example, installed STIGs at Sunkist Growers in Ontario (CA) in 1985. Other industrial U.S. users are Frito Lay (Bakersfield, CA) and Hershey Foods (Oakdale, CA) (IPT, 2004). These systems use a 5.6 MW gas turbine.

CHP Integration allows increased use of CHP in industry by using the heat in more efficient ways. This can be done by using the heat as a process input for drying or process heating (see also above) or through tri-generation through supply of power, heating and cooling. The fluegas of a turbine can often be used directly in a drier. This option has been used successfully for the drying of minerals as well as food products. Although NOx emissions of gas turbines vary widely, tests in The Netherlands have shown that the flue gases do not affect the drying air and product quality negatively, depending on the type of gas turbine selected (Buijze, 1998). To allow continuous operation, bypass of the gas turbines makes it possible to maintain the turbine and run the drying process (Buijze, 1998). A cement plant in Rozenburg, The Netherlands, uses a standard industrial gas turbine to generate power and to dry the blast furnace slags used in cement making to replace clinker. In the food industry, an Avebe starch plant in Gasselternijveen (The Netherlands) uses a steam-injected gas turbine (STIG) installation to provide both power and heat for the plant. The gas turbine was often running at less than full load, reducing the efficiency of the turbine. Another project showed that it is more efficient to use the waste heat (i.e. flue gases) from a gas turbine directly to dry protein rich cattle feed by-product. The excess flue gas is mixed with air and used directly for the drying process. The project was expected to result in savings of 12% of total onsite fuel consumption with a simple payback period of 2.5 years (under conditions in the Netherlands in 1995) (NOVEM, 1995).

Tri-generation has been used at various commercial locations in the U.S., but less so in industry. Bassols et al. (2002) discuss various applications in food processing plants in Europe. Plants that have varying heating and refrigeration loads and that have a large refrigeration load are especially attractive, e.g. margarine and vegetable oils, dairy, vegetable and fruit processing and freezing, and meat processing. Bassols et al. (2002) discuss commercial applications varying from 4 to 9 MW capacity in The Netherlands and Spain, but do not discuss economics.

Pressure recovery turbines are an opportunity to recover power from the decompression of natural gas on industrial sites. Natural gas is transported in pipelines at a pressure of 700 psi, and large industrial facilities receive gas with pressure up to 650 psi. In the U.S. about 3.4% of the gas is used to pressurize the gas. Recovery turbines can recover part of this energy by producing power (Lehman and Worrell, 2001). The reliability of the technology has much improved since the experiments in the U.S. in the 1980s. Industrial facilities are very suitable for this technology as low-temperature waste heat is often available onsite to re-heat the gas during decompression. Many industrial sites have excess low-temperature waste heat that is currently not used due to a lack of suitable uses or due to poor economics. Lehman and Worrell (2001) estimated the technical potential in U.S. industry at 12 TWh, while the payback period depends strongly on the electricity price. With an electricity price of 10 cents/kWh the simple payback period may be as low as 3 years. The Corus iron and steel plant in IJmuiden, The Netherlands, installed a 2 MW power recovery turbine in 1994. Hot water from the hot strip mill is used to reheat the recompressed gas in the system (Lehman and Worrell, 2001).

Small scale (< 1 MW). For small scale industrial applications the major developments are found in improved designs for reciprocating engines, fuel cells, microturbines, and developments in integration of the unit in processes allowing more efficient operation (e.g. tri-generation of power, heat and cooling or drying and other direct process applications, see above). Micro-turbines and fuel cells are the most exciting developments in small-scale CHP technology.

Microturbines (25 – 500 kW) are expected to have an efficiency of 26-30% (Martin et al., 2000). Although this is lower than the efficiency of power generation in large grid-connected power plants, their use as a CHP unit can provide substantial energy savings. Martin et al. (2000) estimate the primary energy savings of a microturbine system at 17%, compared to separate power and heat production. Current development aims mainly at the commercial market, but small-scale industrial facilities may provide a potential application as well. Martin et al. (2000) estimate that up to 5% of the industrial power market by 2015 may technically be suitable for microturbine application, resulting in the power production of up to 40 TWh and 67 TBtu of primary energy savings. However, the high costs of microturbines make the technology less attractive for most industries, and only in cases of high-quality power needs (premium power), microturbines would likely be implemented.

Fuel cells generate 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, or efficiency losses associated with gas turbine technologies. Fuel to electricity conversion efficiencies can theoretically reach 80-83% for low temperature fuel cell stacks and 73-78% for high temperature stacks. In practice, efficiencies of 50-60% are achieved with hydrogen fuel cells while efficiencies of 42-65% are achievable with natural gas as a fuel (Martin et al., 2000). The main fuel cell types for industrial CHP applications are phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC). Proton exchange membrane (PEM) fuel cells are less suitable for cogeneration as they only produce hot water as byproduct. PAFC efficiencies are limited and the corrosive nature of the process reduces the economic attractiveness of the technology. Hence, MCFC and SOFC offer the most potential for industrial applications.

Although PAFC is the most sold fuel cell system, MCFC and SOFC offer the most potential. Currently, several industrial facilities use MCFCs in Japan (Kirin brewery) and Germany (Michelin rubber processing) (Hoogers, 2003). These demonstration systems still cost around $11,000/kW. Stand-alone SOFCs have achieved efficiencies of 47%, and in combination with a gas turbine in a pressurized system, efficiencies of 53% (LHV) have been achieved (Hoogers, 2003). Unfortunately, the production costs of SOFCs are still high. Dow Chemical and GM will collaborate in the installation of a large-scale proton exchange membrane fuel cell (PEMFC) system (up to 35 MW), using hydrogen produced as a byproduct from chlorine production at Freeport, Texas. It is expected that the performance of fuel cells between 100 kW and 5 MW will surpass the efficiency of engine based CHP, and that costs will also come down through improved fabrication techniques, mass production and reduced catalysts loads (in the case of PEMFC).

6.1.3 Current Status

The estimated technical potential for conventional CHP at existing manufacturing facilities is approximately 132,000 MW (Onsite, 2000). Approximately 44,000 MW of CHP-capacity is already in place at existing manufacturing facilities, leaving a remaining 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 focused on large systems (20 MW or larger) and 55% of the remaining CHP potential is in systems of this size. However, small systems represent a largely untapped market for CHP. 32% of the remaining potential is in system sizes of 4 MW or less (Onsite, 2000).

6.1.4 Research & Development Needs

Major barriers to implementation of this technology lay in the need for further research and demonstration to improve the performance, demonstrate reliability and reduce investment costs. However, policies aimed at improved acceptance and interconnection of cogeneration are also important to realize the large potential for cogeneration. The major directions for development of advanced cogeneration concepts have been outlined above. For each technology R&D is needed to commercialize the technology, to improve the performance or to bring the costs of the technology down. We summarize the main R&D needs for each of the technologies:

- High-temperature CHP: Increasing the inlet (and outlet) temperatures of gas turbines, as well as the reliability of the turbines to allow long running times.
- Medium-scale applications: STIG and integration of medium-scale turbines needs to be demonstrated at various scales and various industrial settings. Development of integrated technologies to reduce NO_x in flue gases would allow use of process-integrated applications for food industries. Pressure recovery turbines need to be demonstrated at various locations (e.g. industrial sites and power stations).
- Small-scale systems: The efficiency of micro turbines needs to be improved, and the cost brought down through improved manufacturing techniques. Fuel cell research aims at bringing down the costs through improved materials (e.g. lower catalysts needs, improved lifetime) and manufacturing processes.

6.2 Cost

6.2.1 Baseline and New Technology

The capital costs will vary by technology. Also, CHP is a modular technology, and costs are expected to come down as the volume produced increases. We base our estimates on recent studies on these technologies. Costs are expressed as specific costs, or $/kW-capacity. We include the costs of installation in the estimates. The cost estimates provide a general guideline, and will vary over time and by site. Table 6.1 provides an overview of the costs estimates.

6.2.2 Cost-Effectiveness

The cost-effectiveness of CHP will depend strongly on the price differential between electricity and fuels (mainly natural gas). This means that the cost-effectiveness will vary by region, site and over-time. Table 1 provides estimates of the simple payback period, based on an estimated electricity price of 4-5 cents/kWh and a natural gas price of

$3.4/MBtu. It should be noted that smaller industrial sites are likely to pay higher electricity prices.

Table 6.1. Cost Estimates for CHP Technologies in 2015

Technology	Investments ($/kW)	O&M ($/kWh)	Estimated simple payback period (years)	References
Small – gas turbine	915	0.008		Martin et al., 2000
Small – fuel cell	1500	0.005	> 10	Onsite, 2000
Medium- gas turbine	830	0.005	5-7	Onsite, 2000
Large – gas turbine	625	0.004	3-4	Onsite, 2000
Process	650	0.004	3-5	Onsite, 2000; Worrell et al., 1997
Pressure recovery	1300	0.008	5-8	Lehman & Worrell, 2001

Simple payback period estimates are based on an electricity price of 4-5 cents/kWh and a natural gas price of $3.4/MBtu.

6.3 Energy

6.3.1 Baseline and New Technology

In 1998, manufacturing industry consumed 20.7 Quads of fuels and 3.0 Quads of electricity, which is equivalent to a primary energy consumption of 29.6 Quads. Industry generated around 139 TWh of electricity, of which 125 TWh was generated in co-generation units (EIA, 2004). The installed CHP capacity is estimated at 44,242 MW (Onsite, 2000). Table 2 estimates the additional technical potential for cogeneration in U.S. industry at 134,470 MW of power generating capacity. Small applications (< 4 MW) represent approximately 25% of the total potential. Still, a considerable potential remains in the medium to large-scale applications, especially because of process-integrated CHP opportunities.

Table 6.2. Estimated Technical Potential for Cogeneration in U.S. Industries by Major Sectors

	Small (< 1 MW)	Traditional/ Trigen/STIG	Process-Integrated	Pressure Recovery	Total
Food	1,711	6,375	*100*	*140*	8,326
Paper & Allied	880	25,318	0	*151*	26,349
Chemical	619	8,820	9,660	*700*	19,799
Refineries	84	6,704	34,000	*260*	41,048
Minerals	0	1,924	*50*	*115*	2,089
Primary Metals	208	6,733	*50*	*241*	7,232
Other	13,935	15,056	*500*	*313*	29,804
Total	17,437	70,750	44,360	1,920	134,470

Values are given in MW. Own estimates are given in italics. Sources: Onsite, 2000; Zollar, 2002; Lehman and Worrell, 2001.

Only a part of the technical potential will be implemented by 2025. We estimate that approximately 30% of the technical potential given in Table 6.2 can be realized by 2025, additional to existing CHP-capacity. This is equal to 40.3 GW, and could potentially double the existing CHP capacity.

6.3.2 Potential Energy Savings

The primary energy savings are determined on the efficiency of the cogeneration unit used (see above), the efficiency of the boiler or other equipment replaced, and the average efficiency of electricity generation of the public grid. Martin et al. (2000) estimated the primary energy savings at 17% for micro turbine CHP applications to 33% for larger scale systems. Table 6.3 summarizes the estimated primary energy savings for each technology. Table 6.3 provides rough estimates for the potentials of the specific technologies by 2025. The total potential by 2025 is estimated at nearly 1 Quad of primary energy savings. Actual energy savings will vary by site and operational variables.

Table 6.3. Estimated Primary Energy Savings from Cogeneration in 2025

Application	Technical Potential (GW)	2025 Market Potential (MW)	Estimated Running time (hours/year)	Power generated (TWh)	Estimated Energy savings (%)	Primary energy savings (TBtu)
Small - GT	17,437	3,487	5,000	17.4	17%	30.2
Small - FC		670	5,000	3.4	33%	11.5
Medium- GT	17,407	6,615	6,000	39.7	30%	118.8
Large - GT	53,343	20,270	8,000	162.2	33%	534.1
Process	44,360	8,872	8,500	75.4	36%	270.8
Pressure recovery	1,920	385	6,200	1.4	73%	10.2
Total	134,470	40,299		299.5		975.6

Baseline power generation efficiency is 33.4%.

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7. Conclusions

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. 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.

This report focuses on the long-term potential for energy-efficiency improvement in industry. In 2002, manufacturing industry consumed 33% of the country's primary energy and was responsible for 30% of the energy-related GHG emissions in the U.S. Due to the extremely diverse character of industry, it is not possible to provide an all-encompassing discussion of technology trends and potentials. Instead we focus on a number of key technology areas: near net shape casting, membrane technology, gasification, motor systems and advanced cogeneration. Each section provides a detailed assessment on future contributions to energy efficiency improvement, economics and performance, as well as the potential development path, including potential areas for research, demonstration or other support. Each section also describes ways to model the technology in NEMS (National Energy Modeling System) to aid in further model evaluation of the selected technologies. Some of these technologies have particular applications for a specific industry (e.g. near net shape casting in the metal producing sectors and black liquor gasification in the pulp and paper industry), while others can be found in many industries (e.g. advanced motor systems, membranes and advanced cogeneration applications). Table 7.1 provides a summary of the findings of this report.

Near net shape casting enables the integration of casting and rolling, dramatically reducing the energy demand for rolling, as well as reducing material losses. Assuming that by 2025, 40% of steel is cast using advanced near net shape casting technology, this would result in estimated primary energy savings of nearly 160 TBtu, or 10% of total primary energy use in the iron and steel industry.

Membranes are key development to improve the efficiency of often very energy-intensive separations. Almost all industries use separation processes, although we focus on the food, chemical and wastewater processing industries. In the food industry we estimate energy savings of about 50 TBtu in 2025. In the chemical industry the 2025 energy savings potential is estimated at about 95 TBtu, while in wastewater treatment the savings are likely to be as high as 160 TBtu.

Development of modern *gasification* technology, most notably in the pulp and paper and petroleum refining industries would lead to enhanced energy recovery from by-products in these industries. For 2025, the likely realizable combined potential in both sectors is estimated at 45 TWh. This is equivalent to primary energy savings of 461 TBtu additional to the baseline scenario.

Motor systems are found throughout the industry, and are often inefficient. Motor system improvement is and will remain a major area for energy efficiency improvements. The combined potential energy savings by 2025 are estimated at just below 12% of motor energy use. This is equivalent to additional electricity savings of 67 TWh or 686 TBtu of primary energy.

Finally, *cogeneration* is a technology that has been used by industry for many years. Still, considerable potential remains, while new technology development and cogeneration applications will increase the potential of this technology. The total potential by 2025 is estimated at nearly 1 Quad of primary energy savings.

The report demonstrates 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 foreseeable future. The five technology areas *alone* can potentially result in total primary energy savings of just over 2,600 TBtu by 2025, or about 6.5% of total industrial energy use by 2025. Many other technologies will contribute to additional potential for energy-efficiency improvement in industry, while the technical potential of these five technologies on the long term is even larger.

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Table 7.1 Summary of 2025 Achievable Primary Energy Savings from Selected Industrial Sector Technologies.

Technology	Industrial Sector	2025 Primary Energy Use by Sub-Sector (TBtu)*	2025 Technical Potential Primary Energy Savings from Technology (TBtu)	2025 Assumed Penetration (%)	2025 Achievable Primary Energy Savings from Technology (TBtu)	Share of Industrial Sub-Sector (%)	Notes
Near net shape casting/Strip casting	Iron and Steel	1578	400	40%	160	10%	Can also be used for casting in aluminum, non-ferrous metals, and metal casting
Membranes	Food	1931	167	30%	50	3%	Can also be used in the automobile, electronics, metal finishing, mining, paper, petroleum refining, and textile industries
	Chemicals	4756	317	30%	95	2%	
	Wastewater	1020	225	70%	158	15%	
Gasification	Pulp and Paper	3433	1153	40%	461	6%	Can also be used in the food industry
	Petroleum Refining	4157					
Motor Systems	Cross-cutting	32653	2288	30%	686	2%	
Cogeneration	Cross-cutting	32653	3333	30%	1000	3%	
Total Savings	**Manufacturing**	**32653**	**7883**		**2610**	**8.0%**	
	Industry	**40980**				**6.4%**	

*Source: U.S. Energy Information Administration, 2004. *Annual Energy Outlook with Projections to 2025*. Washington, DC: EIA. DOE/EIA-0383(2004). http://www.eia.doe.gov/oiaf/aeo/

Appendix

This appendix provides information related to the possibility of modeling each of the five technologies in the U.S. Energy Information Administration's National Energy Modeling System (NEMS).

Near Net Shape Casting/Strip Casting

Strip/near net shape casting will most likely be introduced due to replacement, production expansion or construction of new plants. In NEMS, this can be achieved by modeling it as new technology.

In the **steel industry**, casting and hot rolling are modeled as separate technologies. Strip casting can be modeled by letting the UECs go to zero for hot rolling and the specific energy consumption for strip casting, respectively. This assumes that all new casters by 2025 will be strip/near net shape casters. This is a reasonable assumption as strip and long products, which can all be processed in a near net shape caster, are the majority of steel products in the U.S. steel industry. However, this is only feasible assuming active policy to further support the use of this technology in all kind of steelmills (see section 2.1.3).

NEMS does not model the casting of any of the non-ferrous metals. The **aluminum sector** includes primary smelting alone. However, a substantial amount of gas use is reported in these. It is likely that this figure may include ingot casting, which will be abolished by near net shape casting. Hence, near net shape casting may be introduced in NEMS by reducing the natural gas use and electricity use for new technology by a relatively small amount.

Other metal production and casting activities are incorporated in the NEMS sector **Metals-based Durables**. It is unclear how casting is included in the technology modeling. However, near net shape casting may be introduced by reducing the fuel and electricity UECs for new equipment, based on the share of casting energy use that can be replaced by this technology.

Membrane Technology

NEMS only models process/assembly energy use in eight energy-intensive industries. Of these, only food and kindred products and bulk chemicals have potential for application of membranes in the manufacturing process. In the **food and kindred products industry**, membranes can reduce process heating energy use by replacing evaporation and distillation processes and they can reduce process cooling requirements by replacing refrigeration. Reduced energy use for machine drives in the food processing industry can be seen when membrane use results in reduced pumping demand. In the **bulk chemical industry**, membranes will reduce energy use in the process heating when membranes are used for distillation or drying.

Energy use for water and wastewater treatment in paper manufacturing is accounted for in both the paper-making and the pulping steps of the **paper and allied products industry** in the NEMS model. Membrane use for water and wastewater treatment in all of the other industrial sectors does not appear to be explicitly included in the NEMS model.

Two types of membranes are included in NEMS. The first, the hollow fiber membrane air separation process, is considered an advanced melting/refining technology in the glass industry. The other, the novel membrane-based process for producing lactate esters, is considered an advanced synthesis technology in the chemicals and generic technologies sector.

Membranes typically have 5-year warrantees, but a properly operated facility may easily exceed 10 years (Wiesner and Chellam, 1999).

Gasification

Pulp & Paper. Kraft and chemical pulping are separate processes in the NEMS industrial module. We propose to adapt the TPCs for electricity and steam consumption of both processes for a new plant and old plant to simulate the gradual uptake of this technology. A gasifier can both be added to an existing pulp mill and to a new one. Over the next 20 years the majority of the Tomlinson boilers are expected to be replaced. Gasification is expected to penetrate earlier in chemical pulping due to the reduced sulfur loads. Based on the development plans for both the low- and high-temperature gasifiers we expect commercial application to start in 2006 for chemical pulping and 2008 for kraft pulping.

Petroleum Refining. Marano (2003) has performed a study co-funded by the Energy Information Administration on characterizing gasification to allow inclusion in the Petroleum Marketing Module (PMM) of NEMS. It may be that EIA has included gasification in the PMM for the AEO 2004 model. In that case, we propose that only the efficiency of power generation should be gradually increased to 45% by 2025, compared to 38%, as assumed by Marano (2003).

EIA has not included gasification in the PMM of the AEO 2004 NEMS model. Close collaboration with EIA is recommended to determine how NEMS can be modified to include the development and market penetration of gasification in petroleum refining.

Motor Systems

Currently, in the NEMS model, motor systems energy use is separated out of the energy use of each of the industrial sectors and motors are modeled as a separate subroutine “MOTORS.” There are five sections to this motor stock model: (1) determining the purchases of new motors and percentage of motors that are rewound for each size group within each industry; (2) determine the cost differential, energy savings and payback period for premium motors versus EPACT minimum efficiency motors; (3) estimating the fraction of premium motors and EPACT motors purchased based on the above; (4)

calculating average energy efficiency of the set of motors at year's end (including premium motors, EPACT motors, rewound motors and surviving motors); and (5) calculating the total electricity consumption of machine drive and the effects of system efficiency improvements. Systems are broken down into three types: pump systems, fan systems and compressed air systems, which are set to sum to 100%.

In addition to the premium motors now considered in NEMS, additional new motors should be considered in the model, including superconductor motors, copper rotor motors, switched reluctance motors, permanent magnet motors and written pole motors. New motors will be added by increasing both the share of "premium" motors (or eventually, if warranted, establish a new category of efficient motors in addition to premium motors) and increasing the efficiency of machine drive. Hence, the percentage of new motors purchased will increase (part of item #1, above). The efficiencies of premium motors should be increased over time (on a per year basis for the current model), to account for increased efficiency due to continuing research on the new motors. In addition, currently only motors up to 200 HP can be set to be premium motors; however, depending on the motor type, emerging motors discussed in this report can be applicable a range of motors including sizes greater than 200 HP (e.g., superconductor motors will be used for motors greater than 1000 HP). Furthermore, basing the total percentage of "premium" or high efficiency motors that are installed each year on energy efficiency and payback period alone will inevitably underestimate total high efficiency motors installed because of the following: many motors are chosen based not only on installed capital costs or energy savings potential but also on reliability or other cost factors such as long term maintenance requirements. Currently NEMS does not include an option to address these considerations for buyers.

System design optimization obviously must be included in system efficiency improvement potentials of the motor stock model (item #5, above). Likewise, controls, such as magnetically – coupled adjustable speed drives, must also be included in the system improvements section of the motor stock model. The three variables that define the system improvement efficiency savings - $PumpSavPct_{i,s}$, $FanSavPct_{i,s}$ and $CompSavPct_{i,s}$ which define motor system efficiency savings for pump systems, fan systems and compressed air systems, must all be increased to include system improvements and controls. Specific end use improvements like slowing pumps, trimming the impellers, or replacing an existing pump should be applied only to the applicable system (in these cases, $PumpSavPct_{i,s}$).

Advanced Cogeneration

The latest version of NEMS includes a cogeneration module. The module allocates steam demand to cogeneration and boilers based on technology and economic characteristics. This module is not suitable to model the potential contribution of cogeneration technologies that do not produce steam. It may not be suitable to model technologies that provide cooling or a varying heat to power-ratio (such as STIG), as it underestimates the amount of power that can be generated given a set steam demand (and allocation). Hence, changes to the NEMS model may need to be made to the:

- cogeneration module
- technology characteristics of modeled cogeneration equipment (including heat to power ratio and economics)
- individual sectors in the industrial demand module to reflect process integrated CHP opportunities and pressure recovery turbines.

Cogeneration Module: Within the cogeneration module the following "levers" are available to increase penetration of CHP: improving the profitability by decreasing the investments of the various CHP units (see below), changing the payback acceptance rate to increase the share of companies accepting a specific payback criterion, or changing the penetration rate (reflecting the annual uptake of cogeneration, currently set at 5%).

Technology Characteristics: The investment (total installed cost) can be changed to reflect a decrease in specific investments. The current costs are relatively high (Onsite, 2000), and are based on current costs. Reflecting the effects of R&D and increased penetration will lead to lower investments. The performance of the CHP units can be changed in the module by changing the power to steam ratio, allowing for increased power consumption for a given thermal output.

Industrial Module. For those sectors that have a considerable potential for alternative CHP options, i.e. chemicals, petroleum refining (see table 2), the technology characteristics, i.e. the UEC and TPC, may be changed to reflect the additional savings of the advanced CHP technologies. This approach would be valid because many of these technologies would be integrated with modeled processes, through pre-coupling of a gas turbine or use of waste heat from processes to allow pressure recovery from natural gas.