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Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry

An ENERGY STAR® Guide for Energy and Plant Managers

Ernst Worrell, Paul Blinde, Maarten Neelis, Eliane Blomen, and Eric Masanet

Environmental Energy Technologies Division

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ABSTRACT

Energy is an important cost factor in the U.S iron and steel industry. Energy efficiency improvement is an important way to reduce these costs and to increase predictable earnings, especially in times of high energy price volatility. There are a variety of opportunities available at individual plants in the U.S. iron and steel industry to reduce energy consumption in a cost-effective manner. This Energy Guide discusses energy efficiency practices and energy-efficient technologies that can be implemented at the component, process, facility, and organizational levels. A discussion of the structure, production trends, energy consumption, and greenhouse gas emissions of the iron and steel industry is provided along with a description of the major process technologies used within the industry. Next, a wide variety of energy efficiency measures are described. Many measure descriptions include expected savings in energy and energy-related costs, based on case study data from real-world applications in the steel and related industries worldwide. Typical measure payback periods and references to further information in the technical literature are also provided, when available. The information in this Energy Guide is intended to help energy and plant managers in the U.S. iron and steel industry reduce energy consumption and greenhouse gas emissions in a cost-effective manner while maintaining the quality of products manufactured. Further research on the economics of all measures–and on their applicability to different production practices–is needed to assess their cost effectiveness at individual plants.

Table of Contents

List of Figures

List of Tables

1 Introduction

As U.S. manufacturers face an increasingly competitive global business environment, they seek out opportunities to reduce production costs without negatively affecting product yield or quality. Energy efficiency technologies and practices meet this challenge and have become increasingly cost-effective in recent years due to high and uncertain energy prices. This is also true for the iron and steel industry.

Energy use is also a major source of emissions in the iron and steel industry, making energy efficiency improvements an attractive opportunity to reduce both emissions of pollutants and greenhouse gases. The global steel industry has already taken the lead on developing future low-carbon iron and steelmaking technologies. As there is global concern about the emissions of greenhouse gases and stringent climate policies are foreseen in the near future, increasing energy efficiency is an important opportunity to reduce both costs and risks associated with these policies. Energy efficiency can thus be an efficient and effective strategy to work towards the so-called "triple bottom line" that focuses on the social, economic, and environmental aspects of a business.[1] In short, energy efficiency investment is a sound business strategy in today's manufacturing environment.

Voluntary government programs aim to assist the industry to improve competitiveness through increased energy efficiency and reduced environmental impact. ENERGY STAR®, a voluntary program managed by the U.S. Environmental Protection Agency (EPA), highlights the importance of strong and strategic corporate energy management programs. ENERGY STAR® provides energy management tools and strategies for successful corporate energy management programs.

This ENERGY STAR® report aims to serve as a guide for energy managers and decision-makers to help them develop efficient and effective corporate and plant energy management programs through information on potential energy efficiency opportunities for companies within the iron and steel sector. The Energy Guide focuses on practices that are proven and currently commercially available. The energy efficiency measures described in this guide are not prescriptive, but are opportunities. Applicability, selection and realization will be determined by plant-specific circumstances.

The structure of this Energy Guide is as follows: first it describes the trends, structure and production of the iron and steel industry in the U.S. It describes the main production processes. Following, it summarizes energy use in the iron and steel industry and its main end-uses. Finally, it discusses energy efficiency opportunities.

ENERGY STAR® can be contacted through www.energystar.gov for additional energy management tools that facilitate stronger energy management practices in U.S. industry.

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[1] The concept of the "triple bottom line" was introduced by the World Business Council on Sustainable Development (WBCSD). The three aspects of the "triple bottom line" are interconnected as society depends on the economy and the economy depends on the global ecosystem, whose health represents the ultimate bottom line.

2 Industry Overview

2.1 Sector Definition

The U.S. iron and steel industry considered in this guide is defined according to the 2007 North American Industry Classification System (NAICS) as the 6-digit industrial sub-sector NAICS 331111.[2]

The iron and steel industry comprises steel mills, iron and steel foundries, and the suppliers of ferrous scrap and iron ore. Iron ore mines provide the major raw material from which iron and steel products are made. Iron and steel scrap raw materials are collected and distributed by brokers, collectors, and dealers in the ferrous scrap industry to steel mills and foundries. This sector is made up of integrated steel mills that produce pig iron from raw materials (iron ore, coke) using a blast furnace and primary steel using basic oxygen furnace (BOF), and secondary steel mills that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). Steel mills produce relatively simple steel shapes that finishing mills roll or hammer into finished products, such as bar, sheet, or structural shapes. Foundries pour molten cast iron or steel into molds to produce castings with the approximate shapes of the final products. Foundries are excluded from this Energy Guide.

Apart from the steel production process, sintering of iron ore and the making of coke are also considered in this guide, since these activities often form an integrated part of the iron and steel production process.

2.2 Production and Use

Iron

Pig iron is produced by seven companies operating integrated steel mills at 16 locations (see Appendix A). Figure 2-1 depicts pig iron production in the U.S. and apparent consumption from 1992 to 2007.[3] As can be seen from the figure, both production and consumption have decreased over the past decade. In 2007, the U.S. ranked as the fourth producer of pig iron globally with a share of 3.8% (40 Mtons or 36.3 Mtonnes) (USGS, 2009a). More than 95% of the iron made is transported in molten form to steelmaking furnaces located at the same site (USGS, 2009a).

In the past five years, DRI production in the U.S. has typically been less that 1% of pig iron production, and concentrated at one or two plants (in different points in time).

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[2] This industry comprises establishments primarily engaged in one or more of the following: (1) direct reduction of iron ore; (2) manufacturing pig iron in molten or solid form; (3) converting pig iron into steel; (4) making steel; (5) making steel and manufacturing shapes (e.g., bar, plate, rode, sheet, strip, wire); and (6) making steel and forming tube and pipe. Establishments primarily engaged in manufacturing ferroalloys or operating coke ovens are classified elsewhere.

[3] Defined as: shipments + imports – exports

Steel

There are about 116 operating steel plants in the U.S. operated by 57 companies. The locations of steel mills are depicted in Figure 2-2. Integrated mills producing both pig iron and primary steel are concentrated in the Great Lakes region, near supplies of coal and iron ore and near key customers such as the automobile manufacturers. Minimills use electric arc furnaces, do not need coal for fuel, and are less reliant on water transport than integrated steel mills. As a result, they are more widely distributed across the United States.

The largest steel-producing states are Indiana with 25% of the total, Ohio with 14%, Pennsylvania with 6% and Michigan with 5%. The distribution of steel shipments for 2008 is estimated to be from warehouses and steel service centers, 19%; construction, 16%; transportation (predominantly for automotive production), 13%; cans and containers, 3%; and other, 49% (USGS, 2009a).

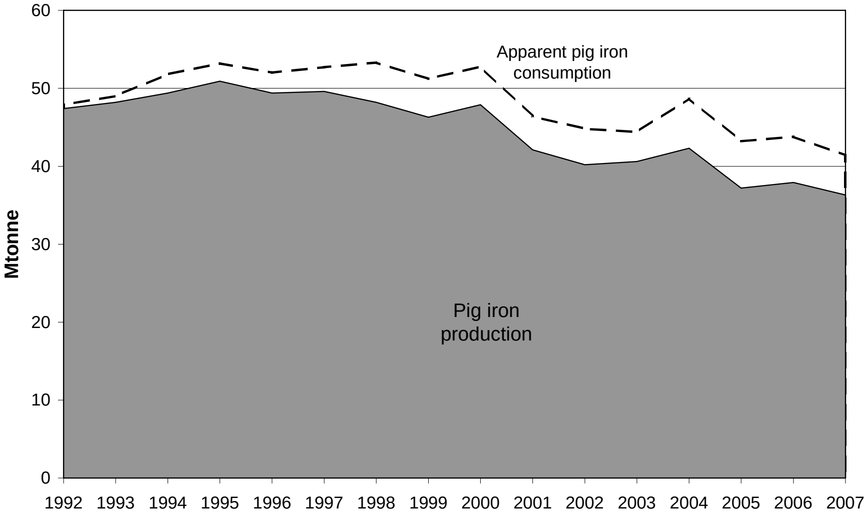

Figure 2-1. Annual U.S. pig iron production and apparent consumption from 1992 to 2007 (Source: USGS)

The iron and steel industry is undergoing a rapid process of globalization. Today, U.S. companies operate steel plants in other parts of the world (e.g. United States Steel Corporation in Europe), while transnational companies also operate facilities in the U.S (e.g. ArcelorMittal, Severstal). Within the integrated steel segment, ArcelorMittal and United States Steel Corporation are the largest, followed by Severstal and AK Steel. Within the mini-mill segment, Nucor is by far the largest company, operating 15 mini-mills across the country (AIST, 2008).

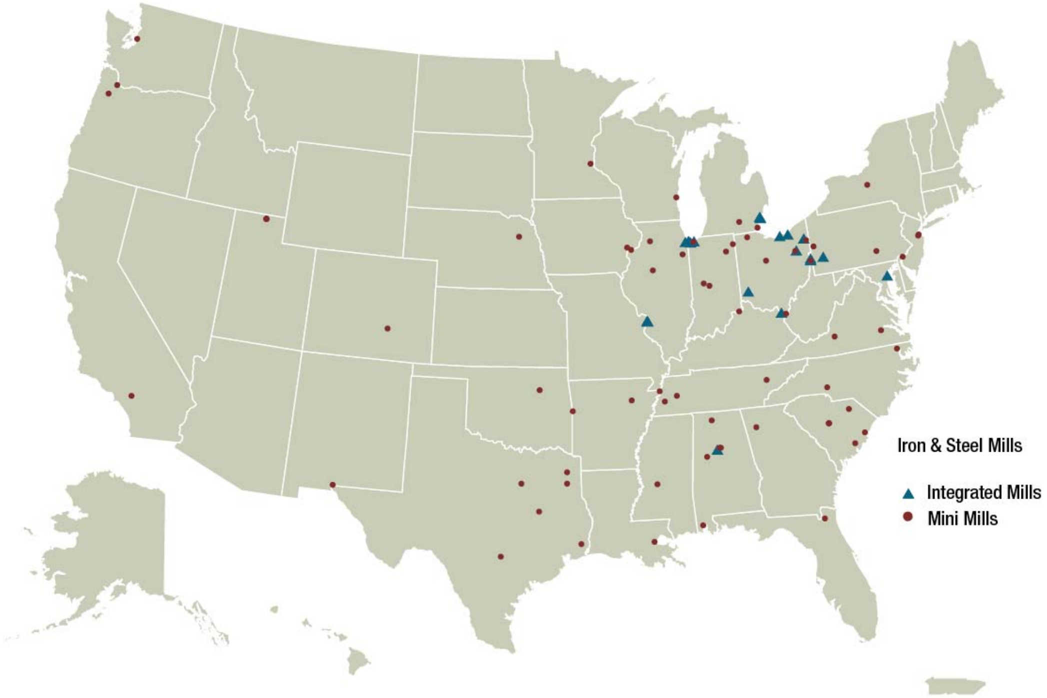

Figure 2-2: Locations of integrated mills and mini mills (Source: U.S. EPA, 2008a)

In 2007, the U.S. was the third largest steel manufacturing country in the world with a share of 7.3% (108.1 Mtons or 98.1 Mtonnes) of the world steel output (USGS, 2009a). Production represented about 87% of estimated capacity (USGS, 2009b). Apparent steel consumption was 126 Mtons (114 Mtonnes).[4] 96.7% of the raw liquid steel was cast into semi-finished products by continuous casting (USGS, 2009a). Figure 2-3 shows the annual U.S. crude steel production by process and apparent consumption from 1992 to 2007.

Figure 2-3 shows that total production increased from 92.9 Mtons (84.3 Mtonnes) in 1992 to 112.4 Mtons (102.0 Mtonnes) in 2000. In that year production declined by 11%. Total production of *primary steel* in 2007 was 62.9 Mtons (57.1 Mtonnes) constituting 58.2% or total steel production. The share of steel produced from *secondary steel mills* was 38% in 1992. This share steadily increased to 55% in 2005 after which it rapidly decreased. In 2007, the total production of secondary steel was 45.2 Mtons (41.0 Mtonnes) constituting 41.8% of total steel production.

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[4] Defined as: shipments + imports - exports –semi-finished imports ± stock changes

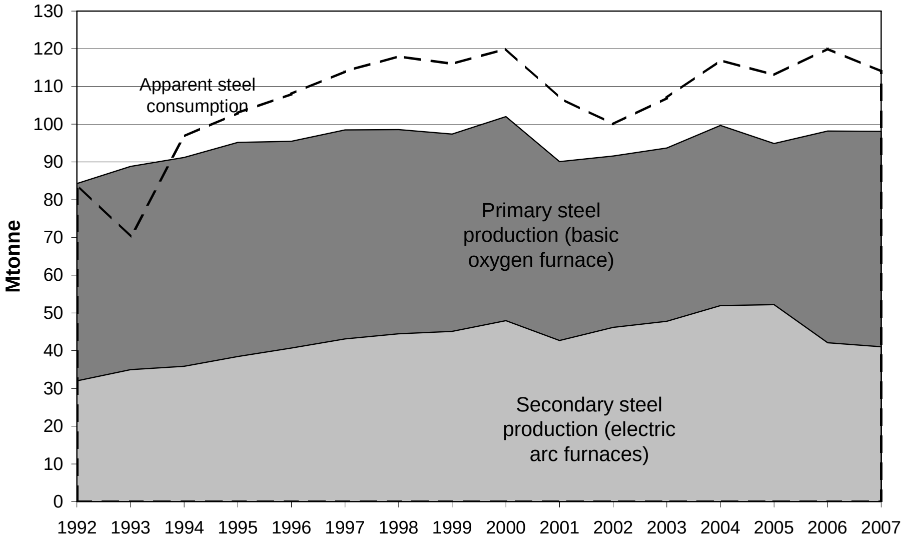

Figure 2-3. Annual U.S. crude steel production by process and apparent consumption from 1992 to 2007 (Source: USGS).

2.3 Imports and Exports

Figure 2-4 shows the annual imports and exports of pig iron. Figure 2-4 demonstrates that imports are substantially greater than exports and that imports increased over the last decade. In 2007, 5.7 Mtons (5.2 Mtonnes) of pig iron were imported and total exports were less than 0.1 Mton (0.1 Mtonne) (USGS, 2009c).

As shown in Figure 2-5, imports and exports of crude steel are much greater than those of pig iron. In 2007, the U.S. imported 33.3 Mtons (30.2 Mtonnes) of steel products, while exporting approximately 11.1 Mtons (10.1 Mtonnes). The net import reliance[5] as a percentage of apparent consumption was 16% (USGS, 2009a). The major import sources in the period 2004-2007 were Canada (16%), the European Union (16%), Mexico (10%), and China (10%) (USGS, 2009a). Taking the semi-finished steel into consideration, the share of U.S. steel market represented by imported steel was an estimated 26% in 2007 (USGS, 2009b).

Scrap is a globally traded commodity. Over the period 2000-2007 scrap exports tripled. In 2007, the U.S. was the world's largest exporter of scrap with 18.1 Mtons (16.5 Mtonnes) of exported scrap. Scrap imports in that year were 4.1 Mtons (3.7 Mtonnes) (USGS, 2008).

DRI import has been around 1.1 Mton (1.0 Mtonne) from 1993 to 2000. After a rapid increase and some fluctuations, the DRI import was 2.5 Mtons (2.3 Mtonnes) in 2007. DRI export has been zero from 2005 to 2007.

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[5] Defined as: imports – exports + adjustments for Government and industry stock changes

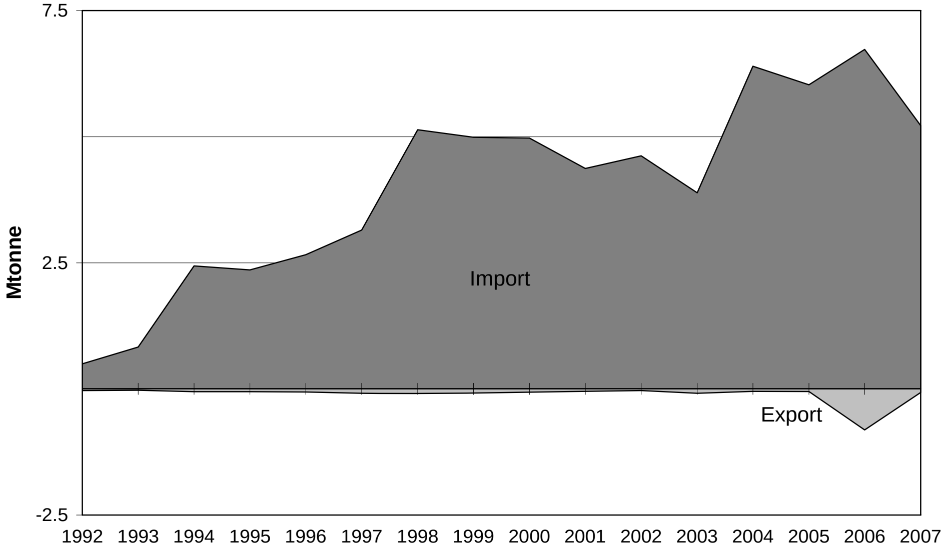

Figure 2-4. Annual imports and exports of pig iron from 1992 to 2007 (Source: USGS)

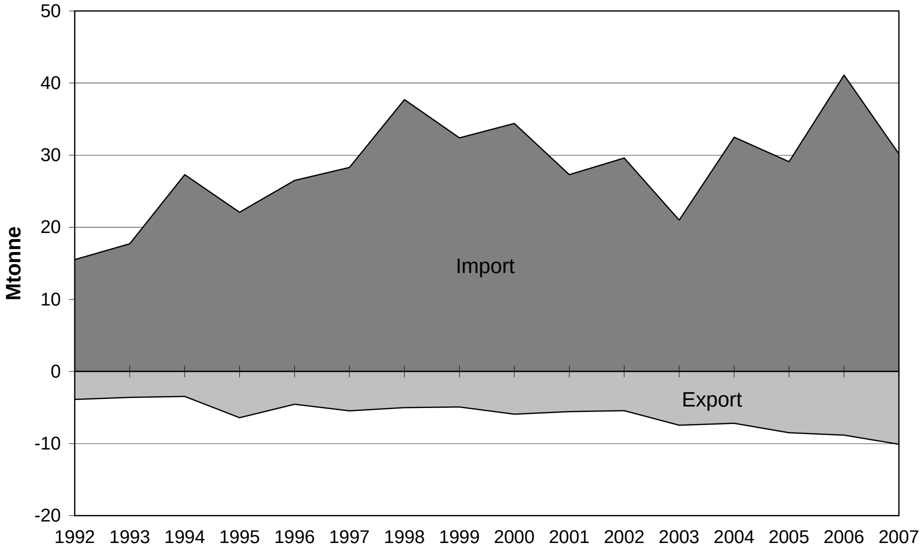

Figure 2-5. Annual imports and exports of crude steel from 1992 to 2007 (Source: USGS)

2.4 Economic Trends

The iron and steel industry and ferrous foundries produced goods in 2008 that were valued at about $117 billion (USGS, 2009a). Figure 2-6 depicts the value of shipments added value together with the unit value of a tonne of steel in 2000 dollars in the U.S. iron and steel industry from 1997 to 2007. Despite a quite constant steel production volume over the last decade, the value of shipments increased from close to $60 billion in 1997 to about $85 billion in 2006 due to a worldwide increase in commodity prices observed after 2003.

The producer price index as calculated by the U.S. Department of Labor for steel mill products climbed from 107 in 2003 to 183 in 2006 (1982 = 100). Value added increased less than the value of shipments since energy prices also increased in the same period. As a result of constant improvements in productivity, the number of employees decreased by a third over the last decade. In 2007, blast furnaces and steel mills provided about 121,000 jobs (USGS, 2009a). The largest iron producers are by far ArcelorMittal Steel and United States Steel Corporation, accounting for 47% and 39% of total U.S. production in 2006 (USGS, 2009a; I&ST, 2007) (see Appendix A).

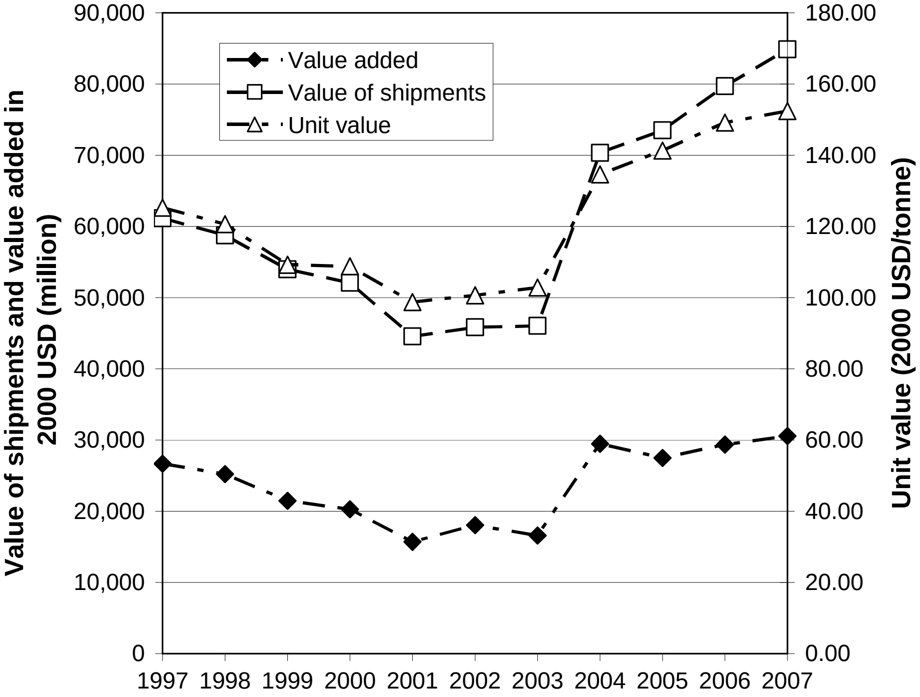

Figure 2-6. Value of shipments and added value in USD (2000) of the U.S. iron and steel industry from 1997 to 2007. (Data sources: U.S. Census, USGS).

Dramatically increasing global demand, company consolidations that decreased competition, and a weakening dollar, combined to cause a tripling of steel prices (Fletcher, 2008). However, by late 2007, domestic demand for steel had decreased because of the weakening housing construction and automobile markets, and steel inventories were low, which caused U.S. steel prices to decline below those in Europe and China. Exporting steel products became attractive for U.S. producers, and U.S. steel mills responded by adding capacity and employees (USGS, 2009a).

Soaring demand for steel products and ferrous raw materials in China and other countries caused record price increases and profits for steelmakers and raw material suppliers during 2008. The global economy entered a recession at the end of 2008 that has been characterized by major problems in the commodity, credit, and financial sectors, adversely affected key markets of the steel industry, e.g. automotive, construction, and industrial equipment. Reduced consumption of steel led to rapidly declining steel prices, prompting steelmakers in Asia, Europe, and North America to slash output, delay mill-expansion plans, and furlough workers. In the U.S. several furnaces were idled, and steel production declined sharply in the last quarters of 2008. Before the end of 2008, the world's leading iron ore miners saw spot iron ore prices fall as global steel output declined. The world's leading iron ore producer announced cuts in iron-ore pellet production in Brazil by 65%, while the world's third-leading iron ore exporter also planned to cut production (USGS, 2009b).

In addition, the coking coal market began to deteriorate before year end 2008. The world's largest steel producer by volume of production announced plans to reduce production in North America by 35% and in Europe by 30%. China's steelmakers are expected to collectively decrease active production capacity by 20% in 2009. A general economic recovery was not anticipated until at least the latter part of 2009, and U.S. steel production and revenues were likely to decline in 2009 (USGS, 2009b). Due to increasing demand from Asia, global and U.S. steel production has started to recover in 2010.

3 Production Processes

The U.S. iron and steel industry produces a variety of products such as slabs, ingots to thin sheets. Figure 3-1 presents a simplified scheme of the production routes. Only two main methods are used in the production of crude steel (see Figure 3-1):

- Primary: blast furnace (BF)/basic oxygen furnace process (BOF) using primarily iron ore
- Secondary: electric arc furnace (EAF) process using primarily scrap

These two production routes are expected to remain the mainstay of steel production for years to come (Fruehan *et al.*, 2005). Other processes do however exist, most notably the production of direct reduced iron (DRI). DRI is produced by reduction of the ores below the melting point in relatively small scale plants (< 1 Mton/year) and has different properties than pig iron. It serves as a high quality alternative for scrap in secondary steelmaking. The process is not considered here since its operation in the U.S. is negligibly small, i.e. 0.51 Mtonnes in 2008 (Midrex, 2009). In the following, different steps in the two production routes will be discussed.

3.1 Treatment of Ore and Recycled Ferrous Materials

Iron ores rocks and minerals from which metallic iron can be economically extracted are found in diverse locations. The iron itself is either found in the form of hematite (Fe_2O_3) or magnetite (Fe_3O_4) and the iron content ranges from 25% to 65%. The treatment of ores starts with the removal of earth and the sizing of the ore into pieces that range from 0.5 to 1.5 inches. Iron rich ore can be charged directly into a blast furnace without any further processing. Iron ore that has lower iron content is first processed to increase its iron content (AISI, 2008a). This can be done either by sintering or by pelletizing. Pelletizing is the primary ore agglomeration technology, but normally takes place at the mine site. It is therefore not considered as part of the iron and steel industry according to the NAICS classification and hence excluded from this Guide. In the U.S., the average pellet-to-sinter ratio is about 6 to 1 (Stubbles, 2000), but this varies significantly from plant-to-plant, as not all integrated steel works in the USA operate sinter plants.

Sinter Plant. The purpose of the sinter plant is to sinter fine ore particles and ferrous revert materials together into a porous clinker. Sintering of fine ore particles is required to improve the permeability of the burden in the blast furnace and to make it easier to reduce. The sinter process starts with blending of different ores and ferrous revert materials, such as flue dust. Coke breeze is usually used as fuel and is mixed with the blended ores. The sinter strand is a large travelling gate upon which the sinter feed is deposited. The coke in the upper layer is ignited by gas burners. While the grate moves forward, air is drawn through the sinter feed by fans causing the combustion to proceed through the entire sinter feed layer. Temperatures are 2370-2700°F (1300-1480°C). At the end of the strand, sinter is cooled in the sinter cooler by air.

Pellet Plant. In a pellet plant, iron ore and additives are agglomerated into small crystallized balls with a size of 0.4-0.6 in (10-16 mm). The process starts with upgrading of the ore with crushing and grinding as intermediate steps. Then, so-called green balls are formed in the balling drum. Green balls are heated in a grate kiln and cooled. This process is known as **induration**. At the end of the process the balls contain 60% to 65% iron.

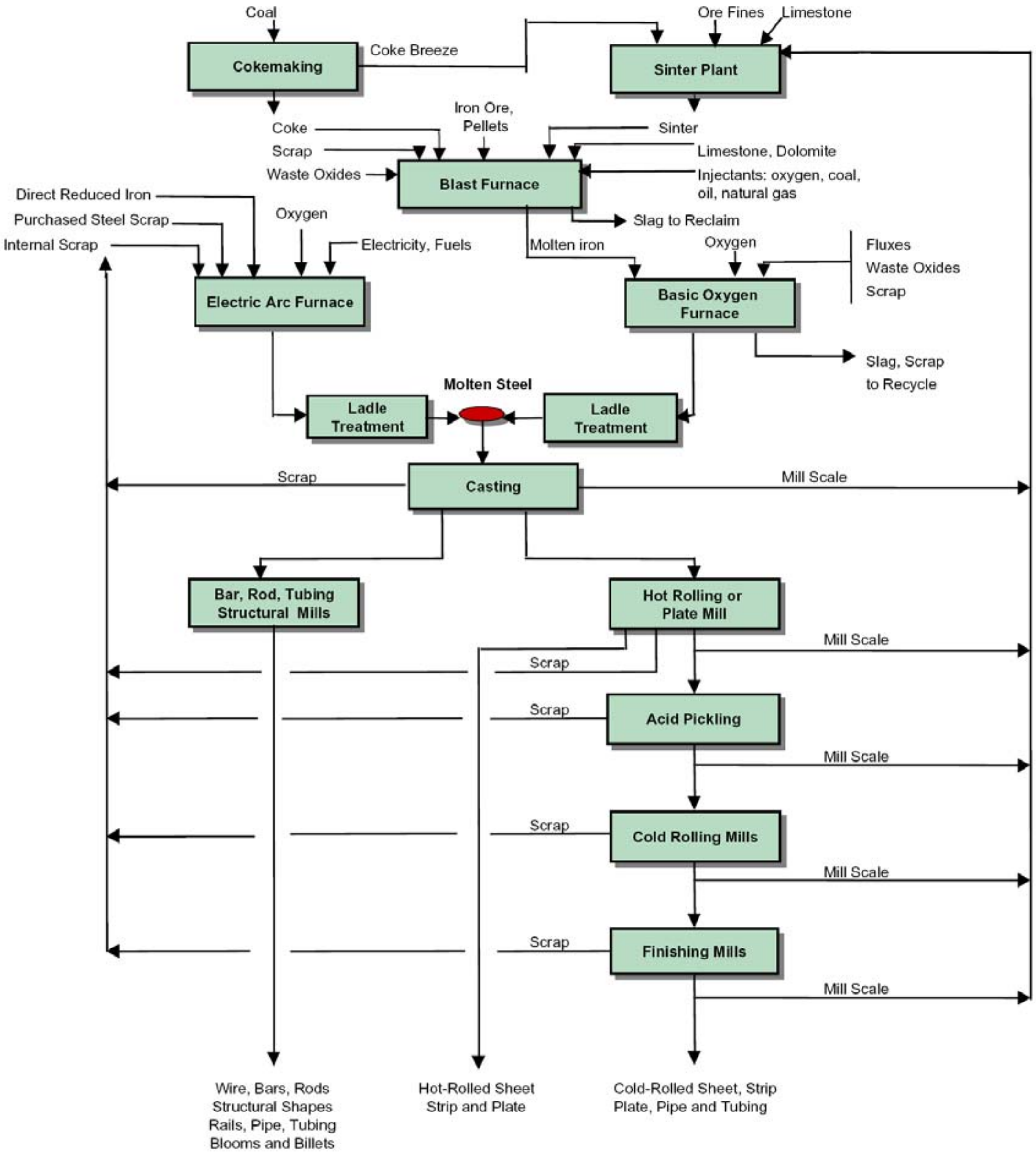

Figure 3-1. Simplified scheme of iron and steel production routes (Source: U.S. DOE, 2003)

3.2 Coke making

Coke is used in the blast furnace for two functions:

- chemical reductant in the reduction of iron ore to iron,
- strong and permeable support to allow a free flow of gases through the furnace.

The latter function is the key reason for using coke rather than coal or another reductant. Coke is stronger and retains its strength even at high temperatures, whereas coal tends to soften at elevated temperatures, thereby reducing its permeability.

Bituminous, or coking coal, is blended and crushed before being charged to a coke oven via a coal tower. Coke ovens are assembled in batteries and have a typical capacity of 33 ton (30 tonne) of coal. The coke ovens are separated by heating flues. In a coke oven, coal is heated to 1830-2010°F (1000-1100°C) for 14-24 hours in the absence of air (to prevent combustion) to remove the volatile matter.

The volatile matter and moisture that are driven off during the coking process are collected, dried and cleaned (e.g. sulfur, tar and other compounds are removed and either sold or disposed of properly). The resulting coke oven gas is used as a fuel, flared or sold. Approximately 360 Nm^3 coke oven gas is formed (3.25 Nm^3 per tonne of coal) per ton of coal (IPCC, 2008), with a calorific value of about 16-17 $kBtu/Nm^3$ (19-20 MJ/Nm^3) (Spakman et al., 1997). However it should be noted that coke yield and coke oven gas production and composition depend to a large extent on coal consumption and coking time.

3.3 Iron Production

In a blast furnace, iron oxides are reduced and the resulting iron is melted. Iron oxides enter the blast furnace plant in the form of raw ore, pellets or sinter. The mixture between these three varies considerably from plant to plant. The product of the blast furnace, pig iron, is molten iron containing 3-4% of carbon and some other impurities. There are three basic components of a blast furnace: cold blast blowers, hot blast stoves, and the blast furnace itself. All are described below.

Cold Blast Blowers. Blowers compress cold air that later is heated by hot stoves to provide a hot blast. A hot blast is needed to transfer heat to the solid burden in order to raise the temperature for reaction. The blast also helps to provide the oxygen necessary for coke gasification. The pressure is required to overcome the resistance of the burden and is generally on the order of 29-73 psi (3-5 bar). The pressure drop over the furnace is 15-29 psi (1-2 bar), so the top gas has still a pressure of 29-44 psi (2-3 bar). The blower can be driven by a steam turbine or an electric motor.

Hot Blast Stoves. The cold compressed air from the cold blast blowers is heated by hot blast stoves. Hot blast stoves are dome-topped cylinders made of brick. Hot blast stoves operate on a cyclical basis. They are heated up by burning gases until the dome is at the correct temperature (2010-2730°F or 1100-1500°C). Combustion gas is then cut off and cold ambient air is forced through the stoves in the reverse direction. The cold air is heated by the hot bricks and thus forms the hot blast (1650-2460°F or 900-1350°C), which is fed to the blast furnace. The process continues until the stove can no longer generate the proper blast gas temperature, after which the initial heating cycle is started again.

Blast furnace. The blast furnace is a shaft furnace that is charged from the top with a mixture of ore, sinter or pellets, coke and lime (to remove impurities and as a fluxing agent). Hot compressed air – blast - is injected through tuyères at the lower part of the furnace. Auxiliary fuels are injected from the bottom. Over the past decade there has been a significant reduction in the coke consumption in the blast furnace, due to increased injection of fossil fuels – pulverized coal, oil and gas. However, fossil fuels cannot serve as a strong and permeable support. Therefore, as long as blast furnace technology is used, coke will remain necessary.

Different zones can be discerned in a blast furnace. The hottest zone is at the bottom, where coke is gasified providing the heat and the high temperature required for chemical reactions. Hot gases ascend, and carbon dioxide can react with coke according to the Boudouard reaction to form carbon monoxide. The temperature of the gas decreases with height because heat is exchanged with the coke bed and with molten materials coming down, and because of the endothermic Boudouard reaction and the direct reduction of molten iron oxide.

Molten iron trickles down and collects in a well at the base of the furnace. Although the melting point of iron is 1530°C (2790°F), a pasty, porous mass is already formed at 1200°C, which is related to the fact that carbon is dissolved. Impurities are removed by reaction with calcium oxide, and a slag is formed. The molten slag floats on the molten iron. Silica that does not react with calcium oxide is reduced by carbon, increasing energy consumption.

The blast furnace produces also a low calorific gas, blast furnace gas (~3 MJ/Nm^3 (LHV) or 90 kBtu/ft^3 (HHV)), at a rate of about 1200 to 2000 Nm^3 per tonne (1300 to 2200 Nm^3 per ton) of pig iron (IPPC, 2001). After cleaning, blast furnace gas can be used as a fuel. Usually it is enriched with coke oven gas or natural gas. The smallest blast furnaces have a capacity of 550 ktonne (550 kton) pig iron per year. However, state-of-the-art blast furnaces around the world have a pig iron production of 2-4 Mtonne (2.2-4.4 Mton) per year.

3.4 Steel Production – Primary

After producing iron, the steelmaking process takes place in a basic oxygen furnace (BOF). The objective of the BOF is to adjust the composition of the hot metal so that:

- concentration of carbon is reduced from approximately 4-5% in pig iron to - depending on the type of steel produced - less or far less than 1%;
- undesirable impurities are removed (by the slag);
- concentration of desirable elements is brought to product specifications.

These objectives are achieved by blowing pure oxygen through a water-cooled lance or submerged tuyères in a pear-shaped refractory-lined vessel filled with hot, liquid iron. Such a vessel typically has a capacity of 100 to 300 tonnes (110-330 tons) and is insulated to reduce temperature loss to about 100-150°C (210-300°F). The oxygen is produced in a separate plant, usually applying air liquefaction. About 55 Nm^3 of oxygen is required per tonne (50 Nm^3 per tonne) of liquid steel. Nitrogen, also a product of air liquefaction, can be used for bottom stirring to increase the reaction speed in the vessel.

The oxidation of carbon (and some impurities, notably silicon) is a highly exothermic reaction. The temperature in the basic oxygen furnace normally is about (2910-3000°F or 1600-1650°C) and depends on the scrap input. Scrap, or scrap substitutes, e.g. DRI, are added to prevent uncontrollable temperature rise. The scrap should meet purity requirements. The hot metal ratio, the ratio of liquid pig iron input and steel output, ranges from 65 to 90%. Limestone is added to dissolve impurities and form a slag. This slag is often used in road construction. During the process a gas is formed containing large amounts of carbon monoxide (CO).

Each cycle from charging to tapping requires about 30-40 minutes of which about 50% is blowing time. After the oxidation cycle is completed the liquid steel is tapped into ladles by tilting the vessel. In the ladles, a series of secondary metallurgy operations can be performed. Other secondary metallurgy operations can take place in a vacuum facility, a ladle furnace, a tundish of a continuous caster, and in some cases in the BOF or EAF (see next section) during steelmaking. The main target of these operations is the conditioning of the liquid steel to achieve a homogenous chemical composition, an exact casting temperature and a proper steel purity level. A review of secondary metallurgy operations can be found in Fandrich *et al.* (2008).

Although basic oxygen steelmaking is considered an autogenous process, it is not a zero-energy process. The installation of ladle furnaces and vacuum degassers increases energy consumption in BOF shops. The lime and oxygen used also require energy for their production, and the energy needed to operate facilities such as baghouses, cranes, ladle preheaters, torches, and tundish driers must be considered. However, this additional energy consumption is minor in comparison with the energy associated with production of the hot metal.

3.5 Steel Production – Secondary

In an electric arc furnace (EAF) steel is melted via electric arcs between a cathode and one (for DC) or three (for AC) anodes. The anodes can be placed just above the bath or be submerged in it. The electrodes are made of carbon and are consumed during operations.

The traditional and main charge for EAFs is scrap, which is in large supply in the U.S.. In addition, manufactured iron units (DRI, pig iron, iron carbide) are good to excellent scrap substitutes. The iron units are loaded in a basket together with limestone – for slag formation – and charged into the furnace. Oxygen can be injected to promote metallurgical reactions, notably the oxidation of carbon present in the charge. Coal powder can also be added to promote slag foaming through CO formation and oxy-fuel burners may be used.

Higher value added processes require better control of the chemical composition of steels. Chemical composition control improvements of the raw materials used have been achieved through screening and sorting of scraps or through the inclusion of primary iron into the EAF, such as molten or solid pig iron from the coke-BF-BOF route, DRI and iron carbide.

Once the whole EAF process is completed, the liquid steel is tapped into ladles. As in BOF steelmaking, various secondary metallurgy operations can be performed at this time.

3.6 Casting

The next process in steel production is casting, which results in a series of semi-finished steel products such as slabs, blooms or billets. In 2008, 97.1% of all steel in the U.S. was cast continuously; compared to 96.3% in 2006 (USGS, 2009). The remaining share is finished through ingot casting, mostly used for specialty products. The cast material is sold to steel manufacturing industries or further processed on site.

With the trend of a higher integration of the downstream transformation, new technologies are being adopted towards a near net-shape production. These include thick slab casting for thick plates, direct strip casting for sheets, and rod casting. The general idea behind these processes is to go from the molten metal directly to the desired shape with the desired mechanical properties and geometric tolerances with less or even without intermediate processing, thus saving energy and increasing productivity.

3.7 Shaping

Most steel products from the casting operations are further processed to produce finished steel products in a series of rolling and finishing operations. It is beyond the scope of this study to outline all operations and products in detail. Instead, two common shaping processes, hot-rolling and cold-rolling, are discussed below

Hot-rolling. Slabs are reduced in thickness in a hot strip mill. A hot strip mill consists of a reheating furnace that brings the slabs to the correct temperature for rolling, and rolling mills. Slabs can be charged hot directly, after temperature normalization, from the continuous caster. However, a considerable share of the slabs are first cooled and stored before being milled or scarfed. Rolling normally takes place in two steps. First, slab thickness is reduced from 6.9 to 10.6 inches (150-270 mm) to 0.8-3.1 inches (20-80 mm) in the roughing mill. Next, a further reduction to 0.04-1.1 inches (1-30 mm) is achieved in the finishing mill. The product is coiled and sold or sent to the cold mill for further processing.

Cold-rolling. Cold mills produce rolled sheet 0.014-0.071 inches (0.35-1.8 mm) or tinplate 0.006-0.012 inches (0.15-0.3 mm) for a variety of uses, e.g. for car bodies to tin cans. This is done by reducing hot rolled coil in thickness. The process begins with the removal of a thin film of iron oxide by a warm acid bath. The strip is then immediately cold rolled in the tandem mill before further oxidation can take place. To make the cold rolled steel soft and malleable it is annealed, which involves heating to about 1300°F (700°C) followed by slow cooling. After annealing a number of operations can be carried out such as pickling to improve metallurgical properties or to obtain the correct steel specifications for downstream processing.

4 Energy Use

The iron and steel industry is the fourth largest energy-consuming industry in the U.S. after the petroleum and coal industry, the chemical industry, and the paper industry. In 2006 the iron and steel industry consumed a total of 1,390 TBtu primary energy (1470 PJ) or an estimated 5.2% of the total energy consumed in the whole U.S. manufacturing sector (U.S. EIA MECS, 2010).

4.1 Break-down of Energy Use by Fuel

Figure 4-1 shows the breakdown of final energy usage by fuel in the iron and steel industry in 2002. While the share of electricity in final energy consumption was 13%, it accounted for roughly 33% of primary energy use, depending on the way that electricity was generated.[6]

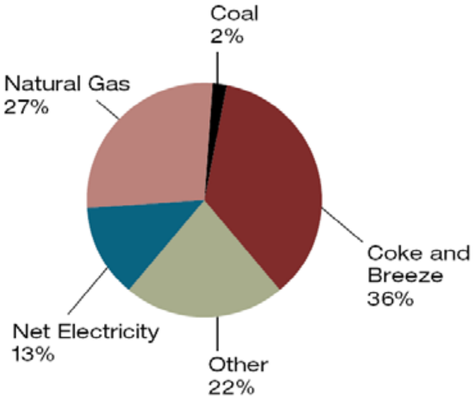

Figure 4-1. Fuel use for energy. Other is net steam (the sum of purchases, generation from renewables, and net transfers), and other energy that respondents indicated was used to produce heat and power. Net electricity is an estimate of (final) purchased power and power generation onsite (Source: U.S. EPA 2008a, 2002 data).

4.2 Break-down of Energy Use by Process

Table 4-1 shows fuel consumption, electricity consumption, and net primary energy use by process for the main steel making processes. Average values are given between brackets. All values were obtained from IISI (1998) who investigated the energy consumption of multiple plants.

From the table it can be seen that integrated primary steel making route is more energy intensive than that of the secondary steel making due to the fact that coke has to be produced as a fuel and that iron ores have to be reduced to molten iron. Electric arc furnaces use steel scraps and therefore do not need energy for the reduction of iron ore to iron.

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[6] Final energy is defined as the purchased energy at the "gate". Primary energy includes the fuels and energy needed to produce the purchased power, by converting purchased electricity with the average power generating efficiency of the U.S. public grid.

Table 4-1. Energy use by process; energy use due to fuel consumption, electricity consumption, and net primary energy use; average value is given in parentheses (IISI, 1998)[7].

	Fuel (MBtu/ton product)	Electricity (final) (kWh/ton product)	Primary (net) (MBtu/ton product)
Sinter	1.4 - 1.6 (1.4)	28-20 (26)	1.4 - 1.6 (1.6)
Coke	2.8 - 3.0 (2.8)	33- 38 (36)	3.1 - 4.4
Hot stove	1.4 - 1.7(1.5)	-	1.4 - 1.7 (1.5)
Blast Furnace	9.9 - 10.4 (10.0)	-	9.9 - 10.4 (10.0)
BOF	0.7 - 1.0 (0.8)	13-38 (23)	0.06 - 0.5 (0.3)
EAF	0.2 - 0.8 (0.4)	304 - 525 (401)	3.2 - 5.2 (3.9)
Continuous Casting	0.02 - 0.06 (0.04)	5.4 – 13 (8)	0.10 – 0.15 (0.12)
Reheating furnace	0.7 - 1.4 (1.1)	2 - 10 (6)	0.7 - 1.4 (1.1)
Hot strip mill	0.01	90-152 (121)	0.6 - 1.2 (0.8)

4.3 Break-down of Energy Use by End-Use

Figure 4-2 shows a breakdown of the final energy end-use. Fired heaters (excluding boilers), particularly the blast furnace and other furnaces, represent the bulk of the energy use (81%). Boilers use another 7% of total energy use. Motor systems, which include motor driven units such as rolling mills, pumps, conveyors, fans, and materials handling equipment, consume another 7% of steel industry energy use. Heating, cooling, and lighting of facilities accounts for just 3% (U.S. DOE, 2004).

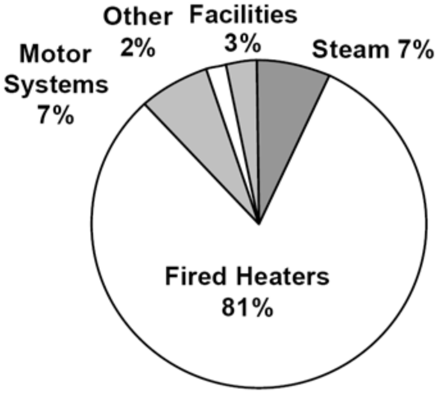

Figure 4-2. Final energy end-use in the iron and steel industry (Source: U.S. DOE 2004)

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[7] 1.00 MBtu/ton is about 1.16 GJ/tonne, 1.00 kWh/ton is about 1.10 kWh/tonne

Figure 4-3, which is based on the overall industry primary energy use, illustrates the general flow of energy and losses within the average steel mill. As the figure shows, nearly one-quarter of the energy that enters the plant (23%) is lost prior to use in process units. These losses occur in equipment and distribution systems supplying energy to process operations or converting energy to usable work. The majority of onsite losses in the iron and steel industry occur in energy conversion systems (U.S. DOE, 2004). Offsite losses due to the generation of electricity were close to 18% of the industry primary energy use in what year? (U.S. DOE, 2004).

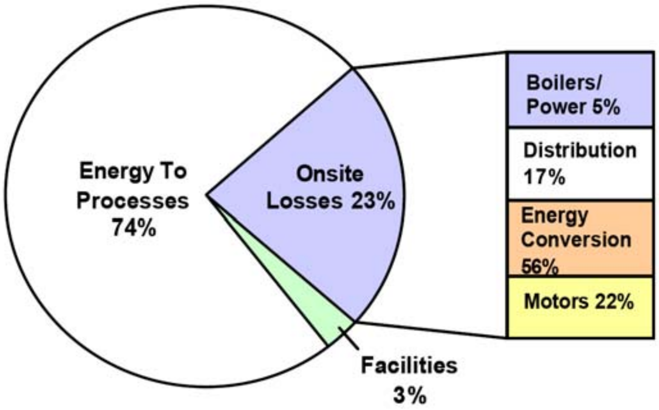

Figure 4-3. Onsite energy loss profile for the iron and steel industry (Source: U.S. DOE 2004)

A profile of the iron and steel industry's fired systems and cooling use and losses is depicted in Figure 4-4. As can be seen, about 18% of energy inputs are lost due to system inefficiencies. The losses occur in equipment and distribution systems supplying energy to process operations or converting energy to usable work. Losses can vary between facilities, as they are dependent on plant configurations, the effectiveness of the integration of heat sources and sinks, and operating and maintenance practices (U.S. DOE, 2004).

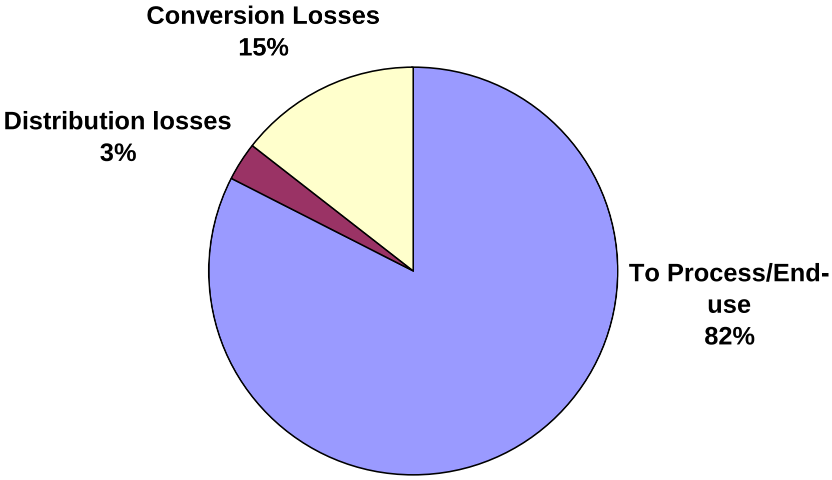

Figure 4-4. Use and loss profile of fired systems and cooling in the U.S. iron and steel industry (Source: U.S. DOE, 2004)

Steam represents up to 10% of all energy used in an integrated mill (U.S. DOE-OIT, 2001a). Eleven percent of the steam generated in the U.S. iron and steel industry is produced in combined heat and power (CHP) systems and the remainder is produced in boiler systems (U.S. DOE-ITP 2008a). A profile of the U.S. iron and steel industry's steam use and losses is provided in Figure 4-5, which shows that about 44% of energy inputs are lost due to system inefficiencies. Most of these losses occur in the boiler, where thermal efficiencies range between 55-85%, depending upon the age of the boiler and fuel type burned. Distribution losses occur in steam traps, valves, and pipes carrying steam to processes and energy conversion units. As stated above, the losses vary widely between facilities, as they are highly dependent on plant configurations, the effectiveness of the integration of heat sources and sinks, and operating and maintenance practices (U.S. DOE, 2004).

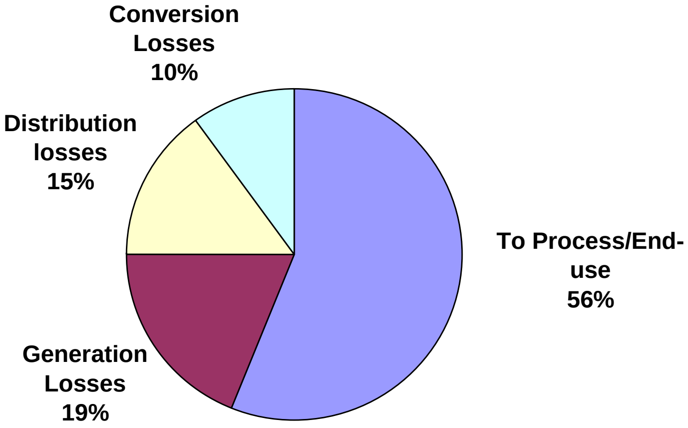

Figure 4-5. Use and loss profile of steam systems in the U.S. iron and steel industry (Source: U.S. DOE, 2004)

A profile of the energy use and losses for motor systems in the U.S. iron and steel industry is shown in Figure 4-6. Energy use and loss profile of motor systems in the U.S. iron and steel industry (Source: U.S. DOE 2004) indicating that about 70% of the energy input to motor-driven systems is lost due to system inefficiencies.

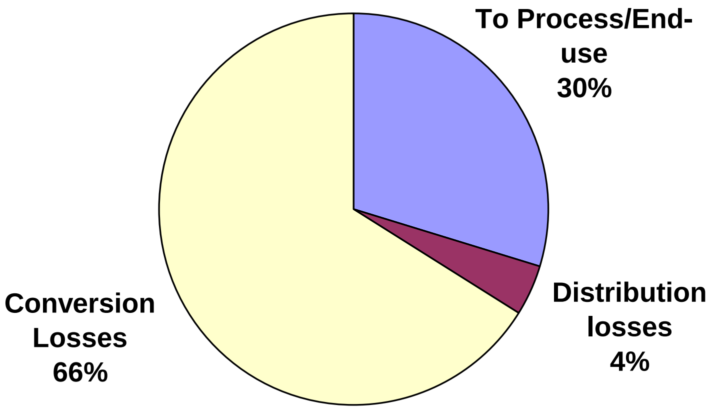

Figure 4-6. Energy use and loss profile of motor systems in the U.S. iron and steel industry (Source: U.S. DOE 2004)

A more detailed breakdown of the energy use and losses for motor systems is depicted in Figure 4-7. The figure shows that compressed air systems and materials processing (e.g., grinding, mixing, crushing) account for the largest losses.

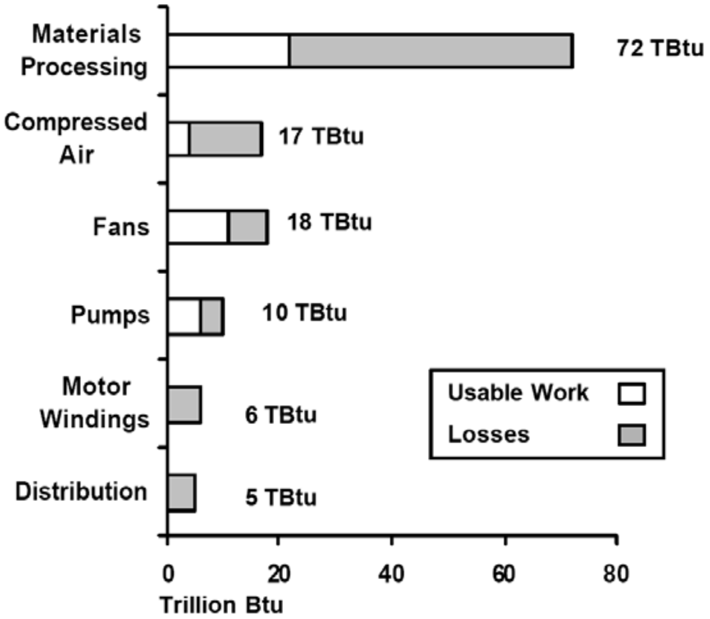

Figure 4-7. Breakdown of motor systems energy use and loss in the U.S. iron and steel industry (Source: U.S. DOE 2004).

4.4 Trends in Energy Intensity

According to the American Iron and Steel Institute (AISI), the energy intensity of the U.S. steel industry has been reduced by more than 60% in the last two-and-a-half decades (see figure 4-8). This decrease can mostly be attributed to an increase in the share of EAF production, and more scrap use in BOFs (WSA, 2008). Energy efficiency improvement also played a role, which was primarily due to a move to almost 100% continuous casting in this time period, as well as efficiency improvements as new EAFs were build (Worrell and Biermans, 2005).

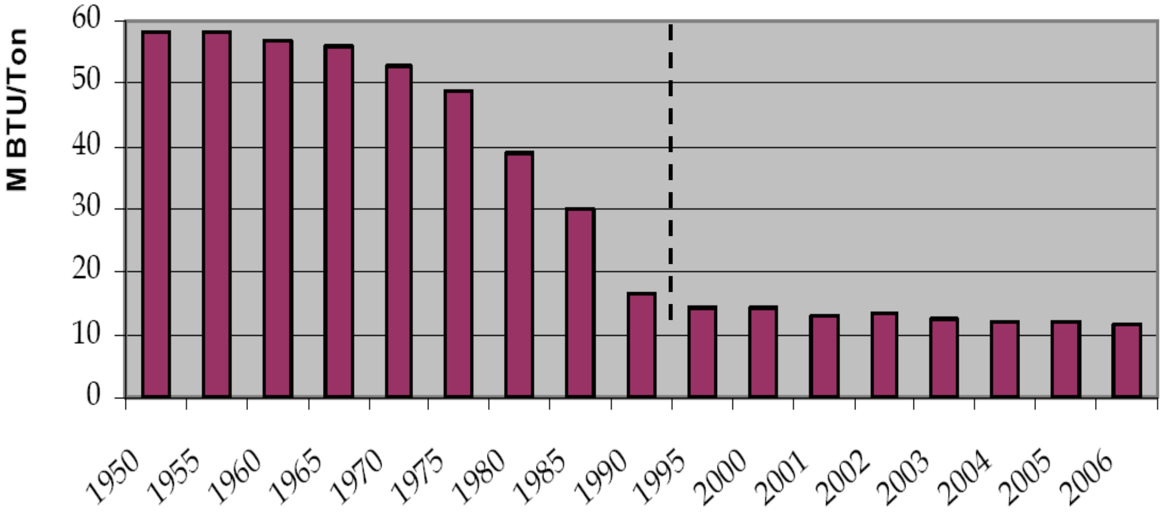

Figure 4-8. Final energy consumption per ton steel shipped in the U.S. steel industry. The dashed black line indicates a transition in the timescale between subsequent data points. (Source: WSA, 2008)

Figure 4-9 shows a breakdown of the final energy consumption by fuel type from 1958 to 2002. A number of clear trends can be identified. The use of oil in iron and steel mills decreased. The consumption of natural gas generally showed a decreasing trend. The major decrease in energy use over the last decades was due to decreased consumption of coal and coke. This decrease can mainly be explained by an increase in the production of secondary steel for which electricity is the main source of energy. The demand for electricity in the iron and steel industry did not, however, experience a significant increase, mostly as a result of more efficient EAFs with a lower consumption of electricity per ton of steel produced. As mentioned earlier, in terms of primary energy, electricity represents a larger share of the energy use.

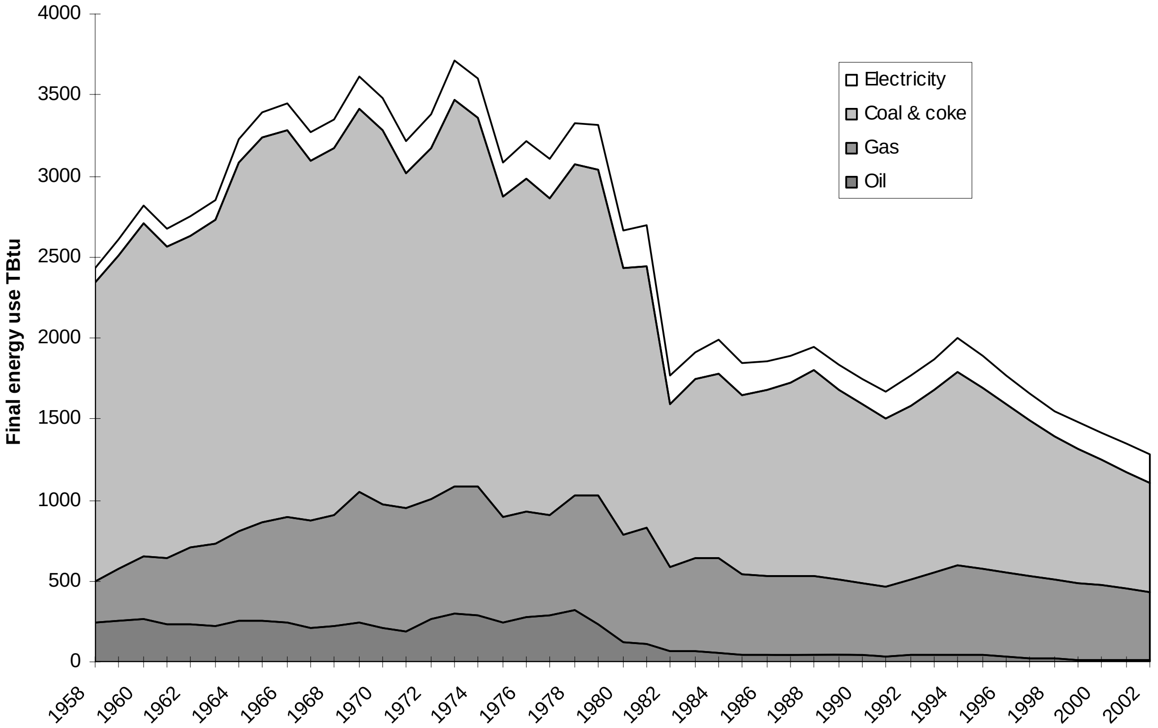

Figure 4-9. Annual final energy consumption at U.S. iron and steel mills (NAICS 331111 – SIC 3312) by type of fuel used from 1958 to 2002 (Source: U.S. EIA).

For both primary and secondary steelmaking it is expected that specific energy use will continue to decline as there is a significant potential for further energy savings. According to Energetics (2005) primary and secondary steelmaking have on average the potential to reduce energy intensity by approximately 30% and 45%, respectively. The potentials are likely to be lower for modern plants. Furthermore, most long-term forecasts agree that energy prices will rise, providing a strong incentive to adopt and develop energy efficiency technologies and operations.

4.5 Trends in Energy Costs

Figure 4-10 depicts the energy prices (2007 $/MBtu) in the U.S. from 1980 to 2007, as well as the forecasts until 2030. Figure 4-10 shows that, apart from the natural gas price, all energy prices increased from 2003 to 2007. Oil experienced by far the largest increase (112% with respect to 2003), but also that of coal is substantial (21% with respect to 2003). The forecasts show that all energy prices are expected to rise in the long term (U.S. EIA, 2008).

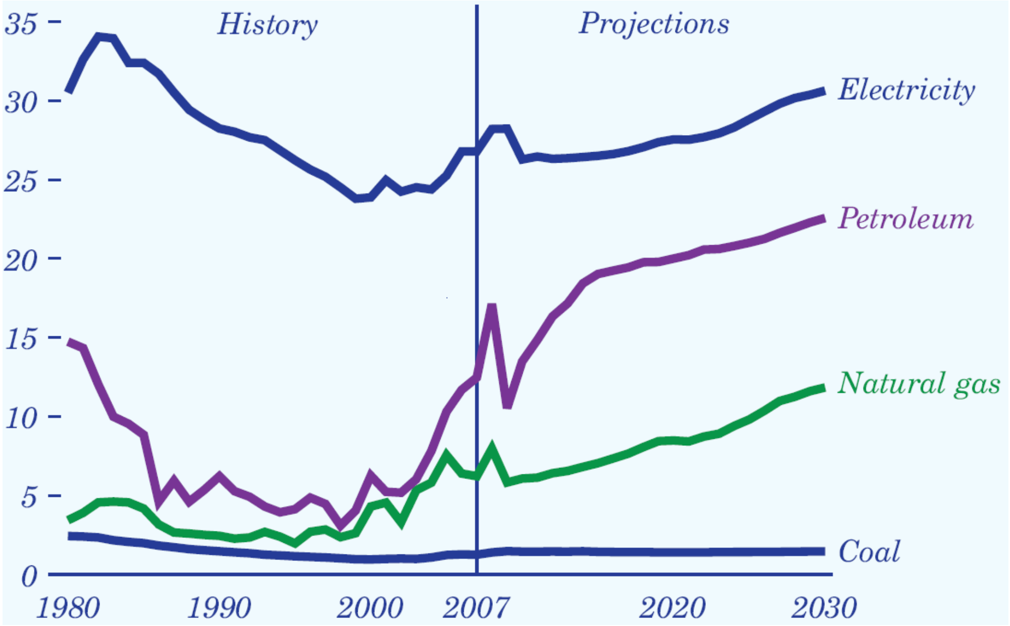

Figure 4-10. Real energy prices (2007 dollars per million Btu) for in chained currency in U.S. from 1980 to 2007 together with forecasts until 2030. Electricity and natural gas prices are specifically for the industrial sector (Source: U.S. DOE-EIA, 2008).

Since energy represents about 20% of the total manufacturing cost of steel (AISI, 2005), an increase in energy costs would significantly affect the iron and steel industry. This is also evident from Figure 4-11 which shows the trend in energy expenditures of the U.S. iron and steel industry including ferroalloy manufacturing together with energy costs as percentage of the value added. Figure 4-11 shows an increase in energy expenses during the 2002-2006 period. Production levels however did not experience a major increase, and energy efficiency continued to improve. The energy costs as a percentage of the value added increased less quickly than energy costs. This is largely due to the fact that international steel prices also increased substantially.

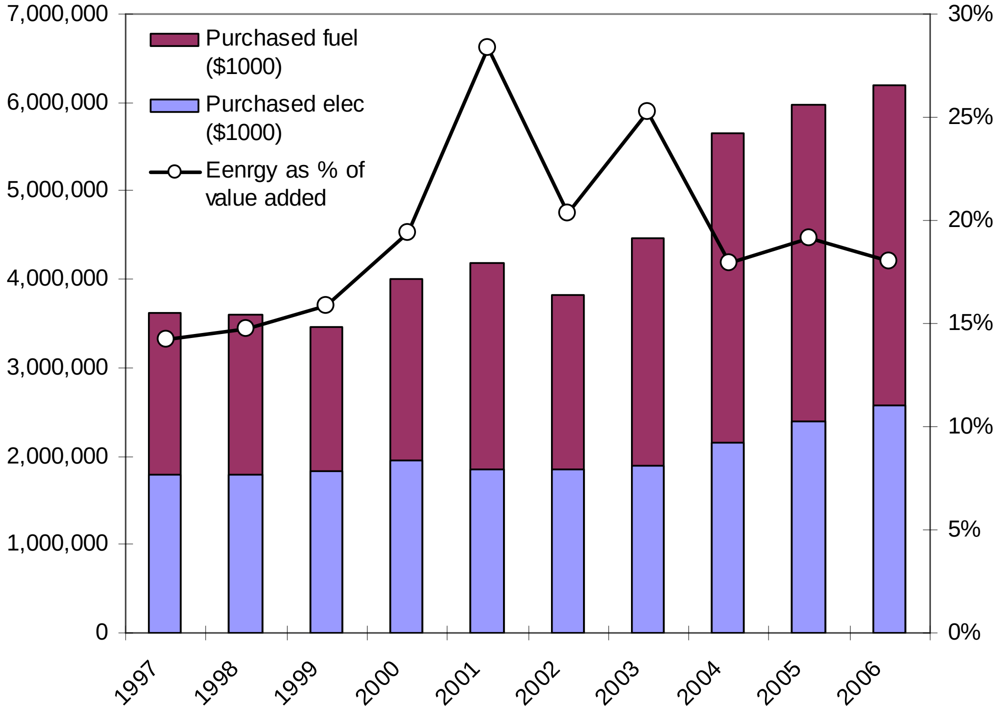

Figure 4-11. Annual energy cost of iron and steel industry (NAICS 331111 and 331112) in the U.S. from 1997 to 2006 for purchased fuels. The value of self-generated fuels is excluded (e.g. steam, coke oven gases, BF gases). The line depicts the energy costs as percentage of the value added (right-hand axis). Source: U.S. Census.

5 Emission of Greenhouse Gases

5.1 Overview of Emissions

In 2005, the U.S. iron and steel industry (including coke ovens but excluding emissions from power supply) accounted for 1.3% of total U.S. greenhouse gas (GHG) emissions, and 14% of total U.S. industry emissions.[8] Total direct emissions of the U.S. iron and steel industry including coke ovens amounted to 91 $MtCO_2$ in 2005, of which 7 $MtCO_2$ can be attributed to process emissions, coming from limestone and dolomite use in blast furnaces (IEA, 2008). Note that direct emissions do not take into account electricity generation emissions. These indirect emissions (~46 $MtCO_2$) represent approximately half of the total steel industry direct emissions.[9]

In the iron and steel industry, direct emissions of CO_2 and methane (CH_4) can be broadly categorized into the following (GHGs emitted by each process are in parentheses):

- Metallurgical coke production (CO_2, CH_4): whether onsite at integrated steel mills or offsite at merchant coke plants, coking coal is heated in a low-oxygen, high-temperature environment within a coke oven. Some carbon contained in the coking coal is emitted during this process as CO, CO_2 and CH_4 which leaves the coke oven as COG; CO is later oxidized to CO_2.
- Pig iron production (CO_2): at integrated steel mills, metallurgical coke is used as a reducing agent in the blast furnace to reduce iron ore to pig iron, which is used as a raw material in producing steel. At an integrated steel mill, the coke produced is used in the blast furnace charge for iron production. The carbon contained in the coke leads to CO/CO_2 emissions that leave the blast furnace as Blast Furnace (BF) gas. Iron-bearing blast furnace feed is produced through sintering, which agglomerates iron-rich small particles, such as iron ore fines and pollution control dusts and sludge, into a porous mass that can be used as blast furnace feed. This process also results in CO_2 emissions that leave the blast furnace as BF gas.
- Steelmaking (CO_2): at an integrated steel mill, molten iron produced by a blast furnace enters a BOF where the iron and some scrap are combined with high-purity oxygen to produce steel. Carbon contained in both the scrap steel and molten iron is emitted as CO/CO_2; and CO is oxidized if BOF gas is not recovered. In EAFs, CO_2 emissions occur from the use of carbon electrodes or other carbon-bearing inputs (e.g. injection fuels) during the melting of scrap steel.

5.2 Trends in GHG Emissions

Figure 5-1 shows the annual direct GHG emissions of the U.S. iron and steel industry in terms of million metric tons of CO_2 equivalents ($MtCO_2$-eq.). Figure 5-1 shows that direct GHG

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[8] The U.S. iron and steel industry direct CO_2 emissions were 91 Mt in 2005 (IEA, 2008); total U.S. greenhouse gas emissions were 7,130 Mt in 2005 (U.S. EPA, 2008b), while total U.S. industry emissions were 659 Mt in 2005 (IEA, 2008).

[9] Indirect emissions result from electricity use from the power grid. According to the IEA Energy Balances , electricity use in the iron and steel industry was 6868 ktoe in 2006 (reference). Converted to CO_2 emissions using the emission factor of the average U.S. power grid in what year? (580 g/kWh), this amounts to 46 $MtCO_2$.

emissions have declined by 43% (or 37.4 Mtonne CO_2-eq.) from 1990 to 2006 (U.S. EPA, 2008b). This is attributed to the restructuring of the industry, technological and energy efficiency improvements, and increased scrap utilization. The higher share of less carbon-intensive mini-mill production has, however, resulted in increased use of electricity and hence indirect GHG emissions. Annual fluctuations in CO_2 emissions per unit of steel produced result, in part, because iron and steel emission estimates include emissions associated with producing metallurgical coke. Metallurgical coke emissions are included here because metallurgical coke is primarily used to produce iron and steel; however, some portion is also used to produce other metals (e.g., lead, zinc). Domestic coke production and imports may also vary over time.

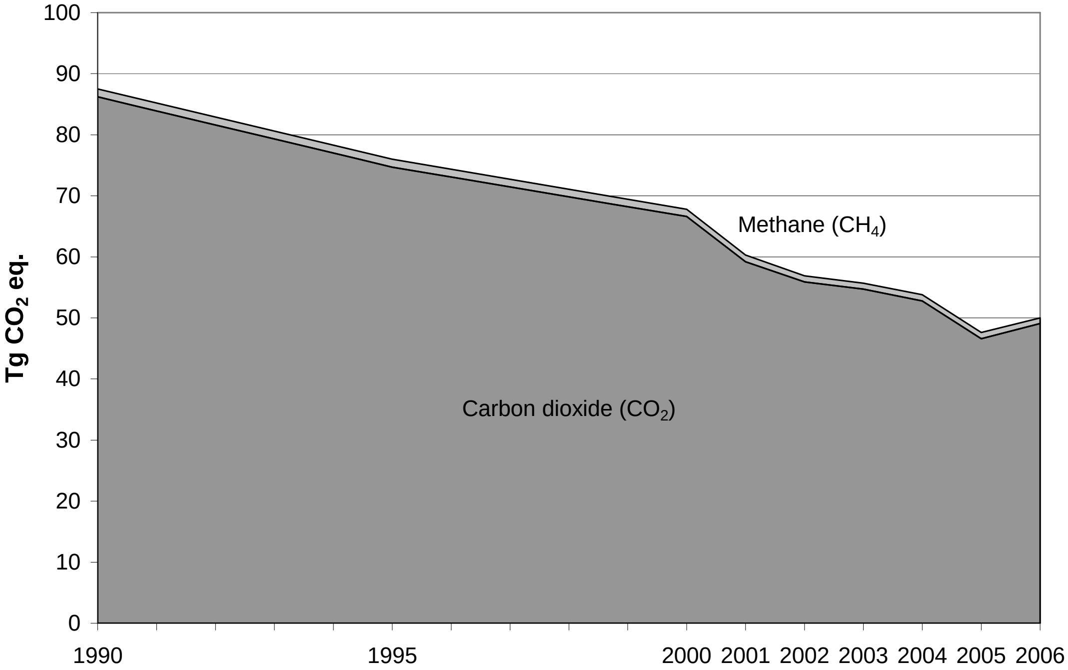

Figure 5-1. Annual carbon dioxide emissions by greenhouse gas from 1990 to 2006 (Source: U.S. EPA, 2008b)

As discussed in section 4.4, energy consumption of the U.S. iron and steel industry is expected to further decline in the future. Since a large portion of iron and steel industry GHG emissions are from energy consumption, these emissions are expected to follow the same trend. Additionally, future climate policies may provide incentives to further decrease emissions and emission intensity. The AISI has developed emission measurement and reporting protocols and is identifying opportunities to reduce GHG emission intensity. Furthermore, AISI invests in research and commercialization of advanced technology.

6 Water use

Steelmakers use water for various processes and purposes. Next to iron and energy, water is the industry's most important commodity (AISI, 1999). Steelmakers require approximately 75,000 gallons of water to produce one ton of steel (313 m^3/tonne) (AISI, 1999). This includes water that has been recycled internally and reused process and cooling water. The fraction of recycled water varies from operation to operation. Not all water can be reused. Mainly due to evaporation losses, steelmakers require 13,000–23,000 gallons of "fresh" water per ton ((54-96 m^3/tonne) of product (U.S. DOE, 2003). Steelmakers obtain this water from municipal sources and adjacent water bodies.

Water is used in the steel industry for three purposes:

- Material conditioning. Water is used for dust control in sinter feeds, slurrying or quenching dust and slag in blast furnaces, mill scale removal in hot-rolling operations, solvent for acid in pickling operations, or rinsing in other rolling operations.
- Air pollution control. Primary operations, particularly in integrated mills, use water in wet scrubbers for air pollution abatement. Water is also used for acid control in pickling operations and for wet scrubbers in coating operations that have caustic washing operations.
- Heat transfer. Primary iron- and steelmaking processes require heating the raw materials beyond the melting point of iron, in the range of 2,600-3,000 °F (1425-1650°C), while hot-rolling operations require heating the materials to 2,100-2,300°F (1150-1260°C). The equipment used for processing is protected by a combination of refractory linings and water-cooling of the refractory and shell of the equipment. Heat transfer applications account for the largest use of water in integrated steel plants.

Overall, approximately 12% of the water use is for material conditioning, 13% is for air pollution control, and 75% is for heat transfer, which does not include the boiler feed water requirements as these require vast amounts of water for heat transfer only (U.S. DOE, 2003).

Figure 6-1 shows a breakdown of the water use by operation using the most water in terms of gallons per ton of production. Figure 6-1 indicates that integrated mills use more water per ton of steel than EAFs.

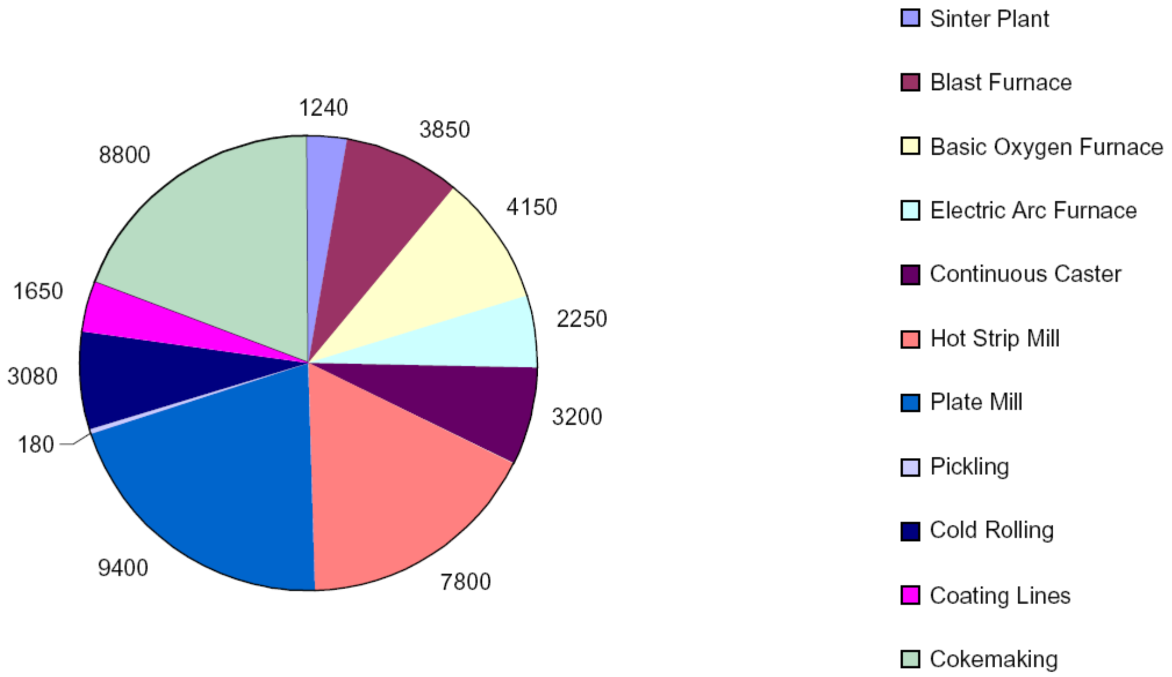

Figure 6-1. Estimated water use by process in the iron and steel industry, expressed as gallons per ton of product (Source: U.S. DOE, 2003)

Each unit operation in the steel-making process exhibits a different relationship between water use and energy consumption. In some cases, there is an inverse relationship. For instance, reheat furnaces in particular hot strip mills have progressed to furnaces with a lower heat rate. However, the cooling requirements, and with it the water use, increased in order to protect the internal components of the furnace. Similar experiences occur with the blast furnaces as more cooling is added to the shell of the blast furnace to extend the life of the linings at the same time that incremental improvements are made to the energy balance with coal injection, heat recovery, oxygen addition, and burden management to increase yields (U.S. DOE, 2003).

7 Energy efficiency Improvement Opportunities

A large variety of opportunities exists within the U.S. iron and steel industry to reduce energy consumption while maintaining or enhancing the productivity of plants. Studies in the iron and steel industries have demonstrated the existence of a substantial potential for energy efficiency improvement in almost all facilities, whether primary or secondary steel producers. The International Energy Agency (2007) estimates the total primary energy and feedstock savings potential to be 9-18% through the adaptation of best practice commercially available technologies while Energetics (2005) reports that the difference between the industry's average and the practical minimum energy requirements is 31% for ore-based steelmaking and 47% for EAF steelmaking. Worrell *et al.* (1999) reported cost-effective energy savings of 18% compared to a 1994 U.S. iron and steel industry's baseline energy use.

Improved energy efficiency may result in other benefits that outweigh the energy cost savings, including:

- decreased business uncertainties and reduced exposure to fluctuating energy costs
- increased product quality and switch to higher added value market segments
- increased productivity
- reduced environmental compliance cost, e.g. greenhouse gases and criteria air pollutants

Experiences of various iron and steel companies have shown that projects can be found with relatively modest investments and that savings with short paybacks can be found. However, to realize selected major energy efficiency opportunities large investments will be needed (e.g. BOF gas recovery, furnace replacements as discussed in the proceeding chapters). These capital investments may not be supported by energy cost savings alone. However, additional productivity and product quality benefits will strongly affect the economics of such an investment. Every plant will be different, and based on each unique situation the most favorable selection of energy efficiency opportunities should be made to address the specific circumstances and design of that plant.

This Energy Guide provides an overview of energy efficiency opportunities and their specific applications to help energy managers to select areas for energy efficiency improvement,. The measures that can be implemented at a plant will largely depend on the specifications of the installed facilities, its energy management as well as its integration with upstream (e.g. production of primary steel) or downstream (e.g. forming of steel products) activities. Although an extensive survey has been performed to identify different measures, this guide is not exhaustive, as new ways to improve energy efficiency are continuously developed.

This guide includes case studies from steel producers around the world with specific energy and cost savings data when available. For some measures, the Energy Guide provides a range of savings and payback periods found under varying conditions. At all times, the reader must bear in mind that the values presented in this Guide are offered as guidelines. Actual payback periods and energy savings for the measures will vary, depending on plant configuration and size, plant location, plant operating characteristics, local supply of raw materials and energy.

To enable easy access to information, this Energy Guide adopts a classification of energy efficiency measures based on technology area and process. However, different components of an industrial sub-system are interconnected and the energy efficiency measures that will be discussed in the remainder of the Guide should not be regarded as independent from one another. In order to achieve optimal efficiency, a systems approach is essential.

Energy efficiency opportunities are discussed in the following order: Chapters 6 to 11 focus on cross-cutting energy efficiency measures. Specifically, Chapter 6 gives a brief overview of corporate energy management programs and Chapters 7 to 11 discuss the following cross-cutting industrial systems: steam systems, motor systems, pumps systems, fan systems and compressed air systems. Chapter 12 discusses the application of combined heat and power (CHP) systems. Subsequently, process-specific measures are discussed in Chapters 13 to 19.

An overview of the cross-cutting measures, defined as energy efficiency measures that are in principle applicable across all manufacturing industries, is given in table 7-1, while Table 7-2 gives an overview of process-specific measures. Note however that the lists of measures in these tables are not exhaustive.

Table 7-1. Summary of cross-cutting energy efficiency measures discussed in this Energy Guide.

Energy Management Programs and Systems (Chapter 8)	
Strategic Energy Management Programs	Assessments
Energy teams	
Energy and Process Control Systems: (Chapter 9)	
Monitoring	Modeling
Optimization	
Steam Systems: (Chapter 10)	
Boiler Energy efficiency Measures (Section 10.2)	
Demand matching	Boiler feed water
Boiler allocation control	Optimization of boiler blowdown rate
Flue shut-off dampers	Reduction of flue gas quantities
Maintenance	Reduction of excess air
Insulation improvement	Flue gas monitoring
Removal of soot and scale	Installation of turbulators
Preheating the water supply with heat from flue gas	Recovery of heat from boiler blowdown
Recovery of condensate	
Combined Heat and Power (CHP) (Section 10.3)	
Steam injected gas turbine	High-temperature CHP
Steam expansion turbine	Combined Cycle
Natural gas expansion turbine	
Steam Distribution System Energy efficiency Measures (Section 10.4)	
Shutting off excess distribution lines	Checking and monitoring steam traps
Proper pipe sizing	Thermostatic steam traps
Insulation related measures	Shutting of steam traps
Reduction of distribution pipe leaks	Vapor recompression to recover waste steam
Recovery of flash steam	Replacement of pressure-reducing valves by backpressure turbogenerators
Motor Systems (Chapter 11)	
Motor management plan	Proper motor sizing

Maintenance	Adjustable-speed drives (ADSs)
Energy–efficient motors	Power factor correction
Rewinding of motors	Minimizing voltage unbalances
Pump Systems (Chapter 12)	
Operation and maintenance	Adjustable speed drives (ASDs)
Monitoring	Avoiding throttling valves
Controls	Proper pipe sizing
Reduction of demand	Replacement of belt drives
More efficient pumps	Precision castings, surface coatings or polishing
Proper pump sizing	Improvement of sealing
Multiple pumps for varying loads	Curtailing leakage through clearance reduction
Impeller trimming (or shaving sheaves)	Dry vacuum pumps
Fan Systems (Chapter 13)	
Minimizing flow	Proper fan sizing
Minimizing pressure	Adjustable speed drives (ASDs)
Control density	High efficiency belts (cog belts)
Fan efficiency	
Compressed Air Systems(Chapter 14)	
Reduction of demand	Maximizing allowable pressure dew point
Maintenance	Optimizing compressor(s) to match load
Monitoring	Controls
Reduction of leaks (in pipes and equipment)	Proper sizing of storage capacity
Electronic condensate drain traps (ECDTs)	Proper pipe sizing
Air quality	Heat recovery
Reduction of the inlet air temperature	Adjustable speed drives (ASDs)

Table 7-2. Summary of process specific measures included in this Energy Guide.

Iron Ore and Ferrous Reverts Preparation (Sintering) (Chapter 15)	
Heat recovery from sintering and sinter cooler	Use of waste fuel in sinter plant
Reduction of air leakage	Improve charging method
Increasing bed depth	Improve ignition oven efficiency
Emission Optimized Sintering (EOS®)	Other measures
Coke Making (Chapter 16)	
Coal moisture control	Coke dry quenching (CDQ)
Programmed heating	Coke oven gas (COG)
Variable speed drive coke oven gas compressors	Next generation coke making technology
Single Chamber System (SCS)	
Iron Making – Blast Furnace (Chapter 17)	
Injection of pulverized coal	Recovery of blast furnace gas
Injection of natural gas	Top gas recycling
Injection of oil	Improved blast furnace control
Injection of plastic waste	Slag heat recovery
Injection of coke oven gas and basic oxygen furnace gas	Preheating of fuel for hot stove
Charging carbon composite agglomerates (CCB)	Improvement of combustion in hot stove
Top-pressure recovery turbines (TRT)	Improved hot stove control
Steelmaking – BOF (Chapter 18)	
Recovery of BOF gas and sensible heat	Improvement of process monitoring and control
Variable speed drive on ventilation fans	Programmed and efficient ladle heating
Ladle preheating	
Steelmaking – EAF (Chapter 19)	
Increasing power	Refractories using engineering particles
Adjustable speed drives (ASDs)	Direct current (DC) arc furnace
Oxy-fuel burners/lancing	Scrap preheating
Post-combustion of flue gases	Waste injection
Improving process control	Airtight operation
Foamy slag practices	Bottom stirring/gas injection
Casting and Refining (Chapter 20)	
Integration of casting and rolling	Tundish heating
Ladle preheating	
Shaping (Chapter 21)	
Use efficient drive units	Installation of lubrication system
Gate Communicated Turn-Off (GCT) inverters	
Hot Rolling (Section 21.1)	
Recuperative or regenerative burners	Integration of casting and rolling
Flameless burners	Proper reheating temperature
Controlling oxygen levels and variable speed drives on combustion air fans	Process control in hot strip mill
Avoiding overload of reheat furnaces	Heat recovery to the product
Insulation of reheat furnaces	Waste heat recovery from cooling water
Hot charging	
Cold Rolling (Section 21.2)	
Continuous annealing	Inter-electrode insulation in electrolytic pickling line
Reducing losses on annealing line	Automated monitoring and targeting systems
Reduced steam use in the acid pickling line	

8 Energy Management Programs and Systems

8.1 Strategic Energy Management Programs

Understanding how energy is used and managed is essential to manage production costs. Changing how energy is managed by implementing an organization-wide energy management program is one of the most successful and cost-effective ways to bring about energy efficiency improvements. Ideally, such a program would include facility, operation, environmental, health, safety and personnel management.

A sound energy management program is required to create a foundation for positive change and to provide guidance for managing energy throughout an organization. Continuous improvements to energy efficiency therefore typically only occur when a strong organizational commitment exists. Energy management programs help to ensure that energy efficiency improvements do not just happen on a one-time basis, but rather are continuously identified and implemented in a process of continuous improvement.

In companies without a clear program in place, opportunities for improvement may be known, but may not be promoted or implemented because of organizational barriers, even when energy is a significant cost. These barriers may include a lack of communication among plants, a poor understanding of how to create support for an energy efficiency project, limited finances, poor accountability for measures, or organizational inertia to changes from the status quo.

Through the ENERGY STAR program, the U.S. EPA works with leading industrial manufacturers to identify the basic aspects of effective energy management programs.[10] The major elements in a strategic energy management program are depicted in Figure 8-1.

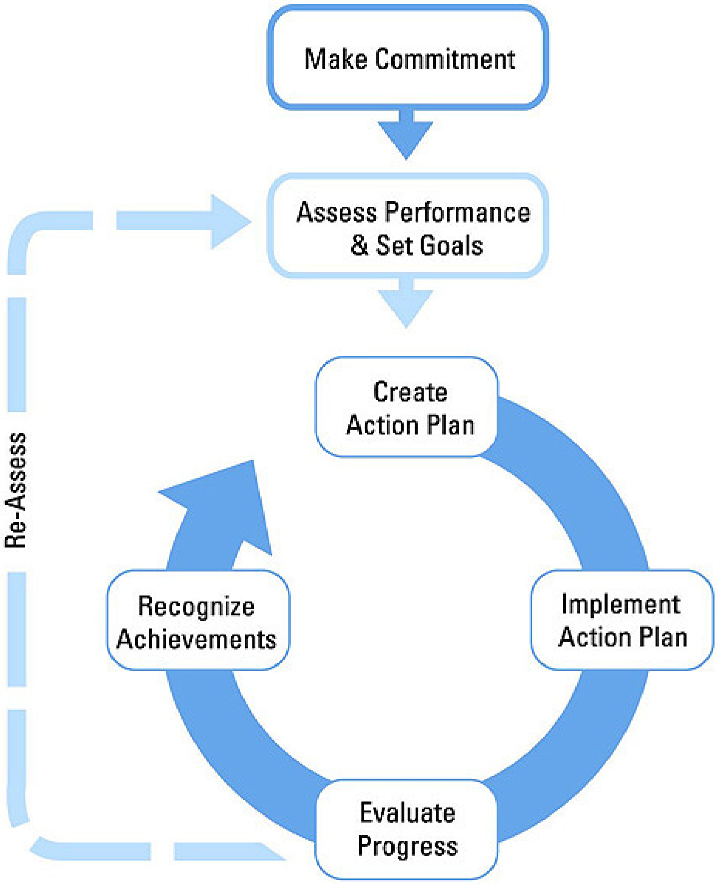

Figure 8-1. Main elements of a strategic energy management program

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[10] Read more about strategic energy management at: http://www.energystar.gov/.

A successful program in energy management begins with a strong organizational commitment to continuous improvement of energy efficiency. This involves assigning oversight and management duties to an energy director, establishing an energy policy, and creating a cross-functional energy team (see the section on energy teams below). Steps and procedures are then put in place to assess performance through regular reviews of energy data, technical assessments, and benchmarking. From this assessment, an organization is able to develop a baseline of energy use and set goals for improvement. Such performance goals help to shape the development and implementation of an action plan.

An important aspect for ensuring the success of the action plan is involving personnel throughout the organization. Personnel at all levels should be aware of energy use and goals for efficiency. Staff should be trained in general approaches to energy efficiency in day-to-day practices. Some examples of simple tasks employees can do are outlined in Appendix B.

Evaluating performance involves the regular review of both energy use data and the activities carried out as part of the action plan. Information gathered during the formal review process helps in setting new performance goals and action plans and in revealing best practices. Establishing a strong communications program and seeking recognition for accomplishments are critical steps to build support and momentum for future activities. A quick assessment of an organization's efforts to manage energy can be made by comparing the current program with the ENERGY STAR Energy Program Assessment Matrix provided in Appendix C.

8.2 Energy Teams

The establishment of an energy team is an important step toward solidifying a commitment to continuous energy efficiency improvement (see U.S. EPA, 2006 for a comprehensive overview) as is indicated by the following example:

In 1998, United States Steel Corporation's Edgar Thomson Plant in Braddock, Pennsylvania, set up an energy team. The goal was to identify and implement energy-saving opportunities and improve the plant performance. Two years later, 40 projects were completed and 18 more were underway. The estimated total annual energy savings of the completed measures was around $2 million. Other benefits included increased productivity, reduced downtime as well as improved product quality (U.S. DOE-OIT, 2000a).

An energy team should primarily be responsible for planning, implementing, benchmarking, monitoring, and evaluating the organizational energy management program, but it can also include delivering training, communicating results, and providing employee recognition (U.S. EPA, 2006).

In forming an energy team, it is necessary to establish the organizational structure, designate team members, and specify roles and responsibilities. Senior management needs to perceive energy management as part of the organization's core business activities, so ideally the energy team leader will be someone at the corporate level who is empowered with the support of senior-level management. The energy team should also include members from each key operational area within an organization and be as multi-disciplinary as possible to ensure a diversity of perspectives. It is crucial to ensure adequate organizational funding for the energy team's activities, preferably as a line item in the normal budget cycle as opposed to a special project.

Prior to the launch of an energy team, a series of team strategy meetings should be held to consider the key initiatives to pursue as well as potential pilot projects that could be showcased at the program's kickoff. The energy team should then perform facility audits with key plant personnel at each facility to identify opportunities for energy efficiency improvements. As part of the facility audits, the energy team should also look for best practice technologies to help highlight success stories and identify areas for inter-plant knowledge transfer.

A key function of the energy team is to develop mechanisms and tools for tracking and communicating progress and for transferring the knowledge gained through facility audits across an organization. Examples of such mechanisms and data tools include best practice databases, facility benchmarking tools, intranet sites, performance tracking scorecards, and case studies of successful projects. Corporate energy summits and employee energy fairs are also effective means of information exchange and technology transfer.

To sustain the energy team and build momentum for continuous improvement, it is important that progress results and lessons learned are communicated regularly to managers and employees and that a recognition and rewards program is put in place.

A checklist of key steps for forming, operating, and sustaining an effective energy management team is offered in Appendix D.

Audits or Assessments. The success of energy efficiency assessments or audits to reduce energy use has been proven in a large number of cases. Embedding audits in an energy management system helps to guarantee successful implementation of audit results.

North Star Steel's Wilton mill in Iowa completed a plant-wide assessment with a focus on energy efficiency, productivity, wastes and environmental emissions. The assessment team estimated the potential for total annual savings to be about 140 TBtu (148 TJ) in natural gas and nearly 39 GWh electricity. Total annual cost savings would be more than $2.6 million (U.S. DOE-OIT, 2003b).

In 2001, a plant-wide energy assessment was conducted at the Weirton steel plant in West Virginia. The focus of this assessment was on the large fossil fuel and electricity expenses at the tin mill. Only measures with a short payback period, limited capital investment, and with a minimal disruption of the production were considered. An annual savings potential of 108,000 MBtu (114 TJ) was identified, representing nearly $1.3 million annual cost savings (U.S.DOE-OIT, 2004).

9 Energy and Process Control Systems

The use of control systems can play an important role in energy management and in reducing energy use. Control systems can reduce the time required to perform complex tasks, often improve product quality and consistency, optimize process operations leading to reduced downtime, reduced maintenance costs, reduced processing time, and increased resource and energy efficiency, as well as improved emissions control. They are therefore often not solely designed for energy efficiency. This is especially true in the production of iron and steel, where increases in productivity most often directly improve energy efficiency.

A variety of process control systems is designed for most, if not all, process steps in iron and steel production, e.g. combustion control systems of coke oven batteries (e.g. Barbosa de Oliveira Mello *et al.* 2008), hot-stove automation (e.g. Derycke *et al.* 1990), blast furnace control systems (e.g. Stelco, 1993; Brunnbauer *et al.* 2001, Hörl *et al.* 2007), post-combustion control in EAFs (Goodfellow *et al.*, 2005), batch annealing operation control (Sahay *et al.*, 2006).

Improvements in control systems are driven by improvements in process monitoring, process modeling, and process optimization. Increasingly, advanced control systems are under continuous development and large potentials to exploit their benefits therefore exist even though some plants may already have modern process control systems in place. For example, Weirton Steel modernized its boiler control and due to the new control strategy, the plant was able to reduce its high-pressure steam production by 20% (U.S. DOE-OIT, 2000b). As a result, the company has been able to save over $17 million annually from reductions in purchased fuels and maintenance costs. Since the project's total cost was about $16 million, it had an 11 month payback.

Specific applications of energy and process control systems are discussed in the process-specific chapters of this Energy Guide.

9.1 Monitoring

As process control systems rely on information from many stages of the processes, an important area is the development of sensors. An example of the benefits of improved monitoring is the real-time monitoring of off-gas in an EAF, allowing a 50% increase on the recovery rate of chemical energy due to post-combustion control (Januard *et al.*, 2006). Also, advances are possible in the BOF process such as improved monitoring using a newly proposed control methodology based on fast and simultaneous determination of the steel/slag composition (Wauters *et al.*, 2006).

Apart from input in control systems, monitored data can also be used to assess the validity of new process models or to improve knowledge of a process. For instance, Sandberg *et al.* (2005) used process data from four Scandinavian EAFs to develop predictive models for endpoint conditions such as yield and energy consumption.

In the following chapters, only examples of monitoring systems that have directly resulted into significant energy savings will be discussed.

9.2 Model-based Controls

A model allows assessing the influence of certain practices and process parameters. This can be supported by running simulations. Modeling therefore helps to improve the understanding of a process, which facilitates the design of control systems, operations and applications that lead to energy savings. This is particularly true for models of, or that incorporate, energy usage. Models also support process planning and can therefore help to make processes leaner and to avoid peaks in the need of a specific input, such as electricity, that may be hard to fulfill. For instance, electricity demand forecasting has become an important module in the energy management system of a plant in Shanghai, China (Zhou *et al.*, 2005).

Models can have different levels of detail. Two specific advanced detailed types of modeling that recently have found their way to steelmaking are computational fluid dynamics (CFD) and finite element method (FEM). The use of these types of models can improve the understanding of flow processes and thus allow improvement of metallurgical processes at the steel plant (e.g., solidification in the caster of continuous casting, melt flow at the beginning of casting ladles for thin strip casters) (Creton, 2008).

Mapelli and Baragiola (2006) simulated the melting process in an EAF. This allowed them to calculate the process performance and the energetic/exergetic efficiency of the process and to provide a guide to the calibration of the process parameters that best fit individual plants. Ferrand *et al.* (2006) developed an innovative modeling strategy to help the design of steel reheating furnaces, facilitated by a set of complementary simulation tools. These efforts resulted in the development of a new furnace with demonstrated advantages in terms of pollutant emissions, operation costs and flexibility. Huber *et al.* (2008) developed a model to evaluate energy efficiency options for a BOF in order to identify process solutions. They found that the modeling approach proved to be a valuable tool for identifying thermal efficiency parameters.

Expanding the system boundary of a model to include more aspects of the process or by considering more installations/plants has the potential to further increase energy efficiency.

9.3 Optimization

In optimizing process efficiency it should be clear which parameter will be optimized, e.g. productivity, energy use, CO_2 emissions, process stability, purity of produced steel. In some cases a combination of parameters will be optimized. Boundary conditions may exist such as the minimum quality of a product.

The extent to which process efficiency can be improved by process control depends on the potential to influence the process (e.g. installation of oxy-fuel lances in an EAF) and the data of the process that are available (e.g. composition of furnace flue gas). The optimization procedure can make use of both simulations and data from processes or experiments. Sahay *et* *al.* (2006) found that archived production data could be a valuable resource to enhance process efficiency in batch annealing operation.

Some optimization procedures apply algorithms to find an optimum. For instance, a genetic algorithm was used to optimize a cold rolling schedule (Yang *et al.*, 2006). Other optimization procedures are model-based or just consist of testing a range of control procedures to find an optimum.

New energy management systems that use artificial intelligence, fuzzy logic (neural networks), or rule-based systems mimic the "best" controller, using monitoring data and learning from previous experiences. Neural network-based control systems have successfully been used in the cement (kilns), food (baking), non-ferrous metals (alumina, zinc), pulp and paper (paper stock, lime kiln), petroleum refineries (process, site), and steel industries (electric arc furnaces, rolling mills, sintering (Zhang *et al.*, 2007)).

Process knowledge based systems (KBS) incorporate scientific and process information applying a reasoning process and rules in the management strategy. Although these systems have been used in design and diagnostics, they are hardly used in industrial processes.

10 Steam Systems

Steam is used to treat semi-finished products and can also be used as the power source in steam-driven equipment like compressors, to heat buildings, and as an intermediate energy carrier in electricity generation.

Steam represents up to 10% of all energy used in an integrated mill (U.S. DOE-OIT, 2001a). 11% of steam generated in the U.S. iron and steel industry is produced in combined heat and power (CHP) systems and the remainder in boiler systems (U.S. DOE-ITP 2008a). Steam boilers play a particularly important role in integrated mills because they not only provide the steam needed for key processes but also consume by-product fuels generated in the coke ovens, blast furnace, and basic oxygen furnace.

A profile of the U.S. iron and steel industry's steam use and losses is depicted in Figure 4-5, which shows that about 44% of energy inputs are lost due to system inefficiencies. Most of these losses occur in the boiler, where thermal efficiencies range between 55-85%, depending on the age of the boiler and fuel type burned. Distribution losses occur in steam traps, valves, and pipes carrying steam to processes and energy conversion units. These losses can vary widely between facilities, as they are highly dependent on plant configurations, the effectiveness of the integration of heat sources and sinks, and operating and maintenance practices (U.S. DOE, 2004).

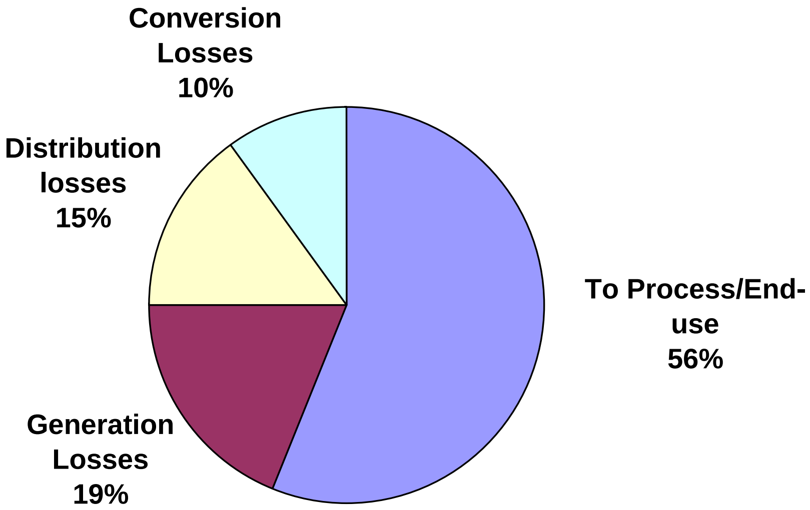

Figure 10-1. Use and loss profile of steam systems in the U.S. iron and steel industry (Source: U.S. DOE, 2004)

Like any other secondary energy carrier, steam is expensive to produce and supply. Its use should therefore be carefully considered and evaluated. It is recommended that a systems approach be followed and to start with benchmarking the fuel cost of steam generation to assess the efficiency of a steam system.

Twenty-three steel manufacturing facilities that participated in the Save Energy Now Assessment Initiative of the U.S. Department of Energy Industrial Technologies Program identified average steam savings up to 3% per plant (U.S. DOE-ITP, 2008b).

New state-of-the art technology provides additional potential to increase energy efficiency. This is demonstrated by the SuperBoiler project which developed a boiler with a 50% smaller footprint than conventional boilers and minimal environmental impacts by bundling innovations such as a transport membrane condenser (TMC), compact humidifying air heater (HAH), compact convective zones with intensive heat transfer, and a staged/intercooled combustion system (U.S. DOE-ITP, 2007b).

An overview of energy efficiency opportunities is given in this chapter. A typical steam system is described in section 10.1. To structure the overview, energy efficiency opportunities are divided into four sections: boiler energy efficiency measures (section 10.2), CHP systems (section 10.3), and steam distribution energy efficiency measures (section 10.4). Steam systems are highly interlinked and as a result, many links exist between the measures discussed in the various sections. Payback periods are given for many measures. Payback periods will vary with fuel price and plant-specific circumstances.

10.1 Description of Typical Steam System

While the exact size and use of a modern system varies greatly, there is an overall pattern that steam systems follow. A schematic presentation of such a pattern is depicted in figure 10-2. Treated cold feed water is fed to the boiler, where it is heated to form steam. Chemical treatment of the feed water is required to remove impurities, because impurities would otherwise collect on the boiler walls. Even though the feed water has been treated, some impurities still remain and can build up in the boiler water. As a result, water is periodically drained from the bottom of the boiler in a process known as blow down. The generated steam travels along the pipes of the distribution system to get to the process where the heat will be used. Sometimes the steam is passed through a pressure reduction valve if the process requires lower pressure steam. In steam transport, the steam cools down and some of it is condensed. The condensate is removed by a steam trap, which allows condensate to pass through, but blocks the passage of steam.

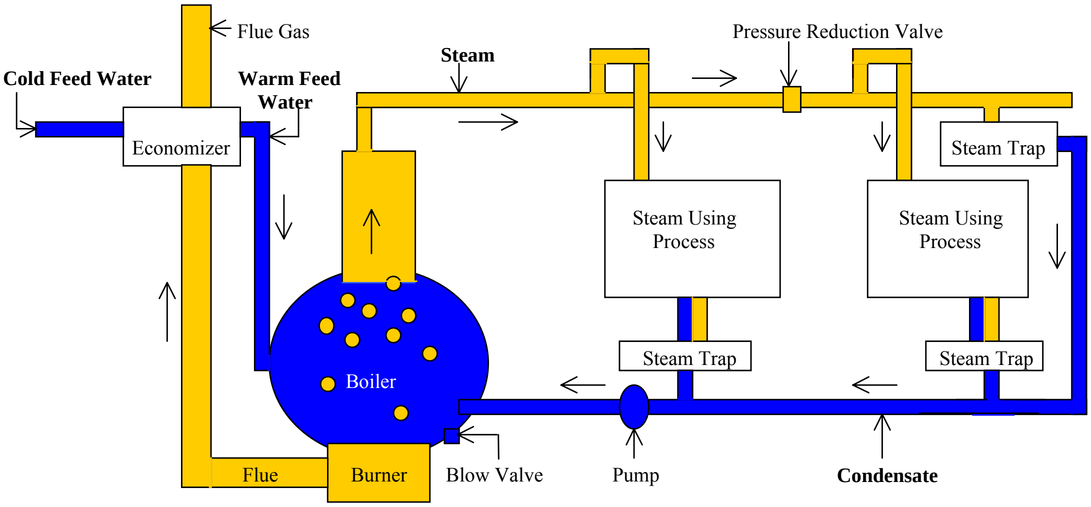

Figure 10-2. Schematic representation of a steam production and distribution system

Process Integration. Process integration refers to the exploitation of potential synergies that are inherent in any system that consists of multiple components working together. In plants that have multiple heating and cooling demands, the use of pinch analysis techniques may significantly improve efficiencies. Developed in the early 1970's, pinch analysis is now a well established methodology for continuous processes (Linnhoff et al., 1992). The methodology involves the linking of hot and cold streams in a process in a thermodynamic optimal way (i.e. not over the so-called 'pinch'). Process integration is the art of ensuring that the components are well suited and matched in terms of size, function and capability. Pinch analysis takes a systematic approach to identifying and correcting the performance limiting constraint (or pinch) in any manufacturing process. It was developed originally in the late 1970s at the University of Manchester in England and other places (Linnhoff, 1993) in response to the "energy crisis" of the 1970s and the need to reduce steam and fuel consumption in oil refineries and chemical plants by optimizing the design of heat exchanger networks. Since then, the pinch approach has been extended to resource conservation in general, whether the resource is capital, time, labor, electrical power, water or a specific chemical compounds such as hydrogen.

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

The analytical approach to this analysis has been well documented in the literature (Smith, 1995; Shenoy, 1994). Energy savings potential using pinch analysis far exceeds that from well-known conventional techniques such as heat recovery from boiler flue gas, insulation and steam trap management.

Pinch analysis, and competing process integration tools, have been developed further in recent years. The most important developments in the energy area are the inclusion of alternative heat recovery processes such as heat pumps and heat transformers, as well as the development of pinch analysis for batch processes (or in other words bringing in time as a factor in the analysis of heat integration). Furthermore, pinch analysis should be used in the design of new processes and plants, as process integration goes beyond optimization of heat exchanger networks (Hallale, 2001). Even in new designs additional opportunities for energy efficiency improvement can be identified. Pinch analysis has also been extended to the areas of water recovery and efficiency, and hydrogen recovery.

Total Site Pinch Analysis has been applied by many chemical sites around the world to find optimum site-wide utility levels by integrating heating and cooling demands of various processes, and by allowing the integration of CHP into the analysis. Process integration analysis of existing processes should be performed regularly, as continuous changes in product mix, mass flows and applied processes can provide new or improved opportunities for energy and resource efficiency.

Typical savings identified in site-wide analyses are around 20-30%. Typically, 10-15% savings are achievable under normal economic investment criteria (Linnhoff-March, 2000). Total site pinch analysis has been applied in over 100 case studies in many industries on all continents.

10.2 Steam Supply – Boiler

Demand Matching. A boiler is more efficient in the high-fire setting. Since process heating demands may change over time, situations can occur in which a boiler is operating beneath its optimum efficiency. Also, boilers may have been oversized because of additions or expansions that never occurred. Installing energy conservation or heat recovery measures may also have reduced the heat demand. As a result, a facility may have multiple boilers, each rated at several times the maximum expected load (U.S. DOE-OIT, 2006). An additional common problem with oversized boiler is boiler “short cycling”, which occurs when an oversized boiler quickly satisfies process or space heating demands, and then shuts down until heat is again required.

Fuel savings can be achieved by adding a smaller boiler to a system, sized to meet average loads at a facility, or by re-engineering the power plant to consist of multiple small boilers. Multiple small boilers offer reliability and flexibility to operators to follow load swings without over-firing and short cycling. In particular, facilities with large seasonal variations in steam demand should use operate small boilers when demand drops, rather than operating their large boilers year-round.

Operation measures to operate boilers on the high-fire setting have an average payback time of 0.8 years and the installation of smaller boilers to increase the high-fire duty cycle has an average payback time of 1.9 years (U.S. DOE-IAC, 2006).

Boiler Allocation Control. Systems containing multiple boilers offer energy-saving opportunities by using proper boiler allocation strategies. This is especially true if multiple boilers are operated simultaneously at low-fire conditions.

Automatic controllers determine the incremental costs (change in steam cost/change in load) for each boiler in the facility, and then shift loads accordingly. This maximizes efficiency and reduces energy costs. If possible, schedule loads to help optimize boiler system performance.

The efficiency of hot water boilers can improve through use of automatic flow valves. Automatic flow valves shut off boilers that are not being used, preventing the hot water from the fired boiler getting cooled as it passes through the unused boilers in the system. Where valves are left open the average flow temperature is lower than designed for and more fuel is used (CADDET, 2001).

Flue Shut-off Dampers. Where boilers are regularly shut down due to load changes, the heat lost to the chimney can be significant. A solution to stop this loss of hot air is to fit fully closing stack dampers, which only operate when the boiler is not required. Another alternative is to fit similar gas tight dampers to the fan intake (CADDET, 2001).

Maintenance. In the absence of a good maintenance system, the burners and condensate return systems can wear or get out of adjustment. These factors can end up costing a steam system up to 20-30% of initial efficiency over 2-3 years (U.S. DOE-OIT, 2001a). A simple maintenance program to ensure that all components of the boiler are operating at peak performance can result in substantial savings and furthermore reduce the emission of air pollutants. On average the possible energy savings are estimated at 10% (U.S. DOE-OIT, 2001a). The establishment of a maintenance schedule for boilers has an average payback time of 0.3 years (U.S. DOE-IAC, 2006).

Insulation Improvement. The shell losses of a well-maintained boiler should be less than 1%. New insulation materials insulate better, and have a lower heat capacity. As a result of this lower heat capacity, the output temperature is more vulnerable to temperature fluctuations in the heating elements. Improved control is therefore required to maintain the output temperature range of the old firebrick system. Savings of 6-26% can be achieved by combining improved insulation with improved heater circuit controls (Caffal, 1995).

Reduce Fouling. Fouling of the fireside of the boiler tubes and scaling waterside of the boiler should be controlled. Tests show that a soot layer of 0.03 inches (0.8 mm) reduces heat transfer by 9.5%, while a 0.18 inch (4.5 mm) layer reduces heat transfer by 69% (CIPEC, 2001). Scale deposits occur when calcium, magnesium, and silica, commonly found in most water supplies, react to form a continuous layer of material on the waterside of the boiler heat exchange tubes. Tests showed that for water-tube boilers 0.04 inches (1 mm) of buildup can increase fuel consumption by 2% (CIPEC, 2001). In fire-tube boilers scaling can lead to a fuel waste up to 5% (U.S. DOE-OIT, 2006). Moreover, scaling may result in tube failures.

Scale removal can be achieved by mechanical means or acid cleaning. The presence of scale can be indicated by the flue gas temperature (see flue gas monitoring) or be determined by visual inspection of the boiler tubes when the unit is shut down for maintenance. Fouling and scaling are more of a problem with coal-fed boilers than natural gas or oil-fed ones (i.e. boilers that burn solid fuels like coal should be checked more often as they have a higher fouling tendency than liquid fuel boilers) (U.S. DOE-OIT, 2006).

Boiler Feed Water. Redesigning the boiler feed water supply can lead to substantial energy savings as is indicated by the example of Bethlehem Steel Corporation's Burns Harbor (Indiana) plant (since 2005 owned by ArcelorMittal), who rebuilt their steam turbine generators at their Burns Harbor Facility in Indiana. By incorporating the latest steam path technology, using a portion of the warm condenser cooling water exhaust stream instead of cool lake water for boiler feed water make-up, and injecting the low-pressure steam previously used to heat the lake water into the turbine, the plant was able to significantly increase the capacity and efficiency of the steam turbine generator system. The project resulted in annual savings of approximately 40,000 MWh of electricity, 85,000 MBtu (90,000 GJ) of natural gas, and nearly $3.3 million. With a cost of $3.4 million more than a standard maintenance overhaul, the simple payback for the project was just over one year. The project also reduced high-temperature water discharge into the harbor, and decreased coke oven and blast furnace gas emissions (U.S. DOE-OIT, 1999).

Optimization of Boiler Blowdown Rate. Insufficient blowdown may lead to carryover of boiler water into the steam, or the formation of deposits. Excessive blowdown will waste energy, water, and chemicals. The optimum blowdown rate is determined by various factors including the boiler type, operating pressure, water treatment, and quality of makeup water. Blowdown rates typically range from 4% to 8% depending on boiler feed water flow rate, but can be as high as 10% when makeup water has a high solids content (U.S. DOE-OIT, 2006). Minimizing blowdown rate can therefore substantially reduce energy losses, makeup water and chemical treatment costs. The reduction of the blowdown rate has an average payback time of 1 year (U.S. DOE-IAC, 2006)

Optimum blowdown rates can be achieved with an automatic blowdown-control system. In many cases, the savings due to such a system can provide a simple payback of 1 to 3 year (U.S. DOE-OIT, 2006).

Reduction of Flue Gas Quantities. Often, excessive flue gas results from leaks in the boiler and the flue, reducing the heat transferred to the steam, and increasing pumping requirements. These leaks are often easily repaired. This measure consists of a periodic repair based on visual inspection or on flue gas monitoring which is discussed below.

Reduction of Excess Air. The more air is used to burn the fuel, the more heat is wasted in heating air. Air slightly in excess of the ideal stoichiometric fuel/air ratio is required for safety, and to reduce NO_x emissions, and is dependent on the type of fuel. Poorly maintained boilers can have up to 140% excess air leading to excessive amounts of waste gas. An efficient natural gas burner however requires 2% to 3% excess oxygen, or 10% to 15% excess air in the flue gas, to burn fuel without forming carbon monoxide. A rule of thumb is that boiler efficiency can be increased by 1% for each 15% reduction in excess air (U.S. DOE-OIT, 2006). Fuel-air ratios of the burners should be checked regularly. On average the analysis of proper air/fuel mixture had a payback time of 0.6 years.

An efficient burner provides the proper air-to-fuel mixture throughout the full range of firing rates, without constant adjustment. Traditionally, this mixture was controlled by the use of linkages or cables to position the air and fuel valves. These are subject to wear, repeatability difficulties and a limited amount of adjustment. An alternative to complex linkage designs, modern burners are increasingly using servomotors with parallel positioning to independently control the quantities of fuel and air delivered to the burner head. These controls provide consistent performance and repeatability as the burner adjusts to different firing rates (U.S. DOE-OIT, 2006). The implementation of a digital system will result in greater control of the combustion process and will lead to an improvement in energy efficiency of 3-5% (CADDET, 2001). Replacement of obsolete burners with more efficient ones averages a payback period of 2.5 years (U.S. DOE-IAC, 2006).

Using a combination of CO and oxygen readings, it is possible to optimize the fuel/air mixture for high flame temperature (and thus the best energy efficiency) and low emissions (see flue gas monitoring).

Flue Gas Monitoring. The oxygen content of the exhaust gas is a combination of excess air (which is deliberately introduced to improve safety or reduce emissions) and air infiltration (air leaking into the boiler). By combining an oxygen monitor with an intake airflow monitor, it is possible to detect small leaks. Using a combination of CO and oxygen readings, it is possible to optimize the fuel/air mixture for high flame temperature and thus the best energy efficiency and for low emissions. The payback of installing flue gas analyzers to determine proper air/fuel ratios on average is 0.6 years (U.S. DOE-IAC, 2006).

The monitoring of flue gas temperature can also help to indicate scaling, since the flue gas temperature is an indirect indicator of scale or deposit formation is flue gas temperature. If the flue gas temperature rises (with boiler load and excess air held constant), the effect is likely due to the presence of scale.

The percentage of oxygen in the flue gas can be measured by inexpensive gas-absorbing test kits. More expensive (ranging in cost from $500 to $1,000) hand-held, computer-based analyzers display percentage of oxygen, stack gas temperature, and boiler efficiency. They are a recommended investment for any boiler system with annual fuel costs exceeding $50,000 (U.S. DOE-OIT, 2006).

Installation of Turbulators on Two- and Three-pass Firetube Boilers. The packaged firetube boiler is the most common boiler design used to provide heating or process steam in industrial and heavy commercial applications. In a firetube boiler, hot combustion gases pass through long, small-diameter tubes where heat is transferred to water through the tube walls.

These gases enter the tubes in a turbulent flow regime, but within a few feet laminar flow begins and a boundary layer of cooler gas forms along the tube walls. This layer serves as a barrier, retarding heat transfer. Turbulators, which consist of small baffles, angular metal strips, spiral blades, or coiled wire, may be inserted into the boiler tubes to break up the laminar boundary layer (U.S. DOE-OIT, 2006). This increases the turbulence of the hot combustion gases and the convective heat transfer to the tube surface. The result is improved boiler efficiency. Turbulator installers can also balance gas flow through the tubes by placing longer turbulators in the uppermost tubes. This practice increases the effectiveness of the available heat-transfer surface by eliminating thermal stratification and balancing the gas flow through the firetubes.

The cost of installing turbulators is about $10 to $15 per boiler tube and the average payback time is 1.2 years (U.S. DOE-IAC, 2006). A manufacturing facility installed 150 turbulators into its firetube boiler. Tests conducted both before and after turbulator installation indicated a reduction in the stack gas temperature of 130°F (55°C). More combustion heat was being transferred into the boiler water. Because each 40°F (22°C) reduction in the boiler flue gas temperature results in a 1% boiler-efficiency improvement, overall boiler efficiency was improved by about 3.3%, while fuel costs decreased by approximately 4%.

Preheating Boiler Feed Water with Heat from Flue Gas (economizer). Heat from flue gases can be used to preheat boiler feed water in an economizer. By preheating the water supply, the temperature of the water supply at the inlet to the boiler is increased, reducing the amount of heat necessary to generate steam thus saving fuel. While this measure is fairly common in large boilers, there often still is potential for more heat recovery.

The limiting factor for flue gas heat recovery is the economizer wall temperature that should not drop below the dew point of acids in the flue gas. Traditionally this is done by keeping the flue gases at a temperature significantly above the acid dew point. However, the economizer wall temperature is more dependent on the feed water temperature than on the flue gas temperature because of the high heat transfer coefficient of water. As a result, it makes more sense to preheat the feed water to close to the acid dew point before it enters the economizer. This allows the economizer to be designed so that the flue gas exiting the economizer is just above the acid dew point.

Generally, boiler efficiency can be increased by 1% for every 40°F (22°C) reduction in flue gas temperature. By recovering waste heat, an economizer can often reduce fuel requirements by 5% to 10% and pay for itself in less than 2 years (U.S. DOE-OIT, 2006).

Recovery of Heat from Boiler Blowdown. When the water is blown from the high-pressure boiler tank, the pressure reduction often produces substantial amounts of steam. Up to 80% of the heat in the discharge is recoverable by using flash vessels and heat exchangers (CADDET, 2001). The recovered heat can subsequently be used for space heating and feed water preheating increasing the efficiency of the system. Any boiler with continuous blow down exceeding 5% of the steam rate is a good candidate for the introduction of blow down waste heat recovery. If there is a non-continuous blow down system, then consider the option of converting it to a continuous blow down system coupled with heat recovery (U.S. DOE-OIT, 2006). Larger energy savings occur with high-pressure boilers. The use of heat from boiler blow down on average has payback period of 1.6 years (U.S. DOE-IAC, 2006).

Recovery of Condensate. By installing a condensing economizer, companies can improve overall heat recovery and steam system efficiency by up to 10% (U.S. DOE-OIT, 2007). Many boiler applications can benefit from this additional heat recovery. Condensing economizers require site-specific engineering and design, and a thorough understanding of the effect they will have on the existing steam system and water chemistry.

Hot condensate can be returned to the boiler to save energy and reduce the need for treated boiler feed water since condensate, being condensed steam, is extremely pure and has a high heat content. Increasing the amount of returned condensate has an average payback period of 1.1 years (U.S. DOE-IAC, 2006). Condensate has also been used to provide for hot water supply. This measure had an average payback period of 0.8 years (U.S. DOE-IAC, 2006).

Care should be taken to prevent the forming of corrosion. Corrosion in condensate systems can limit the quality or quantity of returned condensate, which may contain iron and copper corrosion products, which can deposit on boiler heat transfer surface, reducing heat transfer efficiency. In addition, corrosion may cause steam leaks. As a result, corrosion increases maintenance and equipment costs.

10.3 Steam Supply - Combined Heat and Power (CHP)

Combined heat and power (CHP, or cogeneration) is the sequential production of two forms of useful energy from a single fuel source. In most CHP applications, chemical energy in fuel is converted to both mechanical and thermal energy. The mechanical energy is generally used to generate electricity, while the thermal energy or heat is used to produce steam, hot water, or hot air.

CHP systems have the ability to extract more useful energy from fuel compared to traditional energy systems such as conventional power plants that only generate electricity and industrial boiler systems that only produce steam or hot water for process applications. CHP provides the opportunity to use internally generated fuels for power production, allowing greater independence of grid operation and even export to the grid. This increases reliability of supply as well as the cost-effectiveness. In addition, transportation losses are minimized when CHP systems are located at or near the end user (Oland, 2004).

The cost benefits of power export to the grid will depend on the regulation where the industry is located, but can provide a major economic incentive. Not all states allow wheeling of power (i.e. sales of power directly to another customer using the grid for transport) and for the states that do allow wheeling, regulations may also differ with respect to the tariff structure for power sales to the grid operator.

Third parties can also develop CHP. In this scenario, the third party company owns and operates the system, which avoids the capital expenditures associated with CHP projects, but gains part of the benefits of a more energy-efficient system of heat and electricity supply. In

2000, about 60% of the cogeneration facilities operated within the U.S. manufacturing industry had some third party involvement (Onsite 2000). In some cases, the plant neighborhood offers opportunities for innovative collaborations.

For cogeneration projects, heat recovery schemes are broadly classified as topping-cycle, bottoming-cycle, or combined cycling systems depending on the sequence the fuel energy is used (Oland, 2004). In topping-cycle systems, in which the fuel is first used to generate electricity. Waste heat from the prime mover is then recovered and used for process heating or cooling applications. In bottoming-cycle systems, high-temperature thermal energy is produced and first used for industrial applications, such as metal smelting furnaces. Waste heat recovered from the industrial process is then used to drive a turbine to produce electric power. It is possible to use both cycles in the same system to create what is commonly referred to as a combined-cycle system. In these systems, electricity is produced by two separate electrical generators. One generator is part of the topping-cycle system, while the other is part of the bottoming-cycle system.

Prime movers for industrial CHP systems include steam turbines, gas turbines, reciprocating engines, fuel cells, and microturbines (Oland, 2004). Selecting a prime mover that is well suited for a particular CHP application requires knowledge of its design and performance characteristics.

There are a variety of CHP applications. In order to be concise, this chapter only describes a few energy efficiency measures. For more information on CHP systems, the reader is referred to Oland (2004).

Combined Cycle. Conventional cogeneration uses a steam boiler and steam turbine (back pressure turbine) to generate electricity. Steam systems generally have a low efficiency and high investment costs. Modern cogeneration units are gas turbine based, using either a simple cycle system (gas turbine with waste heat recovery boiler), a Cheng cycle or STIG (with steam injection in the gas turbine, see below), or a combined cycle integrating a gas turbine with a steam cycle for larger systems. The latter system can also be used to “re-power” existing steam turbine systems. Gas turbine systems mainly use natural gas, although specially designed combustion chambers allow the use of varying gas mixtures.

Integrated steel plants produce significant levels of off-gases (i.e. coke oven gas, blast furnace gas, and basic oxygen furnace gas). Specially adapted turbines can burn these low calorific value gases at electrical generation efficiencies of 45% (low heating value, LHV) but internal compressor loads reduce these efficiencies to 33%. Mitsubishi Heavy Industries has developed such a turbine and it is now used in several steel plants, e.g. Kawasaki Chiba Works (Japan) and Corus IJmuiden (The Netherlands). These systems are also characterized by low NOx emissions (20 ppm) (Worrell et al., 1999).

Steam Injected Gas Turbines (STIG or Cheng cycle) can absorb excess steam that is produced for example due to seasonal reduced heating needs, to boost power production by injecting the steam in the turbine. The size of typical STIGs starts around 5 MW_e, and is currently scaled up to sizes of 125 MW_e. STIGs have been installed at over 50 sites worldwide, and are found in various industries and applications, especially in Japan and Europe, as well as in the U.S. Energy savings and payback period will depend on the local circumstances (e.g. energy patterns, power sales conditions). In the United States, the Cheng cycle is marketed by International Power Systems (San Jose, California). The Austrian oil company OMV has considered the use of a STIG to upgrade an existing cogeneration system. The authors do not know of any current commercial applications of STIG in the steel industry.

Steam turbines are often used as part of the CHP system in the chemical industry or as standalone systems for power generation. The efficiency of the steam turbine is determined by the inlet steam pressure and temperature as well as the outlet pressure. Each turbine is designed for a certain steam inlet pressure and temperature, and operators should make sure that the steam inlet temperature and pressure are optimal. An 18°F decrease in steam inlet temperature will reduce the efficiency of the steam turbine by 1.1% (Patel and Nath, 2000). Similarly, maintaining exhaust vacuum of a condensing turbine or the outlet pressure of a backpressure turbine too high will result in efficiency losses.

Combined cycle CHP plants include heat-recovery boilers. The design of these units differs considerably from the design of conventional oil or gas fired boilers and requires good understanding of the temperature profile in the unit. Options to improve efficiency include proper pinch analysis and auxiliary firing as discussed by Ganapathy (2001).

High-Temperature CHP. Turbines can be pre-coupled to a crude distillation unit (or other continuously operated processes with an applicable temperature range). The off gases of the gas turbine can be used to supply the heat for the distillation furnace, if the outlet temperature of the turbine is high enough. One option is the so-called `repowering' 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.

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 or to preheat the combustion air. This option requires replacing the existing furnaces, since the radiative heat transfer from gas turbine exhaust gases is much smaller than from combustion gases, due to their lower temperature (Worrell *et al.*, 1997). A distinction is made between two different types. In the first type, the exhaust heat of a gas turbine is led to a waste heat 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. By means of a heat exchanger, the heat content is transferred to the process feed. In both systems, the remaining heat in the exhaust gases after heating the process feed should be used for lower temperature purposes to achieve a high overall efficiency. The second type is more reliable, due to the fact that a thermal oil buffer can be included. 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. An installation of the first type is used at a Shell refinery in Fredericia, Denmark. The remaining low temperature heat is used for district heating.

Steam Expansion Turbines. Steam is generated at high pressures, but often the pressure is reduced to allow the steam to be used by different processes. For example, steam is generated at 120 to 150 psig. This steam then flows through the distribution system within the plant. The pressure is reduced to as low as 10-15 psig for use in different process. Once the heat has been extracted, the condensate is often returned to the steam generating plant. Typically, the pressure reduction is accomplished through a pressure reduction valve (PRV). These valves do not recover the energy embodied in the pressure drop. This energy could be recovered by using a micro-scale backpressure steam turbine. Several manufactures produce these turbine sets, such as Turbosteam (previously owned by Trigen) and Dresser-Rand.

The potential for application will depend on the particular steam system used. Applications of this technology have been commercially demonstrated for various installations. The investments of a typical expansion turbine are estimated at 600 $/kWe, and operation and maintenance costs at 0.011 $/kWh.

In an energy efficiency assessment of 3M's Hutchinson, Minnesota, facility, the installation of a steam turbine replacing a pressure reduction valve was identified as a project that would save 3,166 MWh of electricity per year. Capital costs for the project were estimated at $604,034 and avoided first year energy expenses at $163,999 (U.S. DOE-OIT, 2003c), resulting in a payback period of 3-4 years.

Natural Gas Expansion Turbines. Lehman and Worrell (2001) describe that it is possible to install expansion turbines that capture the energy from high-pressure gas transmission. These turbines use the pressure drop when natural gas from high-pressure pipelines is decompressed for local networks to generate power, utilizing otherwise unused pressure in the natural gas grid. Gas is transmitted at high pressures, from 200 to 1500 psi (14 to 100 bar). A typical pressure for gas entering a turbine is 580 to 1020 psi, with an exit pressure (back pressure) of 70 to 150 psi (5-10 bar) (Lehman and Worrell, 2001). Gas generally enters an expansion turbine at ambient temperature, and expansion from this temperature leaves gas too cold for further transmission upon exiting the expansion turbine. This necessitates heating the gas just before or after expansion. The heating is generally performed with either a combined heat and power (CHP) unit, or a nearby source of waste heat. For power recovery applications, turbines are generally rated from 150 kW to 2500 kW (Lehman and Worrell, 2001).

An expansion turbine was installed by Corus (Netherlands) in 1994. The 2 MW expansion turbine generates roughly 11,000 MWh of electricity, while the strip mill delivered a maximum of 12,500 MWh of low-temperature waste heat to the gas flow (Lehman and Worrell, 2001). Thus, roughly 88% of the maximum heat input to the high-pressure gas produced as electricity.

10.4 Steam Distribution System Efficiency Measures

Shutting Off Excess Distribution Lines. Installations and steam demands change over time, which may lead to under-utilization of steam distribution capacity utilization, and extra heat losses. It may be too expensive to optimize the system for changed steam demands. Still, checking for excess distribution lines and shutting off those lines is a cost-effective way to reduce steam distribution losses.

Proper Pipe Sizing. When designing new steam distribution systems, it is very important to account for the velocity and pressure drop. This reduces the risk of oversizing a steam pipe, which is not only a cost issue but would also lead to higher heat losses. A pipe that is too small may lead to erosion and increased pressure drop (Van de Ruit, 2000).

Insulation. Insulation can typically reduce energy losses by 90% and help ensure proper steam pressure at plant equipment (U.S. DOE-OIT, 2006). The application of insulation can lead to significant energy cost savings with relatively short payback periods. For instance, the average payback period of the installation of insulation on steam and hot water lines is 1.0 years, on condensate lines is 1.1 years, and on the feedwater tank is 1.1 years (U.S. DOE-IAC, 2006). Weirton Steel Corporation in Weirton, West Virginia, found that for every 100 feet of piping insulated, energy savings could be up to $19,000 each year (U.S. DOE-ITP EM, 2000).

The improvement of existing insulation can often lead to further savings. This measure can consist of applying more or better insulating material. Crucial factors in choosing insulating material include: low thermal conductivity, dimensional stability under temperature change, resistance to water absorption, and resistance to combustion. Other characteristics of insulating material may also be important depending on the application, e.g. tolerance of large temperature variations and system vibration, and compressive strength where insulation is load bearing (Baen and Barth, 1994).

Some types of insulation can become brittle, or rot. As a result, energy can be saved by a regular inspection and maintenance system (CIBO, 1998). The repair of faulty insulation has an average payback time of 0.8 years (U.S. DOE-IAC, 2006).

During maintenance, the insulation that covers pipes, valves, and fittings is often damaged or removed and not replaced. This can be avoided by using removable and reusable insulating pads which are available to cover almost any surface (U.S. DOE-OIT, 2006).

The U.S. Department of Energy has developed the software tool 3E-Plus to evaluate the insulation for steam systems (see Appendix E).

Checking and Monitoring Steam Traps. A simple program of checking steam traps to ensure they operate properly can save significant amounts of energy. If the steam traps are not maintained for 3 to 5 years, 15-30% of the traps can be malfunctioning, thus allowing live steam to escape into the condensate return system. In systems with a regularly scheduled maintenance program, leaking traps should account for less than 5% of the trap population (U.S. DOE-OIT, 2006). The repair and replacement of steam traps has an average payback time of 0.4 years (U.S. DOE-IAC, 2006). Energy savings for a regular system of steam trap checks and follow-up maintenance is estimated to be up to 10% (Jones, 1997; Bloss, 1997).

Attaching automated monitors to steam traps in conjunction with a maintenance program can save even more energy, without significant added cost. Such a system is an improvement over steam trap maintenance alone, because it gives quicker notice of steam trap malfunctioning or failure. Using automatic monitoring is estimated to save an additional 5% over steam trap maintenance, with a payback of 0.75 year (for the UK) (Johnston, 1995; Jones, 1997). Systems that are able to implement steam trap maintenance are also likely to be able to implement automatic monitoring.

Thermostatic Steam Traps. Using modern thermostatic element steam traps can reduce energy use while improving reliability. The main advantages offered by these traps are that they open when the temperature is close to that of the saturated steam (within 0.6°F (2°C)), purge non-condensable gases after each opening, and are open on startup to allow a fast steam system warm-up. These traps are also very reliable, and useable for a large range of steam pressures (Alesson, 1995). Energy savings will vary depending on the steam traps installed and the state of maintenance.

Examples of thermostatic traps are pinch traps. In these traps, a modulator automatically closes off flow as a chemically resistant elastomer around the modulator expands with the passage of hot condensate. As the condensate builds up and cools, the elastomer around the modulator contracts, allowing the orifice to open and create flow. It automatically responds to condensate temperature, has no live steam losses and uses energy in the steam line at maximum efficiency (Kane *et al.*, 1998).

Shutting of Steam Traps. Other energy savings can come from shutting of steam traps on superheated steam lines when they are not in use. This has an average payback time 0.2 years (U.S. DOE-IAC, 2006).

Reduction of Distribution Pipe Leaks. As with steam traps, the distribution pipes themselves often have leaks that go unnoticed without a program of regular inspection and maintenance. On average leak repair has a payback period of 0.4 years (U.S. DOE-IAC, 2006).

Vapor Recompression to Recover Low-Pressure Waste Steam. Low-pressure steam exhaust from industrial operations is usually vented to the atmosphere or condensed in a cooling tower. Simultaneously, other plant operations may require intermediate-pressure steam at 20 to 50 psig. Instead of letting down high-pressure steam across a throttling valve to meet these needs, low-pressure waste steam can be mechanically compressed or boosted to a higher pressure so that it can be reused. Recovery of the latent heat content of low-pressure steam reduces the boiler load, resulting in energy and fuel cost savings. Low-pressure steam potential uses include driving evaporation and distillation processes, producing hot water, space heating, producing a vacuum, or chilling water.

Vapor recompression relies upon a mechanical compressor or steam jet ejector to increase the temperature of the latent heat in steam to render it usable for process duties. It is noted that the steam jet ejector is known for its simple construction, insensitivity to fouling, easy installation, low capital and installation costs, easy maintenance with no moving parts, and long useful operating lives.

Recompression typically requires only 5% to 10% of the energy required to raise an equivalent amount of steam in a boiler. Vapor recompression can be used in steam distribution systems to boost system pressures that have dropped to unacceptably low levels (U.S. DOE-OIT, 2006).

Recovery of Flash Steam. When a steam trap purges condensate from a pressurized steam distribution system to ambient pressure, flash steam is produced. Depending on the pressures involved, the flash steam contains approximately 10% to 40% of the energy content of the original condensate. This energy can be recovered by a heat exchanger and used for space heating or feed water preheating (Johnston, 1995; U.S. DOE-OIT, 2006). The potential for this measure is site dependent, as it is unlikely that a plant will build an entirely new system of pipes to transport this low-grade steam, unless it can be used close to the steam traps. Sites using multi-pressure steam systems can route the flash steam formed from high-pressure condensate to reduced pressure systems.

The flashing of high pressure condensate can also serve as part of the strategy to regenerate low-pressure steam. Low-pressure process steam requirements are usually met by throttling high-pressure steam, but a portion of the process requirements can be achieved at low cost by flashing high-pressure condensate. Flashing is particularly attractive when it is not economically feasible to return the high-pressure condensate to the boiler. The economics of heat recovery projects are most favorable when the waste steam heat content is high and the flow is continuous. Seasonal space heating is not the most desirable end use. Flashing of high pressure condensate to regenerate low-pressure steam has an average payback period of 0.7 years (U.S. DOE-IAC, 2006).

11 Motor Systems

Motor systems, which include motor driven units such as rolling mills, pumps, conveyors, fans, and materials handling equipment, consume 7% of the U.S. iron and steel industry's energy use. More than 90% of the final energy used for motor systems in the industry is electricity (U.S. DOE, 2004).

A profile of the energy use and losses for motor systems in the U.S. iron and steel industry is shown in Figure 11-1. Figure 11-1 shows that about 70% of the energy input to motor-driven systems is lost due to system inefficiencies.

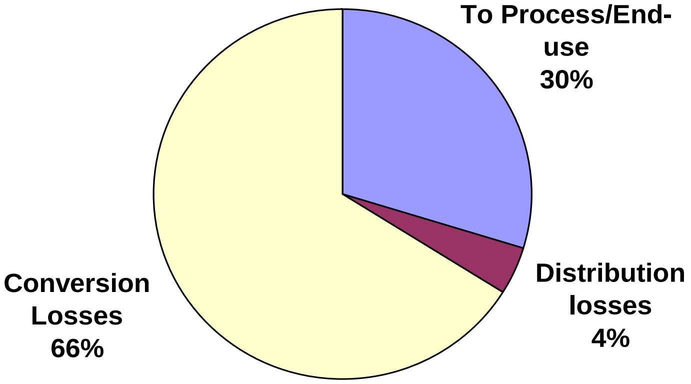

Figure 11-1. Energy use and loss profile of motor systems in the U.S. iron and steel industry (Source: U.S. DOE 2004)

A more detailed breakdown of the energy use and losses for motor systems is depicted in Figure 4-711-2. Figure 11-2 shows that compressed air systems and materials processing (e.g., grinding, mixing, crushing) account for the largest losses.

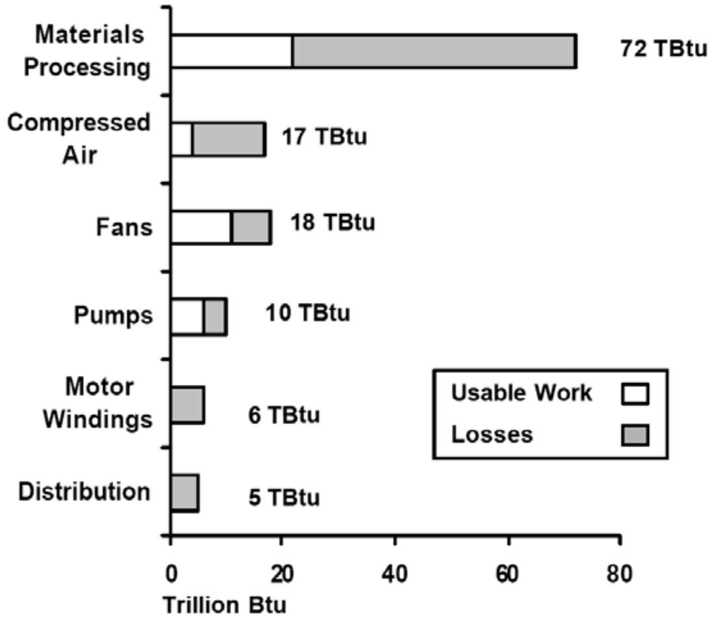

Figure 11-2. Breakdown of motor system's energy use and loss in the U.S. iron and steel industry by type of motor system (Source: U.S. DOE 2004)

When considering energy efficiency improvements to a facility's motor systems, a systems approach incorporating pumps, compressors, and fans must be used in order to attain optimal savings and performance.

In the following, considerations with respect to energy use and energy-saving opportunities for a motor system are presented and in some cases illustrated by case studies. Pumping, fan and compressed air systems are discussed in the next three chapters of this guide.

Motor Management Plan. A motor management plan is an essential part of a plant's energy management strategy. Having a motor management plan in place can help companies realize long-term motor system energy savings and will ensure that motor failures are handled in a quick and cost effective manner. The Motor Decisions Matter^{SM} Campaign suggests the following key elements for a sound motor management plan (CEE, 2007):

1. Creation of a motor survey and tracking program.
2. Development of guidelines for proactive repair/replace decisions.
3. Preparation for motor failure by creating a spares inventory.
4. Development of a purchasing specification.
5. Development of a repair specification.
6. Development and implementation of a predictive and preventive maintenance program.

The Motor Decisions Matter^{SM} Campaign's *Motor Planning Kit* contains further details on each of these elements (CEE, 2007).

Maintenance. The purposes of motor maintenance are to prolong motor life and to foresee a motor failure. Motor maintenance measures can therefore be categorized as either preventative or predictive.

Preventative measures, include voltage imbalance minimization, load consideration, motor alignment, lubrication and motor ventilation. Some of these measures are further discussed later in this chapter. Note that some measures aim to prevent increased motor temperature which leads to increased winding resistance, shortened motor life, and increased energy consumption. The purpose of predictive motor maintenance is to observe ongoing motor temperature, vibration, and other operating data to identify when it becomes necessary to overhaul or replace a motor before failure occurs (Barnish *et al.*, 1997).

The savings associated with an ongoing motor maintenance program could range from 2% to 30% of total motor system energy use (Efficiency Partnership, 2004).

Life Cycle Costing (LCC). Up to 95% of a motor's costs can be attributed to the energy it consumes over its lifetime, while only around 5% of a motor's costs are typically attributed to its purchase, installation, and maintenance (CEE, 2007). When selecting and purchasing a motor, it is therefore important to consider the lifecycle costs of that motor rather than just its initial purchase and installation costs. A specific life cycle costing (LCC) guide has been developed for pump systems and also provides an introduction to LCC for motor systems (Fenning *et al.*, 2001). Although LCC has clear benefits, it may not be adopted, since the electricity bill and the motor selection are handled by different departments within a company, or without a specific corporate purchasing policy or guideline for motors.

Energy-Efficient Motors. Energy-efficient motors reduce energy losses through improved design, better materials, tighter tolerances, and improved manufacturing techniques. With proper installation, energy-efficient motors can also stay cooler, may help reduce facility heating loads, and have higher service factors, longer bearing life, longer insulation life, and less vibration.

To be considered energy-efficient in the U.S., a motor must meet performance criteria published by the National Electrical Manufacturers Association (NEMA). The NEMA Premium Efficiency Electric Motor specification was developed to address confusion with respect to what constituted the most efficient motors available in the market. It currently serves as the benchmark for energy-efficient motors. NEMA Premium® also denotes a brand name for motors which meet this specification.

The choice of installing a premium efficiency motor strongly depends on motor operating conditions and the life cycle costs associated with the investment. In general, premium efficiency motors are most economically attractive when replacing motors with annual operation exceeding 2,000 hours/year. Sometimes, even replacing an operating motor with a premium efficiency model may have a low payback period. According to data from the Copper Development Association, the upgrade to high-efficiency motors, as compared to motors that achieve the minimum efficiency as specified by the Energy Policy Act of 1992 can have paybacks of less than 15 months for 50 hp motors (CDA, 2001).

Rewinding of Motors. In some cases, it may be cost-effective to rewind an existing energy-efficient motor, instead of purchasing a new motor. As a rule of thumb, when rewinding costs exceed 60% of the costs of a new motor, purchasing the new motor may be a better choice (CEE, 2007).

When repairing or rewinding a motor, it is important to choose a motor service center that follows best practice motor rewinding standards in order to minimize potential efficiency losses. Such standards have been offered by the Electric Apparatus Service Association (EASA) (EASA, 2006). When best rewinding practices are implemented, efficiency losses are typically less than 1% (EASA, 2003).

Software tools such as MotorMaster$^+$ (see Appendix E) can help identify attractive applications of premium efficiency motors based on the specific conditions at a given plant. Also, NEMA and other organizations have created the Motor Decisions Matter^{SM} campaign to help industrial and commercial customers to evaluate their motor repair and replacement options, promote cost-effective applications of NEMA Premium® motors and "best practice" repair, and support the development of motor management plans before motors fail.

Proper Motor Sizing. It is a persistent myth that oversized motors, especially motors operating below 50% of rated load, are not efficient and should be immediately replaced with appropriately sized energy-efficient units. In actuality, several pieces of information are required to complete an accurate assessment of energy savings. They are the load on the motor, the operating efficiency of the motor at that load point, the full-load speed (in evolutions per minute, rpm) of the motor to be replaced, and the full-load speed of the downsized replacement motor

The efficiency of both standard and energy-efficient motors typically peaks near 75% of full load and is relatively flat down to the 50% load point. Motors in the larger size ranges can operate with reasonably high efficiency at loads down to 25% of rated load. There are two additional trends: larger motors exhibit both higher full- and partial-load efficiency values, and the efficiency decline below the 50% load point occurs more rapidly for the smaller size motors.

The U.S. DOE's BestPractices program provides a fact sheet that can assist in decisions regarding replacement of oversized and under loaded motors (U.S. DOE, 1996b). Additionally, software packages such as MotorMaster$^+$ (see Appendix E) can aid in proper motor selection.

Adjustable Speed Drives (ASDs)[11]. Adjustable-speed drives better match speed to load requirements for motor operations, and therefore ensure that motor energy use is optimized to a given application. As the energy use of motors is approximately proportional to the cube of

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[11] Several terms are used in practice to describe a motor system that permits a mechanical load to be driven at variable speeds, including adjustable speed drives (ASDs), variable speed drives (VSDs), adjustable frequency drives (AFDs), and variable frequency drives (VFDs). In this guide, these different terms are interchangeable.

the flow rate,[12] relatively small reductions in flow, which are proportional to pump speed, already yield significant energy savings.

Adjustable-speed drive systems are offered by many suppliers and are available worldwide. Worrell *et al.* (1997) provides an overview of savings achieved with ASDs in a wide array of applications; typical energy savings were shown to vary between 7% and 60% with estimated simple payback periods ranging from 0.8 to 2.8 years (Hackett *et al.*, 2005).

Steam Turbines. Steam turbine drives could be considered to drive rotating equipment. Steam turbine drives are equipped with throttling valves or nozzle governors to modulate steam flow and achieve variable speed operation. The steam turbine drive is thus capable of serving the same function as an induction motor coupled to an inverter or adjustable speed drive. This service generally calls for a backpressure non-condensing steam turbine. The low-pressure steam turbine exhaust is available for feedwater heating, preheating of deaerator makeup water, and/or process requirements.

Steam turbine drives may be installed for continuous duty under severe operating conditions, or used for load shaping (e.g., demand limiting), standby, or emergency service. They do not fail when overloaded, exhibit the high starting torque required for constant torque loads such as positive displacement pumps, are inherently rugged and reliable low-maintenance devices. They are also easy to control and offer enclosed, non-sparking operation suitable for use in explosive atmospheres or highly corrosive environments. The total annual energy savings are strongly dependent upon the specific application (U.S. DOE-OIT, 2006).

Power Factor Correction. Power factor is the ratio of working power to apparent power. It measures how effectively electrical power is being used. A high power factor signals efficient utilization of electrical power, while a low power factor indicates poor utilization of electrical power. Inductive loads like transformers, electric motors, and HID lighting may cause a low power factor. The power factor can be corrected by minimizing idling of electric motors (a motor that is turned off consumes no energy), replacing motors with premium efficiency motors (see above), and installing capacitors in the AC circuit to reduce the magnitude of reactive power in the system (U.S. DOE, 1996a).

Minimizing Voltage Unbalances. A voltage unbalance degrades the performance and shortens the life of three-phase motors. A voltage unbalance causes a current unbalance, which will result in torque pulsations, increased vibration and mechanical stress, increased losses, and motor overheating, which can reduce the life of a motor's winding insulation. Voltage unbalances may be caused by faulty operation of power factor correction equipment, an unbalanced transformer bank, or an open circuit. A rule of thumb is that the voltage unbalance at the motor terminals should not exceed 1%, although even a 1% unbalance will

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[12] This equation applies to dynamic systems only. Systems that solely consist of lifting (static head systems) will accrue no benefits from ASDs (but will often actually become more inefficient) because they are independent of flow rate. Similarly, systems with more static head will accrue fewer benefits than systems that are largely dynamic (friction) systems. More careful calculations must be performed to determine actual benefits, if any, for these systems.

reduce motor efficiency at part load operation. A 2.5% unbalance will reduce motor efficiency at full load operation.

By regularly monitoring the voltages at the motor terminal and through regular thermographic inspections of motors, voltage unbalances may be identified. It is also recommended to verify that single-phase loads are uniformly distributed and to install ground fault indicators as required. Another indicator for voltage unbalance is a 120 Hz vibration, which should prompt an immediate check of voltage balance (U.S. DOE-OIT, 2005b).

For a 100 hp motor operating 8,000 hours per year, a correction of the voltage unbalance from 2.5% to 1% will result in electricity savings of 9,500 (U.S. DOE-OIT, 2005b). The typical payback period for voltage controller installation on lightly loaded motors in the U.S. is 2.6 years (U.S. DOE-IAC, 2006).

12 Pump systems

Pump systems consist of pumps, drivers, pipe installation, and controls (such as ASDs or throttles) and are a part of the overall motor system (see also chapter 11). Pump applications in the iron and steel industry include pumps for circulating cooling fluids of walls and injection systems.

Pumps account for about 8% of the electricity use of motor systems in the U.S. iron and steel industry. Accordingly, pump systems account for about 0.5% of the total energy use of the U.S. iron and steel industry (U.S. DOE, 2004). Nadel *et al.* (2002) estimate that a 5-10% increase in energy efficiency can be made by using improved equipment and reduce friction of pumps. Another 10-20% increase can be obtained by optimizing pump systems.

For optimal savings and performance, it is recommended that a systems approach be used incorporating pumps, compressors, motors, and fans. There are two main ways to increase pump system efficiency: reducing the friction in dynamic pump systems or adjusting the system so that it draws closer to the best efficiency point on the pump curve (Hovstadius, 2002).

In the following, considerations with respect to energy use and energy-saving opportunities for a pump system are presented and in some cases illustrated by case studies.

Operation and Maintenance. Inadequate maintenance lowers pump system efficiency, causes pumps to wear out more quickly and increases costs. Better maintenance will reduce these problems and save energy. Proper maintenance includes the following (Hydraulic Institute, 1994; U.S. DOE, 1999):

- Replacement of worn impellers, especially in caustic or semi-solid applications
- Bearing inspection and repair
- Bearing lubrication replacement, once annually or semiannually
- Inspection and replacement of packing seals
- Inspection and replacement of mechanical seals
- Wear ring and impeller replacement
- Pump/motor alignment check
- Avoid throttling losses (a large opportunity)

Typical energy savings for operations and maintenance are estimated to be between 2% and 7% of pumping electricity use for the U.S. industry. The payback usually is less than one year (Xenergy, 1998; U.S. DOE-OIT, 2002).

Monitoring. Monitoring in conjunction with operations and maintenance can be used to detect problems and determine solutions to create a more efficient system. Monitoring can determine clearances that need be adjusted, indicate blockage, impeller damage, inadequate suction, operation outside preferences, clogged or gas-filled pumps or pipes, or worn out pumps. Monitoring should include:

- Wear monitoring
- Vibration analyses
- Pressure and flow monitoring
- Current or power monitoring
- Differential head and temperature rise across the pump (also known as thermodynamic monitoring)
- Distribution system inspection for scaling or contaminant build-up

One of the best indicators to follow for monitoring is specific energy or power consumption as a function of the flow rate (Hovstadius, 2007).

Life Cycle Costing (LCC). Depending on the pump application, energy costs may make up about 95% of the lifetime costs of the pump. Hence, the initial choice of a pump system should be highly dependent on energy cost considerations rather than on initial costs. Hodgson and Walters (2002) discuss software (named OPSOP) developed to optimize of the design of a new pumping system which focuses on the lifecycle costs. In addition, they discuss several case studies in which they show large reductions in energy use and lifetime costs of a complete pumping system.

Controls. The objective of any control strategy is to shut off unneeded pumps or to reduce the load of individual pumps. Remote controls enable pumping systems to be started and stopped relatively quickly and accurately, and reduce the required labor with respect to traditional control systems. In 2000, Cisco Systems (CA) upgraded the controls on its fountain pumps that turn off the pumps during peak hours (CEC and OIT, 2002). The wireless control system was able to control all pumps simultaneously from one location. The project saved 62% of the fountain pumps' total energy consumption. In addition to energy savings, the project reduced maintenance costs and increased the pumping system's equipment life.

Reduction of Demand. Holding tanks can be used to equalize the flow over the production cycle, enhancing energy efficiency and potentially reducing the need to add pump capacity. In addition, bypass loops and other unnecessary flows can be eliminated. Energy savings may be as high as 5-10% for each of these steps (Easton Consultants, 1995). Total head requirements can also be reduced by lowering process static pressure, minimizing elevation rise from suction tank to discharge tank, reducing static elevation change by use of siphons and lowering spray nozzle velocities.

Efficient Pumps. Pump efficiency may degrade 10 to 25% in its lifetime. Industry experts, however, point out that this degrading performance is not necessarily due to the age of the pump but can also be caused by changes in the process which may have caused a mismatch between the pump capacity and its operation. Nevertheless, it can sometimes be more efficient to buy a new pump, also because newer models are more efficient.

A number of pumps are available for specific pressure head and flow rate capacity requirements. Choosing the right pump often saves both in operating costs and in capital costs (of purchasing another pump). For a given duty, a pump that runs at the highest speed suitable for the application will generally be the most efficient option with the lowest initial cost (Hydraulic Institute and Europump, 2001). Exceptions include slurry handling pumps, high specific speed pumps or in applications where the pump needs a very low minimum net positive suction head at the pump inlet.

Replacing a pump with a new efficient one reduces energy use by 2% to 10% (Nadel *et al.* 2002). Higher efficiency motors have been shown to increase the efficiency of the pump system 2 to 5% (Tutterow, 1999).

Proper Pump Sizing. A pump may be incorrectly sized for current needs if it operates under throttled conditions, has a high bypass flow rate, or has a flow rate that varies more than 30% from its best efficiency point flow rate (U.S. DOE-OIT, 2005). Where peak loads can be reduced, pump size can also be reduced. A smaller motor will however not always result in energy savings, as these depend on the load of the motor. Only if the larger motor operates at a low efficiency, replacement may result in energy savings. Pump loads may be reduced with alternative pump configurations and improved operations and management practices.

When pumps are dramatically oversized, speed can be reduced with gear or belt drives or a slower speed motor. This practice, however, is not common. Paybacks for implementing these solutions are less than one year (U.S. DOE-OIT, 2002a). Oversized and throttled pumps that produce excess pressure are excellent candidates for impeller replacement or "trimming," to save energy and reduce costs (see below: Impeller trimming (or shaving sheaves)). Correcting for pump oversizing can save 15% to 25% of electricity consumption for pumping on average for the U.S. industry (Easton Consultants, 1995).

The Welches Point Pump Station, a medium-sized waste water treatment plant located in Milford (CT), decided to replace one of their system's three identical pumps with one smaller model as a participant in the Department of Energy's Motor Challenge Program (Flygt, 2002). They found that the smaller pump could more efficiently handle typical system flows allowing the remaining two larger pumps to be reserved for peak flows. Whereas the smaller pump needed to run longer to handle the same total volume, its slower pace and reduced pressure resulted in less friction-related losses and less wear and tear. Substituting the smaller pump had projected savings of more than 20% of the pump system's annual electrical energy consumption. In addition to the projected energy savings, less wear on the system resulted in less maintenance, less downtime, and longer life of the equipment. The station noise was significantly reduced with the smaller pump.

Multiple Pumps for Varying Loads. The use of multiple pumps is often the most cost-effective and most energy-efficient solution for varying loads, particularly in a static head-dominated system. Alternatively, adjustable speed drives could be considered for dynamic systems (see below).

Parallel pumps offer redundancy and increased reliability. One case study of a Finnish pulp and paper plant indicated that the installation of an additional small pump (a "pony pump"), running in parallel to the existing pump, reduced the load in the larger pump in all cases except during startup. The energy savings were estimated at 58% per year (Hydraulic Institute and Europump, 2001).

The installation of parallel systems for highly variable loads on average would save 10% to 50% of the electricity consumption for pumping for the U.S. industry (Easton Consultants, 1995).

Impeller Trimming (or shaving sheaves). Trimming reduces the impeller's tip speed, which in turn reduces the amount of energy imparted to the pumped fluid; as a result, the pump's flow rate and pressure both decrease. A smaller or trimmed impeller can thus be used efficiently in applications in which the current impeller is producing excessive heat (U.S. DOE-OIT, 2005). In the food processing, paper and petrochemical industries, trimming impellers or lowering gear ratios is estimated to save as much as 75% of the electricity consumption for specific pump applications (Xenergy, 1998).

In one case study in the chemical processing industry, the impeller was reduced from 320 mm to 280 mm (13 to 11 inches), thereby reducing the power demand by more than 25%. In addition to energy savings, maintenance costs were reduced, system stability was improved, cavitation was reduced and excessive vibration and noise were eliminated (Hydraulic Institute and Europump, 2001).

In another case study, Salt Union Ltd., the largest salt producer in the UK, trimmed the diameter of a pump impeller at its plant from 320 mm to 280 mm (13 to 11 inches). After trimming the impeller, they found power reductions of 30%. Maintenance costs were reduced, system stability was improved, cavitation was reduced and excessive vibration and noise were eliminated. Furthermore, due to the large decrease in power consumption, the 110 kW motor could be replaced with a 75kW motor leading to additional energy savings (Best Practice Programme, 1996).

Adjustable Speed Drives (ASDs). ASDs better match speed to load requirements for pumps. As for motors, energy use of pumps is approximately proportional to the cube of the flow rate[13] and relatively small reductions in flow may yield significant energy savings. New installations may result in short payback periods. In addition, the installation of ASDs improves overall productivity, control and product quality, and reduces wear on equipment, thereby reducing future maintenance costs.

Similar to being able to adjust load in motor systems, including modulation features with pumps is estimated to save between 20% and 50% of pump energy consumption, at relatively short payback periods, depending on application, pump size, load and load variation (Xenergy, 1998; Best Practice Programme, 1996). As a general rule of thumb, unless the pump curves are exceptionally flat, a 10% regulation in flow should produce pump savings of 20% and 20% regulation should produce savings of 40% (Best Practice Programme, 1996).

In a systematic assessment of the motor system at the 3M corporate headquarters, it turned out that the reheat water supply system of a building's HVAC system was controlled by diverting

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[13] This equation applies to dynamic systems only (see chapter 11)

the unneeded flow of a full-flow operating pump through a by-pass valve. Replacing the motors with more efficient ones controlled by ASDs saved a substantial amount of electricity and had a simple payback time of approximately 2.6 years (U.S. DOE-OIT 2002b).

Hodgson and Walters (2002) discuss the application of an ASD to replace a throttle of a newly built pumping system. Optimization of the design using a dedicated software package led to the recommendation to install an ASD. This would result in 71% lower energy costs over the lifetime of the system and a 54% reduction in total lifetime costs of the system.

Avoiding Throttling Valves. Variable speed drives or on-off regulated systems always save energy compared to throttling valves (Hovstadius, 2002).The use of these valves should therefore be avoided. Extensive use of throttling valves or bypass loops may be an indication of an oversized pump (Tutterow *et al.*, 2000).

Proper Pipe Sizing. Energy may be saved by reducing losses due to friction through the optimization of pipe diameters. The frictional power required depends on flow, pipe size (diameter), overall pipe length, pipe characteristics (surface roughness, material, etc.), and properties of the fluid being pumped. Correct sizing of pipes should be done at the system design stages where costs may not be restrictive (U.S. DOE-OIT, 2005).

Replacement of Belt Drives. Most pumps are directly driven. However, some pumps use standard V-belts which tend to stretch, slip, bend and compress, which lead to a loss of efficiency. Replacing standard V-belts with cog belts can save energy and money, even as a retrofit. It is even better to replace the pump by a direct driven system, resulting in increased savings of up to 8% and payback periods as short as 6 months (Studebaker, 2007).

Precision Castings, Surface Coatings or Polishing. The use of castings, coatings or polishing reduces surface roughness that in turn increases energy efficiency. It may also help maintain efficiency over time. This measure is more effective on smaller pumps. One case study in the steel industry analyzed the investment in surface coating on the mill supply pumps (350 kW pumps). They determined that the additional cost of coating would be paid back in 5 months by energy savings of 36 MWh (2%) per year (Hydraulic Institute and Europump, 2001). Energy savings for coating pump surfaces are estimated to be 2 to 3% over uncoated pumps (Best Practice Programme 1998).

Improvement of Sealing. Seal failure accounts for up to 70% of pump failures in many applications (Hydraulic Institute and Europump, 2001). The sealing arrangements on pumps will contribute to the power absorbed. Often the use of gas barrier seals, balanced seals, and no-contacting labyrinth seals can help to optimize pump efficiency.

Curtailing Leakage through Clearance Reduction. Internal leakage losses are a result of differential pressure across the clearance between the impeller and the pump casing. The larger the clearance, the greater is the internal leakage causing inefficiencies. The normal clearance in new pumps ranges from 0.014 to 0.04 in. (0.35 to 1.0 mm) (Hydraulic Institute and Europump, 2001). With wider clearances, the leakage increases almost linearly with the clearance. For example, a clearance of 0.2 in. (5 mm) decreases the efficiency by 7 to 15% in closed impellers and by 10 to 22% in semi-open impellers.

Dry Vacuum Pumps. Dry vacuum pumps were introduced in the semiconductor industry in Japan in the mid-1980s. The advantages of a dry vacuum pump are high energy efficiency, increased reliability, and reduce air and water pollution. Dry pumps therefore have major advantages in applications where contamination is a concern. Due to the higher investment costs of a dry pump, it is not expected to make significant inroads in the next years, except for special applications where contamination and pollution control are important drivers (Ryans and Bays, 2001).

13 Fan Systems

In any steel plant, fan systems are critical for process support and operational health and safety in steel plants. They are used in a number of applications, e.g. for shop ventilation, material handling, and boiler applications.

Fans use about 14% of the motor related energy in the U.S. iron and steel industry (U.S. DOE, 2004). Efficiencies of fan systems vary considerably across impeller types. The average energy saving potential in these systems in U.S. manufacturing is estimated to be 6% (Xenergy, 1998). For optimal savings and performance, it is recommended that a systems approach is used.

In the following, energy-saving opportunities for fan systems are presented and illustrated by case studies.

Minimizing Flow. Systems directly connected to a process source are inherently volume-limited, whereas systems that capture emissions with enclosures or hoods need to be optimized during the design process. Total enclosure of an emission source minimizes air flow and worker exposure. However, such enclosures can restrict visual observation of the process and hinder maintenance access. Hoods that cannot be designed for total enclosure should be located as close to the source as possible. A side-draft hood located twice the distance from the source can require as much as four times the exhaust volumetric flow rate as a total enclosure. Capture hoods for high-velocity emissions (from grinding, sawing, etc.) must be located so that the opening is in the direct path of the dust, fume, or mist. The American Conference of Governmental Industrial Hygienists' Industrial Ventilation – A Manual of Recommended Practice provides guidelines for good design of hoods, ducts, and similar equipment. Other factors such as explosive limits for the gas being collected, moisture content (dew point), and heat content, may influence the air volumetric flow-rate requirements, so there may be limits to the optimization (Lanham, 2007).

Minimizing Pressure. Pressure offers greater opportunities to reduce energy costs. A system with good airflow characteristics (duct velocities and sizes optimized), matched with the proper control device, pressure monitors, and variable-frequency drives, can help manage system pressure. Most baghouses or other collection devices will have varying pressure drops over the life of the system. Bags are generally more efficient at higher pressure drops, but then use more energy. Scrubbers, oxidizers, and electrostatic precipitators tend to operate at more constant resistance. A good pressure monitoring system that controls system volumetric flow rate can save thousands of dollars every year on the operation of even medium-sized systems. As ASDs become less expensive they are now being found on many installations. Be mindful of duct inefficiencies and fan system effects (elbows at inlets and outlets, etc). These shortcuts increase static pressure and operating costs for the life of the system (Lanham, 2007).

Control Density. Temperature, moisture, molecular weight, elevation, and the absolute pressure in the duct or vessel affect the density of the transporting gas. A density change may affect the hardware requirements for the system. Evaporative cooling, for example, reduces volume, but the higher-density air requires more power. This may be more than offset by reduced costs for smaller ducts, control devices, and fans (as well as lower the value for volumetric flow rate in the equation). Also, lower temperatures may allow use of less expensive collectors, fans, and peripheral devices (Lanham, 2007).

Fan Efficiency. The key to any design is proper fan selection. The design of the fan and its blade type can affect efficiency and power requirements significantly. Laboratory-measured peak fan efficiency may not be the most stable point of operation. If peak efficiency coincides with the peak of the pressure curve then there may be operational problems as volumetric flow rates vary with small changes in system pressure. The designer must consider both curves when selecting the best fan and operating point to optimize reliability and power usage. Fan type may dictate proper selection. Airfoil wheels, while more efficient, may not be a good choice when handling particulate laden air. (Lanham, 2007).

Proper Fan Sizing. Most of the fans are oversized for the particular application, which can result in efficiency losses of 1-5% (Xenergy, 1998). However, it may be more cost-effective to control the speed than to replace the fan system.

In an assessment of the Formosa Plastics Corporation polyethylene plant, it was discovered that a much smaller venting system than the one currently installed would meet venting requirements. Installation of a smaller vent blower resulted in electricity savings of 896,000 kWh per year and cost savings of $35,840. The payback time of the project was 0.4 year (U.S. DOE-OIT, 2005a).

Another project, identified in the same assessment, was the improvement of a product transfer system, consisting of 14 blowers through the various process steps. By increasing the transfer rate and by reducing the idle time by production control and distributive control system monitoring, 3,344,000 kWh of electricity could be saved annually, resulting in annual cost savings of $133,760 (payback time of 0.7 years).

Adjustable Speed Drives (ASDs). Significant energy savings can be achieved by installing adjustable speed drives on fans. Savings may vary between 14 and 49% when retrofitting fans with ASDs (Xenergy, 1998).

In an energy efficiency assessment of the Bethlehem Steel basic oxygen furnace (BOF) plant the assessment team found out that fan motors ran continuously throughout the year. The maximum flow however was only needed during one third of the cycle and the fan could be shut down during most of the remaining time. Installing variable speed drives on these fan motors was able to increase energy efficiency by nearly 50%, saving 15 GWh per year. The payback period was 2.1 years, and the measure was able to save $542,600 per year (AISI, 1999).

High Efficiency Belts (Cog Belts). Belts make up a variable, but significant portion of the fan system in many plants. Standard V-belts tend to stretch, slip, bend and compress, which lead to a loss of efficiency. Replacing standard V-belts with cog belts can save energy and money, even as a retrofit. Cog belts run cooler, last longer, require less maintenance and have an efficiency that is about 2% higher than standard V-belts. Typical payback periods will vary from less than one year to three years (Xenergy, 1998).

14 Compressed Air Systems

About 13% of the electricity used in motor systems in the U.S. iron and steel industry is used in compressed air systems (U.S. DOE, 2004). More than 85% of the electrical energy input to an air compressor is lost as waste heat, leaving less than 15% of the electrical energy consumed to be converted to pneumatic compressed air energy (U.S. DOE-ITP EM, 2008b). This makes compressed air an expensive energy carrier compared to other energy carriers.

Many opportunities exist to reduce energy use of compressed air systems. For optimal savings and performance, it is recommended that a systems approach be used. An example of the use of such an approach is provided by the case of United States Steel Corporation that completed a project in which the main compressed air system at the Edgar Thomson plant in Braddock, Pennsylvania, was overhauled. The installation of new compressors and dryers, along with the elimination of inappropriate compressed air uses, significantly improved the efficiency of the compressed air system. The overhaul resulted in savings of energy and maintenance costs. The total cost of the project's implementation was $521,000 and with total annual savings of $457,000, the simple payback was just under 14 months.

In the following, energy-saving opportunities for compressed air systems are presented and illustrated by case studies.

Demand Reduction. Because of the relatively expensive operating costs of compressed air systems, the minimum quantity of compressed air should be used for the shortest possible time, constantly monitored and reweighed against alternatives.

Maintenance. Inadequate maintenance can lower compression efficiency, increase air leakage or pressure variability and lead to increased operating temperatures, poor moisture control and excessive contamination. Better maintenance will reduce these problems and save energy. Proper maintenance includes the following (U.S. DOE, 1998, unless noted otherwise):

- Check for flow restrictions of any type in a system, such as an obstruction or roughness. These require higher operating pressures than are needed. Pressure rise resulting from resistance to flow increases the drive energy on the compressor by 1% of connected power for every 2 psi (0.14 bar) of differential (U.S. DOE, 1998; Ingersoll-Rand, 2001). Highest pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles and lubricators (demand side), as well as air/lubricant separators, aftercoolers, moisture separators, and dryers and filters (see below).
- Check for blocked pipeline filters to avoid increased pressure drop: Keep the compressor and intercooling surfaces clean and foul-free by inspecting and periodically cleaning filters. Seek filters with just a 1 psi (0.07 bar) pressure drop. A 2% reduction of annual energy consumption in compressed air systems is projected for more frequent filter changing (Radgen and Blaustein, 2001) and payback for filter cleaning is usually under 2 years (Ingersoll-Rand, 2001). Fixing improperly operating filters will also prevent contaminants from entering into equipment and causing them to wear out prematurely. Generally, when pressure drop exceeds 2 to 3 psig (0.14 to

0.21 bar) replace the particulate and lubricant removal elements. Also, consider adding filters in parallel to decrease air velocity and, therefore, decrease pressure drop. Be especially careful when using coalescing filters used to separate liquid water and oil from compressed air, since these can experience an efficiency drop to values below 30% of design flow (Scales, 2002).

- Keep compressors properly lubricated and cleaned. Compressor lubricant should be sampled and analyzed every 1000 hours and checked to make sure it is at the proper level. In addition to energy savings, this can help to avoid corrosion and degradation of the system.
- Inspect fans and water pumps for peak performance.
- Inspect drain traps to ensure they are not stuck in either the open or closed position and are clean. Malfunctioning traps should be cleaned and repaired instead of left open. According to vendors, inspecting and maintaining drains typically has a payback of less than 2 years (Ingersoll-Rand, 2001).
- Maintain the coolers on the compressor to ensure that the dryer gets the lowest possible inlet temperature (Ingersoll-Rand, 2001).
- Check belts for wear and adjust them. A good rule of thumb is to adjust them every 400 hours of operation.
- Check water-cooling systems for water quality (pH and total dissolved solids), flow and temperature. Clean and replace filters and heat exchangers per manufacturer's specifications.
- Minimize leaks (see also Reduce leaks section, below).
- Applications requiring compressed air should be checked for excessive pressure, duration or volume.
- Compressed air distribution systems should be checked when equipment has been reconfigured to be sure no air is flowing to unused equipment or obsolete parts of the compressed air distribution system.

Monitoring. Maintenance can be supported by monitoring using proper instrumentation, including (CADDET, 1997a):

- Pressure gauges on each receiver or main branch line and differential gauges across dryers, filters, etc.
- Temperature gauges across the compressor and its cooling system to detect fouling and blockages.
- Flow meters to measure the quantity of air used.
- Dew point temperature gauges to monitor the effectiveness of air dryers.
- kWh meters and hours run meters on the compressor drive.

Reduction of Leaks (in Pipes and Equipment). Leaks cause an increase in compressor energy and maintenance costs. The most common areas for leaks are couplings, hoses, tubes, fittings, pressure regulators, open condensate traps and shut-off valves, pipe joints, disconnect and thread sealants. Quick connect fittings always leak and should be avoided. In addition to increased energy consumption, leaks can make pneumatic systems/equipment less efficient and adversely affect production, shorten the life of equipment, lead to additional maintenance requirements and increased unscheduled downtime.

A typical plant that has not been well maintained could have a leak rate between 20 to 50% of total compressed air production capacity (Ingersoll Rand 2001). Leak repair and maintenance can sometimes reduce this number to less than 10%. Similar figures are quoted by Cergel *et al.* (2000). Overall, a 20% reduction of annual energy consumption in compressed air systems is projected for fixing leaks (Radgen and Blaustein, 2001).

The magnitude of a leak varies with the size of the hole in the pipes or equipment. A compressor operating 2,500 hours per year at 87 psi (6 bar) with a leak diameter of 0.02 inches (0.5 mm) is estimated to lose 250 kWh/year; 0.04 in. (1 mm) to lose 1100 kWh/year; 0.08 in. (2 mm) to lose 4,500 kWh/year; and 0.16 in. (4 mm) to lose 11,250 kWh/year (CADDET, 1997a).

A simple way to detect large leaks is to apply soapy water to suspect areas. The best way is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks.

The metal forging plant Modern Forge of Tennessee, located in Piney Flats, Tennessee, performed a leak detection and repair operation that included replacing worn point-of-use components from which air was leaking and training of plant personnel about compressed air system dynamics, and the importance of managing leaks in containing compressed air costs. As a result, energy use for compressed air was reduced by 10% (U.S. DOE-OIT, 2000c). Another forging plant, Citation Corporation, Interstate Forging, in Milwaukee, Wisconsin also performed a leak detection and repair operation and managed to decrease the system's average air demand by 20 – 25% (U.S. DOE-OIT, 2003).

Electronic Condensate Drain Traps (ECDTs). Due to the necessity to remove condensate from the system, continuous bleeding, achieved by forcing a receiver drain valve to open, often becomes the normal operating practice, but is extremely wasteful and costly in terms of air leakage. Electronic condensate drain traps (ECDTs) offer improved reliability and are very efficient as virtually no air is wasted when the condensate is rejected. The payback period depends on the amount of leakage reduced, and is determined by the pressure, operating hours, the physical size of the leak and electricity costs. GKN Sheepbridge Stokes Foundry (Chesterfield, UK) fitted ECDTs of various sizes. The project had a payback period of 14 months. Payback periods for individual ECDTs range from 8 to 24 months (CADDET, 1999a).

Air Quality. Separators, filters, dryers and condensate drains are used to improve compressed air quality. A pressure gauge indicating pressure drop in inches of water is essential to maintain optimum compressor performance. Higher quality air requires additional air treatment equipment, which increases capital costs as well as energy consumption and maintenance needs. Knowing the proper air quality level required for successful production is therefore an important factor in containing compressed air energy and other operating costs, because higher quality air is more expensive to produce.

The effect of intake air on compressor performance should not be underestimated. Intake air that is contaminated or hot can impair compressor performance and result in excess energy and maintenance costs. If moisture, dust, or other contaminants are present in the intake air, such contaminants can build up on the internal components of the compressor, such as valves, impellers, rotors, and vanes. Such build-up can cause premature wear and reduce compressor capacity. To prevent adverse effects from intake air quality, it is important to ensure that the location of the entry to the inlet pipe is as free as possible from ambient contaminants.

Lubrication systems of the compressed air equipment can also be a source of contamination. In case of oil leakage, oil can be carried over into the end-use equipment, leading to unreliable product quality. In addition, oil can contaminate the air dryers and filters to the point that they no longer perform effectively. Finally, the oil's presence in the dryers and filters severely obstruct the airflow, leading to a significant pressure drop across the system.

The Edgar Thomson United States Steel Corporation plant in Braddock, Pennsylvania, found that their compressors leaked substantial amounts of oil, which had several negative impacts on the system and product quality. Although they operated the compressors at discharge pressures of 90 psig (6.2 bar) or more, the end-use applications were barely receiving air at their minimum required pressure of 60 psig (4.2 bar) because the oil had congested the filtration equipment (U.S. DOE-OIT, 2001c).

The metal forging plant Modern Forge of Tennessee, located in Piney Flats, Tennessee, found that oil had degraded the end use components' filters to the point that they were filled with lubricant. Applying new condensate traps, filters, dryer and replacing the dryers to a location upstream of the storage receivers had a direct effect on the operation of the forging equipment and the overall quality of the forged metal parts. Since the air was more consistent and lubricant-free, the hammers were able to reduce the blows needed per part. In addition, the lubricant-free air reduced in the quantity of rejected products (U.S. DOE-OIT, 2000c).

Practices at the powdered metal manufacturing plant GKN Sinter Metals at Salem, Indiana show the importance of moisture in the compressed air system. By applying mist eliminators they reduced moisture levels in the compacting presses. As a result, the quality of the compacted metal parts was improved leading to a 6% reduction in rejected products (U.S. DOE-OIT, 2000d).

Reduction of the Inlet Air Temperature. Reducing the inlet air temperature reduces energy used by the compressor. In many plants, it is possible to reduce this inlet air temperature by taking suction from outside the building. Importing fresh air has paybacks of up to 5 years, depending on the location of the compressor air inlet (CADDET, 1997a). As a rule of thumb, each 5°F (3°C) will save 1% compressor energy use (CADDET, 1997a; Parekh, 2000).

Maximizing Allowable Pressure Dew Point at Air Intake. Choose the dryer that has the maximum allowable pressure dew point, and best efficiency. A rule of thumb is that desiccant dryers consume 7 to 14% and refrigerated dryers consume 1 to 2% of the total energy of the compressor (Ingersoll-Rand, 2001). Consider using a dryer with a floating dew point. Note that where pneumatic lines are exposed to freezing conditions, refrigerated dryers are not an option.

Optimizing the Compressor to Match Load. Plant personnel have a tendency to purchase larger equipment than needed, driven by safety margins or anticipated additional future capacity. Given the fact that compressors consume more energy during part-load operation, this is something that should be avoided. Some plants have installed modular systems with several smaller compressors to math compressed air needs in a modular way (Cergel *et al.*, 2000). In some cases, the pressure required is so low that the need can be met by a blower instead of a compressor which allows considerable energy savings, since a blower requires only a small fraction of the power needed by a compressor (Cergel *et al.*, 2000).

The metal forging plant Modern Forge of Tennessee, located in Piney Flats, Tennessee, discovered that on the weekends the plant utilized less than 20% of the capacity of one of their 200-hp compressor. The plant found that it was cost effective to purchase an additional 40-hp compressor (U.S. DOE-OIT, 2000c) for weekend operation.

Controls. Compressed air applications should be regulated, either by production line sectioning or by pressure regulators on the equipment itself. Equipment not required to operate at maximum system pressure should use a quality pressure regulator in order to prevent the waste of the excess energy. Poor quality regulators tend to drift and lose more air. System pressures that are too high result in shorter equipment life and higher maintenance costs. Also, it is advisable to specify pressure regulators that close when failing.

The objective of any control strategy should be to shut off unneeded compressors or delay bringing on additional compressors until needed. All compressors that are on should be running at full-load, except for one, which should handle trim duty. Positioning of the control loop is also important; reducing and controlling the system pressure downstream of the primary receiver results in reduced energy consumption of up to 10% or more (U.S. DOE, 1998). Radgen and Blaustein (2001) report energy savings for sophisticated controls to be 12% annually. Different options for compressor controls and described below.

Start/stop (on/off) is the simplest control available and can be applied to small reciprocating or rotary screw compressors. For start/stop controls, the motor driving the compressor is turned on or off in response to the discharge pressure of the machine. Start/stop controls are used for applications with very low duty cycles. Applications with frequent cycling will cause the motor to overheat. Typical payback for start/stop controls is 1 to 2 years (CADDET, 1997a).

Load/unload control, or constant speed control, allows the motor to run continuously but unloads the compressor when the discharge pressure is adequate. In most cases, unloaded rotary screw compressors still consume 15 to 35% of full-load power when fully unloaded, while delivering no useful work (U.S. DOE, 1998). Hence, load/unload controllers may be relatively inefficient.

Modulating or throttling controls allow the output of a compressor to be varied to meet flow requirements by closing down the inlet valve and restricting inlet air to the compressor. Throttling controls are applied to centrifugal and rotary screw compressors. Using a model of a compressor system featuring three compressors (190, 190 and 90 kW) savings from changing the compressor control to a variable speed control were calculated to be 8% per year (CADDET, 1997a). Multi-step or part-load controls can operate in two or more partially loaded conditions. Output pressures can be closely controlled without requiring the compressor to start/stop or load/unload.

The metal forging plant Modern Forge of Tennessee, located in Piney Flats, Tennessee, found that the compressor controls were not operating efficiently. In order to overcome this problem they replaced the old run/modulation sequencer with a programmable logic control (PLC) system to centralize the control of all compressors, maintain adequate pressure differential between the compressor pressure settings, and sequence them more efficiently. In addition, the system was linked to the pressure/flow controllers to obtain accurate demand signals (U.S. DOE-OIT, 2000c).

Proper Sizing of Storage Capacity. By properly sizing regulators storage capacity, compressed air will be saved that is otherwise wasted as excess air. Implementing additional storage capacity was found to substantially improve the compressed air system in two considered case studies (U.S. DOE-OIT, 2003; U.S. DOE-OIT, 2000d).

Proper Pipe Sizing. Pipes must be sized correctly for optimal performance or resized to fit the compressor system. Inadequate pipe sizing can cause pressure losses, increase leaks and increase generating costs. Increasing pipe diameter typically reduces annual energy consumption by 3% (Radgen and Blaustein, 2001).

Heat Recovery. More than 85% of the electrical energy used by an industrial air compressor is converted into heat (U.S. DOE-ITP EM, 2008b). A 150 hp compressor can reject as much heat as a 90 kW electric resistance heater or a 400,000 Btu/hour natural gas heater when operating (Cergel *et al.*, 2000).

In many cases, a heat recovery unit can recover 50 to 90% of the available thermal energy for space heating, industrial process heating, water heating, makeup air heating, boiler makeup water preheating, industrial drying, industrial cleaning processes, heat pumps, laundries or preheating aspirated air for oil burners (Parekh 2000). With large water-cooled compressors, recovery efficiencies of 50 to 60% are typical (U.S. DOE, 1998). When used for space heating, the recovered heat amounts to 20% of the energy used in compressed air systems annually (Radgen and Blaustein, 2001). Paybacks are typically less than one year.

In some cases, compressed air is cooled considerably below its dew point in refrigerated dryers to condense and remove the water vapor in the air. The waste heat from these aftercoolers can be regenerated and used for space heating, feedwater heating or process-related heating (Cergel *et al.*, 2000).

Adjustable Speed Drives (ASDs). When there are strong variations in load and/or ambient temperatures there will be large swings in compressor load and efficiency. In those cases installing an ASD may result in attractive payback periods (Heijkers *et al.* 2000). Implementing adjustable speed drives in rotary compressor systems has saved 15% of the annual compressed air energy consumption (Radgen and Blaustein, 2001).

15 Iron Ore Preparation (Sintering)

Most iron ore is processed before it can be charged into the blast furnace. Iron ores are agglomerated via sintering or pelletizing. In the U.S., the average pellet-to-sinter ratio is about 6 to 1. Since pelletizing occurs mainly at the mine site, pelletizing is not included in this Guide. IISI (1998) reports a primary energy intensity 1.6 MBtu/ton (1.8 GJ/tonne) sinter for an average of seven efficient plants worldwide. The theoretical minimum energy needed for iron ore agglomeration is estimated to be 1.0 MBtu/ton (1.2 GJ/tonne) output, suggesting a potential for improvement in energy efficiency (Fruehan *et al.* 2000). Below a number of energy efficiency measures are discussed for the sinter process.

Heat Recovery from Sintering and Sinter Cooler. Two kinds of potentially reusable waste heat are discharged from sinter plants: the sensible heat from the main exhaust gas from sintering machines and the sensible heat of the cooling air from the sinter cooler.

Under normal operating conditions the use of a heat exchanger to recover heat from the waste process gases would result in unacceptable condensation and corrosion problems. The only practical method of recovering heat from the waste gases has therefore been by transferring the sensible heat directly back to the sinter bed by the hot gases. This approach is called waste gas recirculation.

In contrast, there are five practical ways to recover the sensible heat from the hot air from a sinter cooler: steam generation in a waste gas boiler, hot water generation for district heating, preheating combustion air in the ignition hood of the sinter plant, preheating the sinter raw mix, or using the waste gas in a recirculation system. Various systems exist (see e.g. Stelco, 1993; Farla *et al.*, 1998; Hartig *et al.*, 2006; NEDO, 2008; IPCC, 2001)

Steam generation with sinter cooler gases using a waste heat boiler is common in Japan and was reported to recover 0.22 MBtu/ton sinter (0.25 GJ/tonne) (NEDO, 2008). At Sumitomo Heavy Industry's Kokura No. 3 sinter plant, sectional waste gas recirculation is applied. Before recirculation, the waste gases are led through a waste heat boiler. The gases from the sinter cooler are also led through a waste heat boiler. Energy recovery reported at the plant by means of this system is 23% of the energy input (IPCC, 2001). At the Sumitomo Heavy Industry's Wakayama No. 4 sinter plant, the sinter cooler is integrated into the sinter strand ("strand cooling"). At that plant, waste gases from both the sintering and the cooling zone on the grate are led through waste heat boilers and subsequently recirculated to the strand. Recovered heat amounts to 30% of the input heat (IPCC, 2001).

Emission Optimized Sintering (EOS®). The EOS process for sinter plants was developed by Outokumpu Technology in the 1990s (Outokumpu Technology, 2005). EOS® can be retrofitted with minimum production interference. EOS® reduces the substantial off-gas volume by 50–60% through housing the entire sinter strand, re-circulating off-gases and using its CO content as an energy source to minimize off-gas volumes, cutting off-gas cleaning investment costs, save energy, in the form of coke, reducing operational costs, as well as significantly minimize NO_X, SO_X, CO and CO_2 emissions

Reduction of Air Leakage. Reduction of air leakages can reduce electricity use for the fans by approximately 9.5-12 kBtu/ton sinter (11-14 MJ/tonne) (Dawson, 1993), and could have a positive effect on the heat recovery equipment. These savings may need small investments for repair of existing equipment.

Increasing Bed Depth. Increasing bed depth in the sinter plant results in lower fuel consumption, improved product quality, and a slight increase in productivity. The savings amount to 0.3 ton coke per kton sinter per 0.4 inch (10 mm) bed thickness increase, and an electricity savings of 0.05 kWh/ton (0.06 kWh/tonne) sinter (Dawson, 1993).

Use of Waste Fuels in the Sinter Plant. The energy demand in sinter making is met by mixing iron ore with breeze from coke making and gas in burners. Applying this measure means that "scavenge" byproducts such iron scale from the rolling mills and a wide variety of dusts and sludges from waste gas treatment devices can be recovered and used as input in the sinter plant as raw material and fuel. It is possible to use waste oils. However the use will be limited by emissions due to incomplete combustion. A well-monitored combustion process could reduce the use of gas in the burners (Cores *et al.*, 1996).

The savings for this measure depend on the composition and quantity of lubricants and the installed gas clean-up system at the sinter plant. Bethlehem Steel developed a waste recovery and waste injection system, at a cost of about $25 Million to recycle 200 kton (180 ktonne) of various materials (Schriefer, 1997).

Improve Charging Method. Limonite (brown iron ore) used as a raw material for sintering is inexpensive, but decreases the productivity in the sintering process because this ore combines strongly with water and has a coarse particle size. These problems can be overcome by using an improved charging method as described in NEDO (2008). The system adopts a drum chute and a Segregation Slit Wire (SSW). The purpose of the drum chute is to reduce the height difference (dropping difference) in material charging, while the SSW controls the particle size distribution.

Specifically, because a constant particle size is maintained, the permeability of the sintering mixture is increased, resulting in improved sintering efficiency, and the material return ratio due to poor sintering is reduced. This system was developed by a Japanese steel maker and has been introduced at all its plants in Japan. According to a calculation as reported by NEDO (2008), productivity improvement amounts to 5% and energy consumption due to coke use decreases by 0.07 MBtu/ton sinter (79 MJ/tonne sinter) compared to a conventional charging system.

Improve Ignition Oven Efficiency. Large fuel reduction can be achieved by improving the ignition oven efficiency as is illustrated by an application reported by NEDO (2008). In order to reduce the fuel needed for ignition ovens, a heat-retention oven was removed from a conventional ignition oven with a large oven capacity and an ignition oven with less capacity was introduced, in which the inner pressure of the ignition oven was regulated by controlling each window box located immediately under the ignition oven. Moreover, a burner which can achieve uniform ignition in the pallet width direction and rapid heating had been developed and introduced to realize a large fuel reduction. This burner consists of fuel exhaust nozzles located in the sintering floor width direction and a slit-like burner tile containing these fuel exhaust nozzles. The fuel supplied from the fuel exhaust nozzles reacts to the primary air inside the burner tile, then to the secondary air supplied to flame outer periphery area. By using the slit-like burner tile, non-flamed places could be eliminated, and by controlling the ratio between the primary air and the secondary air the length of the flame could be controlled to minimize the ignition energy. In the case, the ignition energy was reduced by approximately 30% (NEDO, 2008).

Other Measures include the use of higher quality iron ores, low iron oxide (FeO) content, replacing silicon dioxide (SiO_2) by Magnesium oxide (MgO), reduction of the basicity of the sinter, and the use of coarse coke breeze (Aichinger, 1993; Dawson, 1993).

16 Coke Making

Coke is needed in order to operate the blast furnace (see section 3.2 for a process description). IISI (1998) reports a total primary energy input of 3.6 MBtu/ton dry coke as an average of five most efficient plants around the world. The theoretical minimum energy needed for coke making is estimated to be 1.7 MBtu/ton (2.0 GJ/tonne) output, indicating a vast potential for energy efficiency improvement (Fruehan *et al.*, 2000).

Coal Moisture Control. Coal moisture control reduces the carbonization heat amount and improves the productivity and coke quality by controlling the moisture of the feed coal for coke making from a normal 8 - 10% to approximately 6% without hindering the feeding operation (NEDO, 2008). Generally, low-pressure steam is used as the humidity control heat source, but in some cases the sensible heat of the coke oven gas (COG) is collected by using a heat medium and used as part of the heat source.

Application of the technique leads to a reduction of 0.11-0.18 MBtu/ton coal (0.13-0.21 GJ/tonne) in carbonization heat requirements, while the strength of the coke is improved by approximately 1.7% and productivity by about 10% (NEDO, 2008).

Programmed Heating. Instead of conventional constant heating of the coke ovens, programmed heating enables optimization of the fuel gas supply to the oven at the various stages of the coking process and reduces the heat content of the coke before charging. Use of programmed heat can lead to fuel savings of about 10% (IISI, 1982), estimated to be 0.15 MBtu/ton (0.17 GJ/tonne) coke.

Variable Speed Drive Coke Oven Gas Compressors. Coke oven gas is generated at low pressures and is pressurized for transport in the internal gas grid. However, coke oven gas flows vary over time due to the coking reactions. Variable speed drives on coke oven compressors can therefore be installed to reduce compression energy. Installing a variable speed drive system on a compressor at a coke plant at Corus in The Netherlands saved 5-7 kBtu/ton (6-8 MJ/tonne) coke (Farla *et al.*, 1998).

Coke Dry Quenching (CDQ). CDQ is an alternative to the traditional wet quenching of the coke. The process reduces dust emissions, improves the working climate, and recovers the sensible heat of the high temperature coke (in a red-hot condition) which accounts for approximately 45% of energy consumption in coke ovens (NEDO, 2008). Furthermore, the treatment of coke by CDQ enhances its quality, which is beneficial because the use of coke of a higher quality reduces the use of coke in the subsequent blast furnace. The enhancement of coke quality by CDQ also makes it possible to reduce the use of expensive heavy coking coal and increase the use of inexpensive semi-coking coal (CADDET, 2003a). The ability to substitute for less expensive coals depends on the required coke quality.

CDQ equipment broadly consists of a coke cooling tower (pre-chamber and cooling chamber) and a waste heat recovery boiler. Red-hot coke (approximately 2,200°F or1,200°C) is charged into the coke cooling tower, and inert gas is blown into the tower from the bottom. Heat exchange is performed with the circulating inert gas. After the gas is heated to high temperature (approximately 1450°F or800°C), it circulates through the heating tubes of the waste heat boiler, converting the water in the boiler into steam. The temperature of the coke at the cooling tower outlet is reduced to approximately 400°F (200°C).

The steam recovery rate with this CDQ equipment is about 0.5 MBtu/ton (0.55 GJ/tonne) coke (NEDO, 2008). In addition, Nippon Steel's performance record shows that the use of coke manufactured by the CDQ reduces the amount of coke consumption in the blast furnace by 0.24 MBtu/ton (0.28 GJ/tonne)[14] molten iron (CADDET, 2003).

Coke oven gas (COG) Coke oven gas, a low-Btu gas, is produced as a by-product of the coke making process. To use coke oven gas, the following techniques can be used (Diemer *et al.*, 2004):

- In the heat recovery process, raw gas is burnt directly at its source in the coking reactor by a prudent air supply. The heat produced is partly used for the coking process. The excess energy subsequently is converted to steam and/or electricity.
- In case of classical coke oven battery operation featuring a cooled collecting main (approximately 185°F or85°C), the raw gas can be burnt and converted to electricity or partially oxidized.
- Another alternative provides discharge at about 1470°F (800°C) hot raw gas from the coke oven and leads it directly to a combustion or partial oxidation system.

In the U.S., approximately 40% of the coke oven gas (COG) is used as a fuel in the coke oven (U.S. DOE-OIT, 2000e). In most U.S. steel plants, the remaining COG is used to fuel equipment such as reheat furnaces and boilers that supply steam for electricity generation, turbine driven equipment such as pumps and fans, and for process heat.

Besides energy production, the following potentials are offered for coke oven gas utilization within the works network (Diemer *et al.*, 2004):

- Injection of coke oven gas and tar as auxiliary reducing agents into the blast furnace.
- Minimization of equipment- and process-related expenditures in conventional coke oven gas treatment by hydrogen recovery.

The first technique was used in a United States Steel Corporation plant in Pittsburgh, Pennsylvania. COG was used in the blast furnace to replace part of the natural gas that was injected in the furnace. It was found that it was more effective to use the COG in the blast furnace than to fuel boilers that feed steam turbines to generate electricity. The payback period was under one year (U.S. DOE-OIT, 2000e).

Single Chamber System (SCS). SCS coking reactors (formerly called Jumbo Coke Reactors) are coke ovens with large coke oven volume and widths between 17.7 – 33.5 in (450-850 mm). The process includes the use of preheated coal. The reactors are separate process controlled modules with rigid, pressure stable, heating walls to absorb high coking pressure (IPPC, 2001). This allows much thinner heating walls to be constructed, thus improving heat

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[14] Using net calorific value of 28.2 TJ/Gg coking coal (IPCC, 2006).

transfer and combustion, and greatly increasing the design flexibility of the plant. The high load bearing capacity of the side walls allows a greater range of coal bends to be charged and the larger dimension ovens decrease the specific environmental emissions. The coal preheater increases coal bulk density, reduces the coking time, improves productivity and leads to increased coke strength (IISI, 1998). It is expected that SCS coke ovens are able to take the place of current multi-chamber batteries with walls of limited flexibility. SCSs have an improvement in thermal efficiency from 38% to 70%, but the technology is currently under development (IPPC, 2001). The Jumbo coke reactor operating in Germany has recently been relocated to China.

Non-Recovery Coke Ovens. In the non-recovery coking process, coke oven slag and other by-products released from coking process are combusted within the oven, offering the potential for heat recovery and cogeneration of electricity. As the ovens operate under reduced pressure and at a temperature at which all potential pollutants break down into combustible compounds, this technique consumes all by-products, eliminating much of the potential for air and water pollution. The process thus requires a different oven design from that traditionally used, resulting in a larger required area. A coke oven gas treatment plant and wastewater treatment plant are not needed (IPPC, 2008).

When the waste gas exits into a waste heat recovery boiler, which converts excess heat into steam for power generation, the process is called Heat Recovery Coke making. Heat recovery coking has a smaller output of blast furnace coke in comparison to conventional coke making systems, but provides more flexibility for coal selection than conventional slot ovens (IPPC, 2008).

In Haverhill, Ohio, a plant produces 500,000 ton (450,000 tonne) of coke per year while producing 220 tonne/hour (200 tonne/hr) of steam, which is used in a nearby chemical plant (Mueller, 2006). Another plant in Granite City, Illinois, began construction in May 2008 and would produce 650,000 ton of blast furnace coke per year and produce approximately 500,000 lb (225 tonne) of superheated steam per hour (SunCoke Energy, 2008).

Several heat recovery coke ovens are in operation in the U.S., South America, Asia and Australia. About 6% of worldwide cokemaking capacity is operated as heat or non-recovery plants.

Next Generation Coke Making Technology. An innovative next-generation coke making technology (SCOPE21) has been developed, which is flexible in coal resources and excellent in environmental performance, energy use and productivity. This technology is not yet commercially available. A commercial oven that incorporates this technique was under construction at the Oita Iron Mill of the Nippon Steel Corporation (NEDO, 2008).

This technology achieves potentially significant energy savings by rapidly heating the coal at 660°F (350°C) in advance (low-temperature carbonization) and directing it into a 1560°F (850°C) oven instead of a conventional 2190°F (1200°C) coke oven.

It is foreseen that the new technology will reduce coke making energy by 21%, while the use of coal resources will be more effective by an increase in use of non-dust binding coal (20-50%), NO_x emissions will be reduced by 30%, and productivity will be 2.4 times greater.

17 Iron Making – Blast Furnace

In a blast furnace, iron oxides are reduced and the resulting iron is melted (see section 3.3 for a process description). Hot metal production in a blast furnace is the most energy-consuming process, and in the U.S. iron and steel industry accounts for 34% of the energy use (Fruehan *et al.*, 2000; Energetics, Inc, 2005; USGS, 2009). IISI (1998) reports an average total primary energy requirement of 1.5 MBtu/ton (1.8 GJ/tonne) hot metal for the hot blast stove and 10.0 MBtu/ton (11.6 GJ/tonne) hot metal for the blast furnace, based on six efficient hot blast stove batteries and blast furnaces around the world. The modern state-of-the-art blast furnace, as far as utilization is concerned, is a highly efficient structure and has reached a state of development where there is relatively little scope for further reductions in energy consumption.

17.1 Blast Furnace Measures

One of the main energy efficiency measures in iron making is replacing part of the coke by another hydrocarbon source that is injected in the blast furnace through the tuyères. By reducing the need for coke, overall pollution and energy demand decrease. It should be stressed, however, that a certain amount of coke is necessary in the blast furnace to allow proper blast furnace operation. The coke provides the required carrying capacity to sustain the blast furnace charge and ensures sufficient gas penetration. Tuyère injection of hydrocarbons requires additional injection of oxygen (at increasing levels as tuyère injection rates increase) in order to achieve the required temperatures within the furnace (IPPC, 2001). The minimal required amount of coke will depend on coke quality, blast furnace geometry, and operating practices.

Improved Blast Furnace Control. Improving process control of the blast furnace is an important way to reduce energy costs, and to optimize operating conditions, hot metal quality and operation costs. Improved blast furnace control systems have been developed that provide improved control over systems currently used. Currently, “third generation” control systems (e.g. VAiron) for the blast furnace and the hot blast stoves have been developed that help to further improve productivity and energy use beyond the older control systems.

The implementation of a closed-loop blast furnace automation system at Voest Alpine (Linz, Austria) has resulted in a reduced coke consumption of approximately 0.458 ton/ton-hot metal in 2000, as well as reduced steam consumption by approximately 10.5 ton (9.5 tonne) per hour (Brunnbauer *et al.*, 2001).

Injection of Pulverized Coal (PCI). PCI is a process in which fine granules of coal are blown in large volumes into the blast furnace as a supplemental carbon source to speed up the conversion of iron ore into metallic iron. Pulverized coal injection saves part of the coke production, thereby saving energy and reducing emissions and maintenance costs. The energy savings in the blast furnace due to coal injection have been calculated at 3.23 MBtu/ton (3.76 GJ/tonne) coal injected (IPPC, 2008). Fuel injection does however require energy for oxygen injection, coal, electricity and equipment to grind the coal.

For every ton of coal injected, approximately 0.85-0.95 ton of coke production is avoided (IPPC, 2008). The theoretical maximum for coal injection at the tuyère level is thought to be 0.27 ton/ton hot metal (IPPC, 2008). This limit is set by the carrying capacity of the coke and the thermo-chemical conditions in the furnace. In 2006, pulverized coal was injected at Corus IJmuiden (Netherlands) at a rate of 0.21-0.26 ton/ton hot metal depending on the carbon content of the coal (IPPC, 2008). High PCI commonly poses technical challenges that lead to requirements for process operations, iron-ore and coke quality, and furnace design (Clairay *et al.*, 2006; Dauwels *et al.*, 2006). The use of oxy-coal makes it possible to increase the coal-injection approximately 20% and correspondingly decrease the coke rate (IPPC, 2008).

Injection of Natural Gas. Like PCI, natural gas injection allows a reduction in coke production with associated benefits. Natural gas injection was developed in the former Soviet Union and the United States (Chu *et al.*, 2004a). This technology requires little extra capital investments and special equipment except for the gas pressure equalizer and gas distributor, and considerably decreases coke consumption. Due to these advantages, natural gas injection in North America has increased substantially since the 1990s (Steiler and Hanrot, 2005). However, current natural gas prices limit the economic attractiveness as injection fuel. Typical injection rates are within the range of 0.04–0.11 ton/ton hot metal, the highest being 0.155 ton/ton hot metal (Chu *et al.*, 2004a). Replacement rates for natural gas vary between 0.9 and 1.15 ton natural gas/ton coke (Oshnock, 1995b).

In the blast furnace with all-coke or PCI, the primary reducing agent is carbon monoxide. The injection of natural gas however enriches the furnace with hydrogen which as a reducing agent has certain benefits over carbon monoxide.[15] Hydrogen reduction does not result in CO_2 as a by-product, and thus helps to reduce CO_2 emissions. The use of natural gas in the ironmaking process has been investigated in various studies (e.g. Beresneva and Kurunov, 2001; Chu *et al.*, 2004a). Chu *et al.* (2004a) found that compared with all-coke operation, the injection of natural gas improves productivity, decreases coke rate and generally improves the performance of the blast furnace due to a decrease in heat demand for direct reduction, belly solution loss, and silicon transfer reactions.

Natural gas can be injected simultaneously with pulverized coal (Babich *et al.*, 1999; Chu *et al.*, 2004a). Babich *et al.* (1999) determined the rate by which natural gas injection can compensate for PCI. They reported a value of 220-550 Nm^3/ton (200-500 Nm^3/tonne), depending on fuel composition and technological conditions.

Injection of Oil. Heavy fuel oil or waste oil can also be injected into the blast furnace. 1 ton of oil replaces 1.2 tons of coke (IPPC, 2008). With oxy-oil technology the amount of oil injected can be increased by 100% to a level of 0.13 ton/ton hot metal (IPPC, 2008). Like natural gas, oil contains hydrogen leading to decreased CO_2 emissions.

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[15] The chemical reaction rate of hydrogen reduction is higher than one by carbon monoxide, a higher diffusivity supplies reactant (hydrogen) faster to site of reaction, a higher heat conductivity improves heat transfer rate between gas and other phases, and a lower viscosity decreases gas flow resistance and decreases pressure drop or allows to increase gas flow rate (Chu *et al.*, 2004a).

Injection of Plastic Waste. The injection of plastic waste also allows for a reduction in coke production. Plastic waste has a higher heating value than coal (Chu *et al.*, 2004a). Moreover, like the injection of natural gas, the injection of plastic wastes increases the amount of hydrogen in the blast furnace. Similar beneficial effects were found in simulations (Chu *et al.*, 2004a). Another advantage of plastic materials is the low sulfur and alkali content (Steiler and Hanrot, 2005). Chlorine content (due to PVC) may lead to dioxin formation, making efficient flue gas control equipment necessary. The theoretical maximum for plastic injection at the tuyère level is thought to be 0.070 ton/ton hot metal and is set by the thermo-chemical and kinetic conditions in the blast furnace (IPPC, 2008). In 2004, plastic injection in a blast furnace at Eisenhüttenstadt (Germany) averaged 0.0674 ton/ton hot metal (IPPC, 2008). The steel industry in Japan effectively reuses both industrial and municipal plastic waste. About 1% of waste plastics are added to the coal charge in the Japanese steel industry. Waste plastic recycling processes using coke ovens were started at Nippon Steel's Nagoya and Kimitsu works in 2000. The treatment capacity is 40,000 tons/year. At Nippon Steel's Yawata and Muroran works, similar processes started in 2002 (Kato et al, 2003).

Injection of Coke Oven Gas and Basic Oxygen Furnace Gas. Coke oven gas and basic oxygen furnace gas can also be injected in blast furnace (also see previous chapter: avoid flaring of excess coke oven gas). The maximum level for COG injection at the tuyère level is thought to be 0.1 ton/ton hot metal (IPPC, 2008). The replacement rate of COG is about 1.0 ton of gas for 0.98 ton of coke (IPPC, 2008). This limit is set by the thermo-chemical conditions in the furnace. A compressor unit is required for COG injection, resulting in an additional energy consumption of about 185 kWh/ton COG (204 kWh/tonne) (IPPC, 2008). Analysis by Ziębik and Stanek (2006) indicated that injection of pulverized coal leads to higher energy effectiveness than that of coke oven gas.

Charging Carbon Composite Agglomerates (CCB). CCB are the mixtures of fine iron ore (hematite, magnetite, iron-bearing ironmaking dust, and pre-reduced iron-bearing ore fine) and fine carbonaceous materials (fine coke fine coal, charcoal, and char) adding some binding agents in most cases. CCBs were tested in some practical blast furnaces or blast furnace simulator and it revealed that the use of CCB can improve the energy efficiency of a blast furnace (Chu *et al.*, 2004b). Furthermore, the effective use of non-coking coal, and iron-bearing dust and sludge in steel works would extend the variety of raw materials and promotes resource recycling (Chu *et al.*, 2004b).

Top-Pressure Recovery Turbines (TRT). Top gas pressure in modern blast furnaces is approximately 3.6-36 psig (0.25-2.5 bar gauge) (IPPC, 2008). Electric power can be generated by employing blast furnace top gases to drive a turbine-generator. Although the pressure difference over the generator is low, the large gas volumes can make the recovery economically feasible (Worrell *et al.*, 1999). This is typically the case when the top pressure is in excess of 22 psig (1.5 bar gauge) (IPPC, 2008). After the blast furnace gas is used in top-pressure recovery turbines it can be used as a fuel in iron and steel manufacturing processes.

Generating methods are classified as wet or dry depending on the blast furnace gas purification method. In the wet method dust is removed by Venturi scrubbers and in the dry method by a dry-type dust collector. When dust is treated by the dry method, the gas temperature drop is small in comparison to the wet method, and as a result generated output is at maximum 1.6 times greater than with the wet method (NEDO, 2008).

Assuming pig iron production of 1.1 Mton/year (1 Mtonne/year), a blast furnace capacity of 1,500 Nm^3 (daily production scale: 3.3 kton (3.0 ktonne) blast furnace gas generation is estimated to be 212,500 Nm^3/hour. The potential generating capacity with the gas volume is approximately 7 MW for a dry type system (NEDO, 2008).

Turbines are installed at blast furnaces worldwide, especially in areas where electricity prices are relatively high (e.g. Western Europe, Japan) and where the furnace has sufficient top pressure. In fact, in Japan all blast furnaces are equipped with TRTs, either as a system for individual furnaces or in a form that integrates multiple furnaces.

Recovery of Blast Furnace Gas. A typical blast furnace produces about 1320 to 2210 Nm^3 of blast furnace gas per ton of pig iron (1200 to 2000 Nm^3 per tonne). The gas consists of 20-28% of carbon monoxide (CO) and 1-5% hydrogen (H_2), both potential energy sources and thus measures can be taken to recover this energy. Blast furnace gas can be cleaned and stored in a gasholder for subsequent use as a fuel or alternatively to generate electricity in a gas turbine (Komori *et al.*, 2004). The energy content of blast furnace gas typically varies between 2.3 and 3.4 kBtu/Nm^3 (2.7-4.0 MJ/Nm^3) depending on its CO concentration. This is only 10% of the energy content of natural gas, and therefore it is often enriched with coke oven gas or natural gas prior to use as fuel. Total export from the blast furnace is approximately 4.3 MBtu/ton (5 GJ/tonne) pig iron, which equals 30% of the gross energy consumption of the blast furnace (IPPC, 2001).

Where a blast furnace is fitted with a two bell charging system, gas is lost to the atmosphere every time the furnace is charged. It is possible to recover most of this by allowing the high pressure gas between the two bells to discharge into the low pressure side of the gas collection system just prior to opening the top bell for charging, thus saving about 30 kBtu/ton (35 MJ/tonne) hot metal (IISI, 1998)

Top Gas Recycling. Recirculation of the reducing gas components (CO and H_2) of the top gas into the furnace has been considered as an effective method to improve the blast furnace performance, enhance the utilization of carbon and hydrogen, and reduce the emission of carbon oxides. Various recycling processes have been suggested, evaluated or practically applied for different objectives. These processes are distinguished by: 1) with or without CO_2 removal, 2) with or without preheating, and 3) the position of injection (Chu *et al.*, 2004c). This technology has not yet been commercially deployed, but is the focus of intensive R&D in the ULCOS program.

Slag Heat Recovery. In modern blast furnaces around 0.25-0.30 tons of liquid slag with a temperature of approximately 2640°F (1450°C) are produced per ton of pig iron. While a number of slag heat recovery systems have been proposed, none have been applied commercially due to technical difficulties that arise in the development of a safe, reliable and energy-efficient system that also does not influence the slag quality (IISI, 1998). If such a technique were to be developed, associated estimated savings would be approximately 0.30 MBtu/ton (0.35 GJ/tonne) pig iron (IPPC, 2008).

17.2 Hot blast stove measures

Preheating of Fuel for Hot Stoves. The heat of hot blast stove flue gases, with an exit temperature of approximately 480°F (250°C), can be recovered to preheat the combustion air of the stoves to reduce energy consumption. Apart from hot stove flue gases, other heat sources may also be used to preheat the fuel, such as sinter cooling heat. Various recovery systems have been developed and implemented (Stelco, 1993; NEDO, 2008). Preheating can lead to an energy savings of approximately 0.3 MBtu/ton pig iron (0.3 GJ/tonne) (IPPC, 2008). An efficient hot blast stove can run without the need for natural gas (Worrell *et al.*, 1999).

For a specific medium-type waste heat recovery device (consisting of two heat exchangers), NEDO (2008) reports a recovery rate of sensible heat of 40-50% and a reduction in heat consumption of about 0.108 MBtu/ton pig iron (0.126 GJ/tonne) produced.

Improvement of Combustion in the Hot Stove. Improvement of combustion through more efficient burners and adaptation of combustion conditions (fuel/oxygen ratio) are estimated to lead to 0.03 MBtu/ton (0.04 GJ/tonne) pig iron (IPPC, 2008).

Improved Hot Stove Control. Hot stove automation can help to reduce the energy consumption of the stoves, increase the reliability of the operation, increase stove lifetime, and optimize the gas mix (Beentjes *et al.*, 1989; Derycke *et al.*, 1990; Kowalski *et al.*, 1990). At the ISPAT Island plant(now owned by ArcelorMittal), the application of a model based controller for the optimal operation of blast stoves led to 6-7% reductions in natural gas use and an improvement of operational consistency (U.S. DOE-OIT, 2001d).

18 Steelmaking - BOF

After producing iron, the steelmaking process takes place in a blast oxygen furnace (BOF) (see section 3.4 for a process description). IISI (1998) reports an overall energy surplus, taking into account recovered energy, of 0.26 MBtu/ton (0.30 GJ/tonne) liquid steel as an average of five plants around the world. In the U.S., no BOF plants have installed heat or gas recovery and are hence net energy users.

Variable Speed Drives on Ventilation Fans. In a BOF plant, large fans are used to control air quality. The BOF process is a batch process and as a consequence the volumes of flue gases vary widely over time. This can make the installment of variable speed drives a cost-effective option.

The Hoogovens plant in The Netherlands showed that the use of variable speed drives reduces the power demand by approximately 20%, or 0.9 kWh/ton crude steel (1.0 kWh/tonne) (Worrell *et al.*, 1993; Farla *et al.*, 1998).

The Burns Harbor Facility of Bethlehem Steel Corporation was able to better match the fan speed to the BOF's varying requirements by installing a variable frequency drive and making equipment modifications to the induced draft fans that remove gases from this BOF. As a result, the energy use of the BOF was cut by about 50%. In addition, operation costs and system maintenance expenses were reduced. The project's simple payback time was just under two years (CADDET, 1999b).

Improvement of Process Monitoring and Control. Various types of monitoring systems make it possible to increase process control, which can lead to increased productivity and energy and cost savings. Examples of such systems are: exhaust gas analysis systems, a contour sensoring system, and simultaneous determination of steel/slag composition (Wauters *et al.*, 2006). The monitored data can also be used as input into models of the BOF process which can help to improve understanding and to optimize the process. Further progress in modeling is expected from the use of Computational Fluid Dynamics (CFD), including surface deformation, combustion and radiative transfer (Huber *et al.*, 2008). An example of a process control system is an oxygen management system for oxygen supply to the BOF-process. The total savings due to this system are estimated to be 1.5% of the electricity used for oxygen production (Farla *et al.*, 1998).

Programmed and Efficient Ladle Preheating. Programmed ladle heating minimizes the quantity of fuel required to bring ladles up to steel handling temperatures. This may include the scheduling of ladle heating to ensure that ladles are not kept on heat for excessive periods as well as control of the combustion process (IISI, 1998). Furthermore, an efficient burner for ladle pre-heating makes sure that fuels are used efficiently.

Ladle Preheating. The ladle of the BOF vessel is preheated with gas burners. Fuel consumption for preheating the ladle containing liquid steel is estimated at 0.017 MBtu/ton (0.02 GJ/tonne) liquid steel (IPPC, 2001). Heat losses can occur through the lack of lids and through radiation. The losses can be reduced by installing temperature controls (CADDET, 1989), installing hoods, by efficient ladle management (reducing the need for preheating), using recuperative burners (CADDET, 1987), and use of oxyfuel burners.

JFE Steel Corporation's West Japan Works in Kurashiki improved the design of their ladle heating system by adopting a high-speed on-line heating apparatus and by developing a control system that combined this heating system with the control of blowing in a BOF. In comparison with the heat balance before the introduction of the new process, the ratio of the amount of heat stored in a ladle refractory to the amount of heat input into a ladle improved by more than 10 times from 6.5% to 67.5%. The amount of heat stored in the ladle refractory at the time of receiving molten steel from the BOF became 6.3 times as large, which made it possible to reduce steel temperature at tapping by 16°F (9°C), thereby reducing the amount of carbon (coke) used to raise steel temperature in a converter by 16% (CADDET, 2003b)

Recovery of BOF Gas and Sensible Heat Recovery. Recovery of BOF gas is the single most energy-saving improvement in the BOF process, making it a net energy producer. BOF gas produced during oxygen blowing leaves the BOF through the converter mouth and is subsequently caught by the primary ventilation. This gas has a temperature of approximately 2200°F (1200°C) and a flow rate of approximately 55-110 Nm^3/ton (50-100 Nm^3/tonne) steel. The gas contains approximately 70-80% CO when leaving the BOF and has a heating value of approximately 7.6 kBtu/Nm^3 (8.8 MJ/Nm^3).

Heat recovery methods are classified as a combustion method or as a non-combustion method (method of recovering gas in an unburned condition) (NEDO, 2008). Non-combustion method facilities are designed to recover about 70% of the latent heat and sensible heat (NEDO, 2008).

By reducing the amount of air entering over the convertor, CO is not converted to CO_2. The sensible heat of the off-gas is first recovered in a waste heat boiler, generating high pressure steam. The gas is subsequently cleaned and stored. The recovered converter gas can be mixed with other by-product gases (coke oven gas, blast furnace gas) (NEDO, 2008).

The total savings vary between 0.46-0.79 MBtu/ton steel (0.54 and 0.92 GJ/tonne), depending on the way the steam is recovered (Stelco, 1993; NEDO, 2008). Suppressed combustion reduces dust emissions and since the metal content of the dust is high, about 50% of the dust can be recycled in the sinter plant (Stelco, 1993). The costs will depend on the need for extra gas holders. Suppressed combustion is very common in integrated steel plants in Europe and Japan.

19 Steelmaking – EAF

In an electric arc furnace (EAF), steel is melted via electric arcs between a cathode and one (for DC) or three (for AC) anodes. Throughout the period 1990-2002, Worrell and Biermans (2005) found an annual average improvement in the specific electricity consumption of EAFs in the U.S. steel industry to be 1.3% per year, of which 0.7% per year was due to stock turnover and 0.5% per year was due to the retrofit of stock in service throughout the period. IISI (1998) investigated 16 facilities operating 27 EAFs with a wide variety of configurations. It reports an average total primary energy requirement of 3.9 MBtu/ton (4.6 GJ/tonne) liquid steel of which 89% is provided by electrical energy and 11% by fossil fuels. Electricity for oxygen production accounts for an additional 3% (IISI, 1998).

Improved Process Control. Process control can optimize operations and thereby significantly reduce electricity consumption as is demonstrated by many examples worldwide. Modern controls which use a multitude of sensors can help to achieve this to a greater extent than older controls. Control and monitoring systems for EAFs are developed towards integration of real-time monitoring of process variables, such as steel bath temperature, carbon levels, and distance to scrap (Nyssen *et al.*, 2007), and real-time control systems for graphite injection and lance oxygen practice (Goodfellow *et al.*, 2005). As an example, neural networks or "fuzzy logic" systems analyze data and emulate the best controller (Worrell *et al.*, 1999) and can help to reduce electricity consumption beyond that achieved through classical control systems.

By monitoring the furnace exhaust gas flow rate and composition, the use of chemical energy in the furnace can be enhanced. Detailed investigation of the post-combustion of off-gases can be carried by an optical sensor (see e.g. Januard *et al.*, 2006). Using monitored data as input for a control system, post-combustion of off-gases can be controlled on-line. Benefits of this practice include reduced electricity consumption, shorter power-on times, increased productivity, a decrease in production costs, a reduction of electrode consumption, reduced natural gas, oxygen and carbon consumption, and a reduction of refractory wear. It has been demonstrated that, if oxygen injected for post-combustion is continuously controlled by real-time data acquisition of CO and CO_2 concentrations in off-gases, a 50% increase in recovery rate of chemical energy in fumes can be achieved compared to operation based on predefined set-points (Januard *et al.*, 2006). Numerous examples of the use of this technology were reported (see e.g. CADDET, 2000; Thomson *et al.* 2000; Kühn *et al.*, 2005).

A specific system that continuously measures CO, CO_2, H_2, and O_2 to control post-combustion was installed at the Hylsa's Planta Norte plant near Monterrey (Mexico) and by Nucor, Seattle. The system lead to reductions of 2% and 4% in electricity consumption, 8% and 16% in natural gas consumption, 5% and 16% in oxygen use, 18% and 18% in carbon charged and injected. At the same time, yield improved between 1% and 2%, and electrode consumption decreased between 3.5% and 16%, while productivity increased by 8% (Goodfellow *et al.*, 2005).

In Tamsa, Veracruz (Mexico) the complete chemical fuel injection system was revised between 2002 and 2004. A supersonic wall-mounted injector system was installed together with a flue-gas monitoring system and an advanced process control system. Substantial reductions in the use of electricity and natural gas were attained (12.3% and 33%, respectively) while carbon and oxygen use increased (11% and 14.6%, respectively). Electrode consumption was reduced by 9% (Goodfellow *et al.*, 2005).

Increasing Power. Transformer losses can be as high as 7% of the electrical inputs (CMP, 1992). These losses will depend mainly on the sizing and age of the transformer. Converting the furnace operation to higher high power, or more specifically to ultra-high power (UHP), increases productivity and reduces energy losses. The increased power can be reached by installing new transformers or paralleling existing transformers. UHP operation may lead to increased heat fluxes, and refractory wear, making cooling of the furnace panels necessary. This results in heat losses partially offsetting the power savings.

Many EAF operators have installed new transformers and electric systems to increase the power of the furnaces, e.g. Co-Steel Raritan, NJ), SMI (Sequin, TX), Bayou Steel (Laplace, LA) (Ninneman, 1997), Ugine Ardoise (France) (Alameddine et al., 2001). The savings are estimated to be 1 kWh/ton (1.1 kWh/tonne) per MW power increase (Ninneman, 1997).

Ugine Ardoise in France implemented new transformers on two furnace lines and invested $1.1 Million on the retrofit of its transformer system. The operating voltage increased from 600V to 660V in one furnace and from 400V to 538V in the second. In turn the power delivered by the electrodes at both furnaces increased. Electrode spraying was introduced as a cooling method. The higher power delivered has decreased the power on time by 7 and 14 minutes leading to a productivity increased by 8 ton (7 tonne) of crude steel per hour. The electrode consumption decreased by 0.24 lb/ton and 1.22 lb/ton, respectively (0.1 kg/tonne and 0.5kg/tonne), while power consumption dropped by 10 and 20 kWh/ton (11 and 22 kWh/tonne), respectively. The new transformer system also increased the transformer reactance and made it possible to obtain a higher stability of the electric arc (Alemeddine *et al.*, 2001).

Adjustable Speed Drives (ASDs). As flue gas flow varies over time, adjustable speed drives (ASDs) offer opportunities to operate dust collection fans in a more energy-efficient manner. Flue gas ASDs have been installed in various countries (e.g. Germany, UK). The electricity savings are estimated to be 15 kWh/ton (16.5 kWh/tonne) (Stockmeyer *et al.*, 1990). EPRI (1997) found that although dust collection rates were reduced by 2-3%, total energy usage decreased by 67%. Operation of the ASDs will permit the production of additional efficient steel heats.

Foamy Slag Practices. By covering the arc and melt surface with foamy slag, heat losses through radiation from the melt can be reduced. Foamy slag can be obtained by injecting carbon (granular coal) and oxygen, or by lancing of oxygen only. Slag foaming increases the electric power efficiency by at least 20% in spite of a higher arc voltage (IPPC, 2008). The net energy savings (accounting for energy use for oxygen production) are estimated at 5-7 kWh/ton (6-8 kWh/tonne) steel (derived from Adolph *et al.*, 1990). Foamy slag practice may also increase productivity through reduced tap-to-tap times (Adolph *et al.*, 1990).

Oxy-Fuel Burners/Lancing. Oxy-fuel burners can be installed in EAFs to reduce electricity consumption by substituting electricity with fuels. The use of oxy-fuels burners has several beneficial effects: it increases heat transfer and reduces heat losses (foamy slag, see above). It reduces electrode consumption and tap-to-tap time (Brhel *et al.*, 2001; Allemand *et al.*, 2001). Moreover, the injection of oxygen helps to remove different elements from the steel bath, like phosphorus, silicon and carbon (Allemand *et al.*, 2001).

Steelmakers are now making wide use of stationary wall-mounted oxygen-gas burners (OGB) and combination lance-burners (CLB), which operate in a burner mode during the initial part of the melting period. When a liquid bath is formed, the burners change over to a mode in which they act as oxygen lances. Advantages of wall-mounted lances compared to traditional lances include:

- Wall-mounted lances allow decarburization to occur with the slag door closed. This should reduce the air ingress into the furnace and save electrical energy (Allemand *et al.*, 2001).
- Injection is possible at several different locations. This leads to effective bath stirring, speeding up the decarburization process and increasing the homogeneity of steel bath temperature and chemistry (Allemand *et al.*, 2001; Abel *et al.*, 2005). Bath stirring and the ability to employ several reaction sites can also minimize the oxidation of iron to the slag (Brhel *et al.*, 2001).
- Lower maintenance costs are recognized because there are fewer or no moving parts associated with the wall-mounted injector. Wall-mounted injectors greatly eliminate the need for replacing water-cooled lance tips or consumable pipes.

During decarburization, oxygen is usually injected under supersonic condition to increase gas penetration into the molten bath. Placing the injection points lower in the sidewall makes supersonic injection more effective and also gives hot combustion gases a longer time to penetrate the scrap, which promotes preheating. The higher the scrap column, the more preheating time is possible (see below for scrap preheating by post-combustion) (Abel *et al.*, 2005).

In order to increase the amount of heat transferred to the charge by the burners, some companies have increased the combined power of the burners by increasing the number of relatively small burners used and distributing them around the perimeter and over the height of the furnace. Another option is to make the burners able to rotate, which allows the direction of the flame to be varied. In the course of operation of such a burner, the flame is moved from the already-heated portions of the scrap to the relatively cold portions. This increases the effective area of the flame several-fold and thus increases the burner’s efficiency (Kiselev *et al.*, 2006).

Savings due to the installation of wall-mounted supersonic jets show a significant variation as they depend on the system that is installed and the system that is replaced. For a certain manufacturer the reduction in furnace power-on time averaged over 53 furnaces worldwide between 1995 and 2005 was reported to be 2 to 5 min/heat accompanied by energy savings between 10 and 20 kWh/ton (11 and 22 kWh/tonne). At the same time, oxygen efficiency was enhanced compared to conventional systems leading to reductions in oxygen consumption up to 3-6 Nm^3/ton (3-5 Nm^3/tonne) and improving metallic yield up to 1%. Gas consumption was reported to remain the same or to slightly reduce (Abel *et al.*, 2005).

Post-Combustion of the Flue Gases. Post-combustion is a process for utilizing the chemical energy in the CO and H_2 evolving off the steel bath to heat the steel in the EAF ladle or preheat scrap to 570-1470°F (300-800°C) (see also below: scrap preheating). It reduces electrical energy requirements and increases the productivity of the EAF. Other benefits include reduction of baghouse emissions, reduction of the temperature of the off-gas system and minimization of high temperature spikes associated with rapid CO evolution. Post-combustion helps to optimize the benefits of oxygen and fuel injection (Grant, 2000). EAF operations that involve large amounts of charged carbon or pig iron are particularly suitable for implementation of CO post-combustion technology during scrap melting (Cantacuzene *et al.*, 2006).

It is critical that post-combustion is done early at melt down while the scrap is still capable of absorbing the evolved heat. The injectors should be placed low enough to increase CO retention time in the scrap in order to transfer its heat. The post-combustion oxygen flow should have a low velocity to promote mixing with the furnace gases and avoid both scrap oxidation and oxygen rebound from the scrap to the water cooled panels. The injectors should also be cooled extremely well as the post-combustion area often gets overheated. In order to distribute the chemical energy uniformly and to make its utilization efficient, it is preferable to bifurcate the post-combustion oxygen flow and to space out the injectors in the colder areas of the shell (Cantacuzene *et al.*, 2006).

For a particular post-combustion system, electricity savings ranged from 6 to 11% and reductions in tap-to-tap time from 3 to 11%, depending upon a large variety of operating conditions (Grant, 2000).

Bottom Stirring/Stirring Gas Injection. This measure consists of injecting an inert gas (e.g. argon) in the bottom of the EAF to increase the heat transfer in the melt. This increased stirring in the bath can lead to electricity savings varying between 11 and 22 kWh/ton (12 to 24 kWh/tonne). In addition, increased interaction leads to an increased liquid metal yield of 0.5% (Schade, 1991). Furnaces with oxygen injection are sufficiently turbulent, reducing the need for inert gas stirring.

Engineered Refractories. Refractories in EAF have to withstand extreme conditions such as temperatures over 2900°F (1600°C), oxidation, thermal shock, erosion, and corrosion. These extreme conditions generally lead to an undesired wear of refractories. Refractories can be provided by a controlled microstructure: alumina particles and mullite microballoons coated uniformly with carbon and carbides. The refractories can be either sintered or cast and can therefore be used in a wide range of components at EAF mills (e.g. furnace, ladle furnace, vessels). As the refractories can reduce ladle leakages and the formation of slags in transfer operations. Savings of 10 kWh per ton (11kWh/tonne) steel are expected (U.S. DOE-OIT, 2001).

Waste Injection. Recently, applied research has demonstrated that plastic wastes can be injected as a fuel into EAFs. Using polyethylene waste plastic, the process is currently able to replace 30% of the coke and coal used in EAF steel making. This new process has shown the capacity to accelerate the slag-foaming process at the top of the melt, thereby saving power and reducing power on-time. Consequently, a higher productivity is achieved. Additional benefits include reduction of plastic waste with a higher (thermal) efficiency, and reduced CO_2 emissions. Energy savings of this process are estimated to be around 11 kWh/ton (12 kWh/tonne) of plastic charge.

Until now, this emerging technology has only been applied at a small scale research EAF at the University of New South Wales. In 2007, the holder of the patent, Onesteel, had commercial trials underway at its Rooty Hill facility in Australia. The first trials confirmed the speed-up of the slag foaming process with a reduced power on time and total power use. The tap-to-tap time was also reduced. A small reduction in the electricity consumption has been achieved. The technology will also be implemented and further developed at the OneSteel Laverton facility.

Apart from waste plastics, used tires can also be charged as a substitute for carbon. Two industrial experiments in France and Belgium have shown that with careful charging and perfect carbon control, it is possible to add 18 to 26 lb of tires for each ton (8 to 12 kg/tonne) of steel produced (Ayed *et al.*, 2007).

Scrap Preheating. Using this technology can reduce the power consumption of EAFs through using the waste heat of the furnace to preheat the scrap charge. Old bucket preheating systems had various problems, e.g. emissions, high handling costs, and a relatively low heat recovery rate. Modern systems have reduced these problems, and are highly efficient (Worrell *et al.*, 1999). In the first half of the 1990s, an electric furnace with a direct-coupled scrap preheating function was developed to improve the scrap preheating device. Today, such preheating is performed either in the scrap charging baskets or in a charging shaft (shaft furnace) added to the EAF or in a specially designed scrap conveying system allowing continuous charging during the melting process (IPPC, 2008).

The shaft technology has been developed in steps. With a single shaft furnace at least 50% of the scrap can be preheated whereas a finger shaft furnace (which means a shaft having a scrap retaining system) allows preheating of the total scrap amount (IPPC, 2008). A further modification is the double shaft furnace which consists of two identical shaft furnaces (twin shell arrangement) positioned next to one another and which are serviced by a single set of electrode arms. The most efficient shaft-furnace design is the finger shaft furnace (Siemens VAI, 2007).

Shaft-furnace technology (both single- and double-shaft furnaces) was pioneered by FUCHS in the late 1980s. Since 2005, the VAI FUCHS furnace has been known as SIMETAL^{CIS} EAF. Examples of this technology are: Stahl Gerlafingen – Swiss Steel, Switzerland; Severstal AG, Russia; Diler Iron & Steel Co., Turkey; Fushun Special Steel, China; Nervacero S.A. – Celsa Group, Spain (Siemens VAI, 2007). With the single shaft furnace up to 70 kWh/ton (77 kWh/tonne) liquid steel of electric power can be saved. The finger shaft furnace allows energy savings up to 100 kWh/ton (110 kWh/tonne) liquid steel which is about 25% of the overall electricity input. The exact energy savings depend on the scrap used, and the degree of post-combustion (oxygen levels). For the finger shaft furnace tap-to-tap times of about 35 minutes are achieved which is about 10-15 minutes less compared to EAF without efficient scrap preheating (IPPC, 2001; Siemens VAI, 2007).

The Consteel® process consists of a conveyor belt with the scrap going through a tunnel, down to the EAF through a "hot heel," allowing continuous charging during the melting process. Various U.S. plants and worldwide plants have installed a Consteel® process (in 2007, 31 installations were in place or under construction in 13 countries) (Memoli and Bianchi Ferri, 2008). Average electricity consumption in EAFs is typically 400 kWh/ton (441 kWh/tonne). Using the Consteel® process, this figure can be decreased to approximately 335 – 355 kWh/ton (369-391 kWh/tonne) (Memoli and Bianchi Ferri, 2008).

Airtight Operation. In EAF operation, there is a large amount of air ingress: around 30 000 Nm^3 in a standard EAF of 165 ton (150 tonne) steel with a heat duration of 1 hour (Huber *et al.*, 2006). This air is at ambient temperature, the nitrogen content and the non-reactive oxygen are heated in the furnace and exit with the fumes at high temperature (around 1800°F or1000°C), resulting in significant thermal losses. Based on the results of pilot scale trials with a 7 ton (6 tonne) EAF at Arcelor Research, Huber *et al.* (2006) assessed the potential benefit for an industrial furnace with an airtight process including a post-combustion practice and an efficient fume exhaust control corresponding to around 100 kWh/ton (110 kWh/tonne) for an industrial furnace having a current electric consumption of 450 kWh/ton (496 kWh/tonne). About 80% of the savings can be attributed to a reduction of energy losses in the fumes. The remaining 20% are accounted for by reduced thermal losses due to a reduced elaboration time. The exhaust gas composition can be used as a fuel in the post-combustion chamber and reduces the required amount of natural gas used for the burner.

Direct Current (DC) Arc Furnaces use direct current (DC) instead of conventional alternating current (AC). In a DC furnace, one single electrode is used, and the bottom of the vessel serves as the anode. Based on the distinctive feature of using the heat and magnetic force generated by the current in melting, this arc furnace achieves an energy savings of approximately 5% in terms of power unit consumption in comparison with the 3-phase AC arc furnace. In addition, it also has other features, including higher melting efficiency and extended hearth life. Power consumption is 454- 544 kWh/ton (500-600 kWh/tonne) molten steel. Electrode consumption is about half that with conventional furnaces. This corresponds to 2.4-4.9 lb/ton (1-2 kg/tonne) molten steel (NEDO, 2008). This measure applies to large furnaces only.

Contiarc® Furnace. This furnace is fed continuously with material in a ring between the central shaft and the outer furnace vessel, where the charged material is continuously preheated by the rising process gas in a counter-current flow, while the material continuously moves down. Located below the central shaft is a "free-melting volume" in the form of a cavern. In 2001, SMS Demag commissioned the first Contiarc® furnace for the production of cast iron (SMS Demag, 2006). Advantages of the Contiarc® furnace: reduced energy losses

(200 kWh/ton or 220 kWh/tonne less than with conventional furnace systems), waste gas and dust volumes are considerably reduced requiring a lower capacity of the gas cleaning system and also lower electric power consumption (23 kWh/ton or 25 kWh/tonne), gas-tight furnace enclosure captures all primary and nearly all secondary emissions, and reduced electrode consumption, about 0.8 kg/t less than a typical AC furnace (Rentz and Spengler, 1997).

Comelt Furnace. The Comelt furnace is an EAF on a DC basis with side electrodes provided by VAI. In most cases the furnace is featured with four slanted electrodes, resulting in electric energy transmission by four inclined DC arcs. The essential advantages are: high productivity (tap-to-tap times of less than 45 min), reduction of total energy consumption (approximately 100 kWh/tonne compared to conventional EAF), reduction of electrode consumption (approximately 30%), complete off gas collection at all times and a reduction of off gas volume by up to 70%, reduction in maintenance costs due to a simpler plant design, reduced noise level by up to 15 dB(A) (Rentz and Spengler, 1997).

20 Casting

Casting results in a series of semi-finished steel products such as slabs, blooms or billets. In 2008, 97% of crude steel in the U.S. was cast into semi-finished products by continuous casting (USGS, 2009). Efficient continuous casting machines use approximately 0.12 MBtu/ton (0.14 GJ/tonne) (IISI, 1998). There is a potential to improve energy efficiency in this step. A large part of this potential can be realized by process integration of casting and shaping.

Ladle Preheating. The ladle of the caster is preheated with gas burners. Fuel consumption for preheating the ladle containing liquid steel is estimated at 0.02 MBtu/ton (0.02 GJ/tonne) liquid steel (IPPC, 2001). Heat losses can occur through lack of lids and through radiation. The losses can be reduced by installing temperature controls (CADDET, 1989), installing hoods, by efficient ladle management (reducing the need for preheating), using recuperative burners (CADDET, 1987), and using oxyfuel burners.

At North Star Steel, Iowa, it was estimated that the installation of recuperators for the ladle and Tundish heating system would result in fuel savings of 28% (ladle heaters) and 26% (Tundish dryer), respectively. Payback periods were estimated to be 1.2 years and 10 years, respectively (Pruszco *et al.*, 2003). While a Tundish heater-dryer (capital cost $45,000) annually saves approximately 1000 MBtu (1.0 TJ) of natural gas, ladle heaters (capital cost $70,000) save 13,500 MBtu (14 TJ) of natural gas per year (Pruszco et al, 2003)

Tundish Heating. Tundishes are heated to reduce the heat loss of the molten steel, to avoid bubbles in the first slab at the beginning of the casting sequence and to avoid degeneration of the refractory due to thermal shocks (Beraldo Andrade *et al.*, 2003).

It is estimated that combustion-heated tundishes on average are only 20% efficient. Although earlier tundishes heated through electrical induction failed to generate enough heat to be effective in the manufacturing process, new methods have been developed to improve heating capacity. Tundishes heated by electrical induction have the potential to reach efficiency levels of 98% and contribute to a higher product quality (CADDET, 1997b). However, the use of electricity may result in indirect energy losses in power generation.

Energy savings can also be attained by refraining from heating the tundish. Practices at Companhia Siderúrgica de Tubarão (CST) in Brazil have shown that the use of a cold tundish is operationally feasible and that it brings with it several main benefits: a 70% reduction in the time for machine return after interruptions at the beginning of the cycle, a 78% reduction of natural gas consumption, a 90% increase of the lifetime of the tundish lids and improvement of the working conditions on the casting platform due to heat and noise reductions. The practice was not found to have any influence on the quality of the product. In order to use a cold tundish successfully, an efficient and controlled drying of the tundish is necessary and the thermal heat loss of the steel should be compensated by an increase in the temperature of the first ladle of the tundish (Beraldo Andrade *et al.*, 2003).

Integrated Casting and Rolling. When applying direct rolling, the casted slab is rolled directly in the hot strip mill, saving handling and energy costs. Direct production of hot-rolled strip by connecting the thin slab caster with the hot-rolling process was introduced around 1990. In existing integrated plants this option may be difficult to implement, as the rolling stands need to be located directly next to the continuous caster, leading to high retrofit costs. Energy savings of direct rolling, with a charging temperature of 1110°F (600°C), may be up to 35-43% (IISI, 1998).

Near net shape casting is a process of casting metal to a form close to that required for the finished product. This means less machining is required to finish the part. 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.

Several production processes have been developed for near net shape casting, most notably Thin Slab Casting (TSC) and Strip Casting (SC). In case of TSC, the steel is cast directly to slabs with a thickness between 1.2 and 2.4 in (30 and 60 mm), instead of slabs with a thickness of 4.72-11.8 in (120-300 mm). TSC has been a success in flat product mini-mills in the U.S. (Birat *et al.*, 2005).

In strip casting, the steel is cast between two rolls, producing directly a strip of around 0.12 in (3 mm) thickness. 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 that Henry Bessemer patented in the mid-19th century (Sosinsky et al., 2008). 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 strip casting 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 first introduced thin slab casting in the U.S. The first commercial strip caster was constructed at Nucor's Crawfordsville Indiana plant. The plant was installed in 2002 and since that time the plant has produced Ultra-Thin Cast Strip products (UCS). The plant has a capacity of 540 ktons/year. Nucor has also commenced construction of its second strip casting plant in Blytheville, Arkansas (Sosinsky et al., 2008). Compared to thick slab casting (hot rolling, pickling and cold rolling), thin slab casting saves approximately 0.9 MBtu/ton (1 GJ/tonne). In turn, compared to thin slab casting, the Castrip® process saves approximately another 0.9 MBtu/ton (1 GJ/tonne) (Sosinsky et al., 2008).
- Eurostrip. Eurostrip is a consortium of ThyssenKrupp Steel (TKS), ArcelorMittal, and Voest Alpine Industries, which merged a number of projects and long-term experience in casting. A first pilot plant was operated in Terni (Italy). This plant is now used to strip cast carbon steel. The first commercial plant opened in 1999 in Krefeld (Germany) and

is focused mainly on stainless steel casting (Cramb, 2004). The technology is offered at a scale of 550 ktons/year.

- Nippon/Mitsubishi. The first commercial twin roll production machine was the Hikari machine of Nippon Steel. It was commissioned in October 1997 and has an output of 420 ktons per year (Cramb, 2004).

This strip casting technology leads to considerable capital cost savings and energy savings. It may also lead to indirect energy savings due to reduced material losses. Operations and maintenance costs are also expected to drop by 20-25%, although this will depend strongly on the lifetime of the refractory on the rollers used in the caster and local circumstances. Energy consumption of a strip caster is significantly less than that for continuous casting, with an estimated fuel use of 0.04 MBtu/ton (0.05 GJ/tonne) and electricity use of 39 kWh/ton (42 kWh/tonne).

A new development of Thin Slab Casting and direct rolling is Endless Strip Production (ESP). Construction of an ESP plant by Arvedi started in 2008 in Cremona (Italy). The specific energy consumption should be 40% lower than that needed for a traditional rolling mill. For thin gauges, the suppression of the cold rolling and annealing cycle will allow energy savings of 60% with regard to the traditional cycle. Processing costs are characterized by lower energy consumption, lower costs for consumables (e.g. mould, rolling cylinders) and improved liquid steel yield (up to 98%) (Arvedi *et al.*, 2008).

21 Shaping

The semi-finished steel products from the casting operations are further processed to produce finished steel products in a series of shaping and finishing operations (see section 3.7 for a process description). It is beyond the scope of this Guide to assess all operations and products in detail. Instead, two common shaping processes will be discussed: hot rolling and cold rolling.

Use Efficient Drives. Energy-efficient drives can replace the currently used AC drives (see Chapter 11). High efficiency motors can save approximately 1-2% of the electricity consumption (de Almeida and Fonsesca, 1997). Assuming an electricity demand of 200 kWh/ton (220 kWh/tonne) hot rolled steel, the electricity savings are estimated to be 4 kWh/ton (4 kWh/tonne) product (de Almeida and Fonsesca, 1997).

Gate Communicated Turn-Off (GCT) Inverters. Drive units for main equipment such as rolling mills in steel plants have been shifted from DC operation to variable-speed AC operation. As switching devices for large-capacity inverted drives, Gate Turn-Off (GTO) thyristors have been widely used. However, a GCT thyristor can be used instead of a GTO thyristor to decrease switching losses. Compared with the GTO, the GCT inverter has higher system efficiency, not only at rated-load operation, but also at light-load operation and reduces energy loss. GCT inverters are typically used to drive steel rolling mills, and are being adopted in every area of steel mills from high-speed wire rolling to low-speed hot rolling. Moreover, they are applicable as energy-saving drive units for large-capacity fans, pumps, and compressors (CADDET, 2002a).

Install Lubrication System. High roll loads lead to increased roll wear and high energy consumption. In addition, specific combinations of rolling loads and speeds can cause stands to vibrate which leads to a special type of roll banding and increased wear of the equipment. These problems can be solved by installing a lubrication system as was done at an EKO Stahl hot strip mill (Bösler *et al.*, 2003). Energy savings due to this project were estimated to be about 4 kWh/ton (4 kWh/tonne).

21.1 Hot Rolling

In any hot rolling operation the reheating furnace is a critical factor to determine end-product quality, as well as the total costs of the operation. Energy use in a reheating furnace depends on production factors (e.g. stock, steel type), operational factors (e.g. scheduling), and design features. IISI (1998) reports an average total primary energy requirement of 1.1 MBtu/ton (1.2 GJ/tonne) cast steel based on seven sites.

Savings can also be accomplished by upgrading existing furnaces. The upgrade of a reheat furnace of North Star Steel (Iowa) led to significant fuel, energy cost and labor savings together with savings due to the reduction of scrap use while furnace refractory life and product quality improved (Pruszco *et al.*, 2003).

Proper Reheating Temperature. In choosing the heating temperature for semi-finished products prior to rolling, an attempt should be made to obtain a fine-grained structure in the metal along with the requisite mechanical properties in the rolled product. The heating operation should also ensure dissolution of the inclusions in the metal in the absence of excessive grain growth. A reduction of the heating temperature by 212 °F (100°C) decreases unit fuel consumption by 9% to 10% (Zhuchov *et al.*, 2004). However, lowering the heating temperature will increase the rolling forces and moments, and hence increase the load on the electric drive motors, i.e. it will have the overall effect of increasing the mechanical and electrical loads on the main components of the mill, thereby increasing energy consumption and wear of the mill equipment. As a result, under certain conditions total unit energy consumption may not decrease with a decrease in heating temperature (even without allowance for the losses associated with electric power generation) (Zhuchov *et al.*, 2004). The heating temperature should therefore be carefully considered using a systems approach.

Avoiding Overload of Reheat Furnaces. Overloading a furnace can lead to excessive stack temperatures. To get the proper rate of heat transfer, combustion gases must remain in the heating chamber for the right amount of time. The natural tendency of an overloaded furnace is to run colder than optimal, unless the temperature is set artificially high. This causes the burners to operate at higher than normal firing rates, which increases combustion gas volumes. The higher gas flow rates and shorter time that the gas remains in the furnace causes poor heat transfer, resulting in higher temperatures of the flue gases. The increased volumes of higher temperature flue gases lead to sharply increased heat losses. Overly ambitious production goals might be met, but at the cost of excessive fuel consumption (U.S. DOE-ITP, 2007c).

Process Control in Hot Strip Mill. Process controls save energy and increase productivity and the quality of rolled steel products (Heesen and Burggraaf, 1991; Schriefer, 1996; Vergote, 1996). Although direct energy savings may be limited, indirect energy savings can be substantial due to reduced rejection of product, improved productivity, and reduced down-time. This measure includes controlling oxygen levels and variable speed drives on combustion air fans, which both help to control the oxygen level, and hence optimize the combustion in the furnace, especially as the load of the furnace may vary over time. The savings depend on the load factor of the furnace and control strategies applied. A system installed at ArcelorMittal's Sidmar plant (Belgium) reduced the share of rejects from 1.5% to 0.2% and reduced the downtime from more than 50% of the time to 6% (Vergote, 1996).

Recuperative or Regenerative Burners. Application of recuperative or regenerative burners can substantially reduce energy consumption. A recuperator is a gas-to-gas heat exchanger placed on the stack of the furnace. There are numerous designs, but all rely on tubes or plates to transfer heat from the outgoing exhaust gas to the incoming combustion air, while keeping the two streams from mixing. Recuperative burners use the heat from the exhaust gas to preheat the combustion air. Recuperative burners can reduce fuel consumption by 10-20% compared to furnaces without heat recovery.

Regenerators are basically rechargeable storage batteries for heat. During an operating cycle, process exhaust gases flow through the regenerator, heating a storage medium. After a while, the medium becomes fully heated (charged). The exhaust flow is shut off and cold combustion air extracts the heat from the storage medium, increasing in temperature before it enters the burners. For continuous operation, at least two regenerators and their associated burners are required. Regenerative burners can theoretically achieve savings of up to 35% compared to furnaces without heat recovery.

Since modern recuperative or regenerative burner systems can have significantly higher efficiencies than older systems, savings can also be attained by replacement of recuperative or regenerative burners. While newer designs can also have lower NOx emissions (CADDET, 1997c) the evaluation of recuperative or regenerative burner systems should include an assessment of the impact on NOx emissions.

Replacement of the recuperator by a newer model can result in substantial savings as is illustrated by an example at North Star Steel (Iowa). Recuperator replacement at this plant was estimated to achieve fuel savings of 9% with an expected payback period of 6 months (Pruszco *et al.*, 2003). Another example in Japan shows that a newer model slab continuous reheating furnace can reduce energy consumption by 25% compared with an older furnace recovering waste heat with a recuperator (CADDET, 2002b). In the Japanese steel industry, some plants use regenerative burners in hot mill reheating furnaces and realize energy savings of 7% to 20%. In China, the technology is also increasingly used. Marketed by Shenwu it has been applied to a number of furnaces, using mixtures of BFG and COG with energy savings by up to 34% compared to traditional burners in Chinese reheating furnaces.

Flameless Burners. A widely used technique to enhance furnace efficiency is extensive air preheating, but the drawback is a parallel increase of NO_x emissions. Another technique is the use of flameless burners. Flameless airfuel combustion uses air as oxidizer, while flameless oxyfuel uses commercial oxygen as an oxidant. This technology carries out combustion under diluted oxygen conditions using internal flue gas recirculation and the flame becomes invisible.

Flameless oxyfuel gives high thermal efficiency, higher levels of heat flux, and reduced fuel consumption compared to conventional oxyfuel (Narayanan *et al.*, 2006). These benefits are combined with low NO_x emissions and better thermal uniformity (Narayanan *et al.*, 2006; Fantuzzi and Ballarino, 2008). Since 2003, more than 30 furnaces within the steel industry have been equipped with flameless oxyfuel combustion (Von Schéele, 2008).

ASCOMETAL in Fos-sur-Mer (France) converted five pit furnaces to flameless oxyfuel furnaces. The goal was to replace the 13 air-fueled furnaces and recuperator systems with nine flameless oxyfuel installations without any reduction in total production volume. Process improvements included a 33% shorter heating time, 40% less fuel consumption (excluding additional electricity needed for oxygen production) and 40% lower emissions of NO_x (Narayanan *et al.*, 2006). The production of 1 Nm3 of gaseous oxygen requires approximately 0.5 kWh of electricity (Von Schéele, 2006).

Controlling Oxygen Levels and Variable Speed Drives on Combustion Air Fans. Excess air can substantially decrease combustion efficiency as it leads to excessive waste gases. Fuel-air ratios of the burners should therefore be checked regularly. The use of variable speed drives on combustion air fans on the reheating furnace also helps to control the oxygen level, especially as the load of the furnace may vary over time. The savings depend on the load factor of the furnace and the control strategies applied. Implementing a variable speed drive on a combustion fan of a walking beam furnace at Cardiff Rod Mill (UK) reduced the fuel consumption by 48% and had a payback period of 16 months (CADDET, 1994).

Another way to control the oxygen levels is to increase oxygen content of the combustion air. This can be done either by mixing in ambient air or by using 100% oxygen. The reduction in exhaust gases can lead to substantial fuel savings. The fuel savings have to be compared to the cost of oxygen to estimate economic benefits.

Insulation of Reheat Furnaces. The use of ceramic low-thermal mass insulation materials (LTM) can lead to lower heat losses through the walls compared to those due to the use of conventional insulation materials. For a continuous furnace, the savings of implementing ceramic fiber lining are estimated to be 2-5% (Flanagan, 1993). The application of coatings was found to lead to even higher savings. For a specific type of coating (CO4 coating), average fuel savings were found to be 9% (Konijnenburg, 2005).

Walking Beam Furnace. A walking beam furnace represents the state-of-the-art of efficient reheating furnaces. WCI Steel also employed a state-of-the-art combustion control in the walking beam furnace. The use of the furnace resulted in a reduction in electricity usage by 25% per ton produced and a reduction in overall fuel consumption by 37.5% per ton produced compared to three pusher-type furnaces (Huskonen, 2006)

Hot Charging. Charging slabs at an elevated temperature into the reheating furnace of the hot rolling mill will save energy. Hot charging not only saves energy, but also improves material quality, reduces material losses, enhances productivity (by up to 6%), and may reduce slab stocking (Ritt, 1996).

Care should be taken to descale the slab before charging in the reheating furnace (CADDET, 1990a). The implementation of the technique depends on the layout of the plant, and the distance between the caster and the hot rolling mill. In some plants the caster and reheating furnace are adjacent, making hot charging practical (e.g. the former LTV plant in Cleveland and Usines Gustav Boel in Belgium). Handling and transport of the slabs (i.e. a so-called “hot connection”) is required if there is more distance between the caster and the rolling mill (Worrell *et al.*, 1993).

Assuming a charging temperature of 1290°F (700°C), the savings may be up to 0.52 MBtu/ton (0.6 GJ/tonne) “hot charged” steel based on experiences at Bethlehem Steel at Burns Harbor (Ritt, 1996). According to IISI (1998) energy savings of hot charging at 1650°F (900°C) are 0.6 MBtu/ton (0.7 GJ/tonne) compared to a furnace charged with slabs at 68°F (20°C).

Heat Recovery to the Product. In cases where it is not possible to hot charge the slabs directly from the caster, energy can be recovered bringing exhaust gases that leave the high temperature portion of the process into contact with the relatively cool slabs. This will preheat the slab charge.

In a plant-wide assessment of North Star Steel (Iowa) it was estimated that by using furnace flue gases to preheat the charge to a moderate temperature of 840-1020°F (450- 550°C) would result in costs savings of about 32% (Pruszco *et al.*, 2003). Zhuchov *et al.* (2004) reports a 50% reduction of the unit energy consumption of a heating furnace when charging semifinished products at a temperature above 1200°F (650°C) and a 70-80% reduction at charging temperatures above 1800°F (980°C).

Waste Heat Recovery from Cooling Water. Waste heat can be recovered from the cooling water of the hot strip mill. When ejected, the rolled steel is cooled by spraying water at a temperature of 175°F (80°C). An absorption heat pump (or heat transformer) has been installed at Corus IJmuiden (The Netherlands) to generate low pressure steam (25-51 psi, 265°F (1.7-3.5 bar, 130°C)), which is delivered to the grid on the site. Fuel savings are estimated to be 0.03 MBtu/ton (0.04 GJ/tonne) product, with an increased electricity consumption of 0.15 kWh/ton (0.17 kWh/tonne) (Farla *et al.*, 1998).

21.2 Cold Rolling and Finishing

Automated Monitoring and Targeting System. Installing an automated monitoring and targeting system at a cold strip mill can reduce the power demand of the mill, as well as reduce effluents. A system installed at the former British Steel plant of Brinsworth Strip Mills, reduced energy demand of the cold rolling mill by approximately 15-20%, depending on the load factor (CADDET, 1990b).

Reduced Steam Use in the Acid Pickling Line. In the pickling line, heat escapes through evaporation from the hydrochloric acid bath. The bath is normally heated to temperatures of 203°F (95°C). IISI (1982) reports that steam use can be reduced by about 17% by installing a system of lids and floating balls on top of the bath.

Inter-Electrode Insulation in Electrolytic Pickling Line. The existing industrial electrolytic steel pickling process is only 30% current efficient. This efficiency can be increased by reducing inter-electrode short circuit current with inter-electrode isolation. Experiments have shown that the current efficiency of the process can be improved from 20% without insulation to 100% with insulation. Complete insulation does however lead to sludge accumulation in the compartments where the steel band is anodic, resulting in a heterogeneous electrolyte and higher maintenance requirements. Use of an insulation which covers less, say 66%, of the electrolyte cross section area between the anode and cathode electrode groups, offers a compromise as it results in a significant improvement in the process efficiency while maintaining good circulation and homogeneity of the electrolyte solution. The method is relatively easily applicable as a retrofit (Ipek *et al.* 2005).

Continuous Annealing. A continuous annealing furnace makes it possible to integrate the conventional batch annealing process, i.e. electrolytic cleaning - annealing - cooling - temper rolling – recoiling, into one line. The use of such a furnace can lead to significant energy savings and productivity improvements.

For example, for a particular continuous annealing furnace (NEDO, 2008) the annealing time for one roll is approximately 30 minutes, compared to approximately 10 days for the conventional bath process. In addition, fuel unit consumption is reduced by about 33%.

Considerable differences in fuel consumption exist between different types of cooling equipment used in continuous annealing: the suction cooling roll uses only 14% of the power used by a gas jet system (CADDET, 1999c). The installation of continuous annealing equipment demands relatively high investment costs. For example, a continuous annealing facility with a capacity of about 500,000 ton/year (450,000 tonne/year) in the Midwest has an estimated cost of $225 million (MP&P, 2007c).

Reducing Losses on Annealing Line. Losses on the annealing line can be reduced by implementing heat recovery (using regenerative or recuperative burners in the annealing furnace), improved insulation, process management equipment, as well as installing variable speed drives, reducing energy use by up to 40-60% (Meunier and Cambier, 1993) compared to furnaces without heat recovery (i.e. from 1.8 MBtu/ton to 0.7 MBtu/ton for a continuous annealing line (Milani, 2000). Compared to current state-of-the-art furnaces, a modern furnace with regenerative burners would still reduce fuel consumption by 25%, while NOx emissions would be reduced by 90% (Milani, 2000).

22 Long-term Opportunities to Reduce CO_2 Emissions

Increasing the primary energy efficiency of the steel production process will lead to a reduction in CO_2 emissions. The energy efficiency measures that are discussed in the previous chapters therefore offer opportunities to reduce emissions. These reductions can be determined by multiplying the reductions in fuel and electricity usage with CO_2 emission factors. Note that CO_2 emission factors are dependent on the type of fuel used and the way electricity is generated.

One way to decrease CO_2 emissions from the blast furnace iron making process is to use hydrogen bearing materials such as steam, natural gas, and waste plastics to substitute for coke and coal (Chu *et al.*, 2006). Apart from CO_2 emission reductions due to energy efficiency of resource utilization, there are several emerging technologies to mitigate emissions. However, none are currently commercially available or used at commercial scale. Development of these technologies may take decades.

The global steel industry collaborates in the Ultra–Low carbon dioxide (CO_2) Steelmaking (ULCOS) project to seek opportunities to dramatically reduce CO_2 emissions from iron and steelmaking. . ULCOS is a consortium of 48 European companies and organizations from 15 European countries that have launched a cooperative research and development initiative to enable drastic reduction in CO_2 emissions from steel production. The aim of the ULCOS program is to reduce the CO_2 emissions of today's most efficient steel production routes by at least 50%.

ULCOS has selected four process concepts that could lead to a reduction of CO_2 emissions by more than half compared to current best practice. The four breakthrough technologies identified are (ULCOS, 2009):

- Top gas recycling blast furnace with carbon capture and storage (CCS)
- HISARNA with CCS
- Advanced direct reduction with CCS
- Electrolysis

Carbon-Free Energy and Reducing Agents. Traditionally, carbon from fossil fuels is used in the steel industry to provide the chemical function of reducing oxide ores. This function could also be performed by hydrogen, carbon-free electricity, or biomass:

- *Hydrogen.* Hydrogen reduction of iron ore has steam as a gas product instead of CO_2. Hydrogen can be produced from natural gas, by electrolysis of seawater, etc. Limitations are not technical, as technologies in the area of pre-reduction are very mature, and are related to the volatile issue of resource depletion in the longer term (Hu *et al.*, 2006). Research projects are underway in different countries. In the U.S. the AISI, U.S. DOE and the University of Utah are investigating a process called Hydrogen Flash Smelting. An overview of the use of hydrogen for the reduction of iron ore is provided by Tacke and Steffen (2004).
- *Biomass and charcoal.* Biological treatment of ores by bacteria is practiced in the precious metals industries, but not in the steel industry (Hu *et al.* 2006). The concept

of using wood to make iron in a charcoal blast furnace is being presently applied in Brazil (Teodoro da Costa and Mayrink Morais, 2006).

- *Electrolysis.* This process leads directly to final products, is to be compared to a whole conventional mill, which has an energy consumption of 15 to 20 GJ/t liquid steel, with a similar order of magnitude. The technology might be attractive in terms of CO_2 emissions, and if the carbon content of electricity is sufficiently low (Hu *et al.*, 2006). The most promising options for electrolysis are aqueous alkaline electrolysis, also called electrowinning, and iron ore pyro-electrolysis. Both technologies have already been shown possible at very small scale while commercial application may still be decades away (ULCOS, 2009). In the U.S., MIT, AISI and U.S.DOE are jointly investigating the opportunities of electrolysis processes for ironmaking.

Carbon Capture and Storage (CCS). A solution for carbon-intensive activities is the capture and storage of CO_2. Many of the concepts developed in the ULCOS project integrate CCS into the design of iron reducing processes. In order to capture CO_2 from emissions created in steel plants, it first needs to be separated from the flue gases and then compressed and/or cooled and transported by a network of pipelines to be stored underground. CCS in geological formations involves injecting CO_2 into porous rock layers. There are three main storage options, i.e. depleted or near-depleted oil and gas fields, deep saline aquifers (porous rock layers containing salty water deep underground) or un-mineable coal seams.

Steel plants appear particularly suitable for carbon capture because their emissions originate from single fixed and easily accessible points and are already highly concentrated in CO_2. The technical feasibility of each individual element of CCS technology has been demonstrated, but the economic viability and technical integration and scale-up needed for routine industrial application will require significant research and demonstration (ULCOS, 2009).

HISARNA. HISARNA is a technology based on bath-smelting. It combines coal preheating and partial pyrolysis in a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. It requires significantly less coal usage and thus reduces the amount of CO_2 emissions. Furthermore, it is a flexible process that allows partial substitution of coal by biomass, natural gas or even hydrogen. The HISARNA process is based on the Cyclone Converter Furnace (CCF) developed by Hoogovens (The Netherlands). The CCF technology incorporates the results of earlier AISI projects to develop convertor-based reduction processes. A pilot plant will be operational in early 2010. Additional work is continuing on using CO_2 capture and storage (CCS) and biomass technology in combination with HISARNA (ULCOS, 2009).

23 Water Efficiency Improvement Opportunities

Steelmaking requires 13,000 to 23,000 gallons of water to produce one ton of steel (54-96 m^3/tonne), even taking into account the water that is reused in the process (U.S. DOE, 2003). There is wide variation in water use levels as well as efficiency of water use for different steelmaking sites, depending on the production processes used. For example, Nippon Steel uses approximately 13.8 m^3 of fresh water per tonne of crude steel produced in its integrated iron and steel plants. At sites with very low fresh water availability, there is a need to save water as much as possible. In such cases, the specific water consumption can be less than 2,400 gallons/ton (10 m^3/tonne) steel, and sometimes less than 1,200 gallons/ton (5 m^3/tonne) steel (IPPC, 2008), indicating a great potential to improve the efficiency of water use.

Within specific processes, large variations in water use are also observed, suggesting a large potential for improvement. Dedicated efforts enable the realization of significant water savings and cost reductions in water purchase and treatment. ArcelorMittal’s integrated mill at Gent (Belgium) implemented several water management projects since the mid-1990s and was able to reduce water intake by half through doubling the amount of water that is internally recycled (Mortier et al., 2007). This improvement can be attained by increasing internal treatment and recycling, as well as more efficient use. Below a number of water efficiency measures are discussed.

Note that water savings may indirectly also lead to additional energy savings, as water treatment and pumping requirements will be reduced.

Water Pinch Analysis. Water used to be seen as a low-cost resource to industry, and was used inefficiently. However, as the standards and costs for waste water treatment increase and the costs for feed water makeup increase, the industry has become more aware of water costs. In addition, large amounts of energy are used to process and move water through the plant. Hence, water savings will lead to additional energy savings. Similar to the pinch technique used for steam system optimization, Water Pinch can be used to develop targets for minimal water use by reusing water in an efficient manner. Optimization software has been developed to optimize investment and operation costs for water systems in a plant (Hallale, 2001). New tools have been developed to optimize water and energy use in an integrated manner (Wu, 2000). Water inch analysis has mainly been used in the food industry, reporting reductions in water intake of up to 50% (Polley and Polley, 2000). While the results may not be representative for U.S. plants, the potential power of the water pinch technique is illustrated by an analysis of a Chinese integrated iron and steel plant. Tian et al. (2008) report the use of water pinch analysis at a Chinese blast furnace site (including power plant), identifying water intake savings exceeding 50%, with a payback period of less than one year.

Cooling Water Use. Virtually all industrial companies operate plants or equipment that requires cooling. Depending on the temperature level required, various cooling methods can be applied including ambient air cooling (for temperature down to 45ºC, or 113°F), water cooling (down to around 15ºC or 59°F) and refrigerated systems for lower temperatures.

It goes without saying that total cooling (and heating) demands should be optimized using process integration techniques. Optimization of the various cooling efforts on a plant site can reduce energy demand. Cooling water systems are historically the most common means of providing industrial cooling, because of multiple advantages such as the safety of water, the ease of operating large centralized systems that are easy to engineer and operate. Regular checks of the cooling water system, e.g. by metering water flows at appropriate spots can help identify water leaks and opportunities for system optimization. A site survey and a full mass balance of all water flows at AH Marks, an organic chemical producer in the UK, resulted in total reduction of water use by 70%. This was achieved by repairing faulty valves, an underground leak and by reducing losses during the filling and emptying of reactor jackets (Best Practice Programme, 1999). Although water savings will not be that high in most cases, good regular maintenance checks can contribute to significant water and hence energy savings.

Use of Cleaned Sewage Water for Process Cooling. For many cooling applications, it is not necessary to use potable water. The cleaned ("recycled") water from sewage water treatment plants is a good substitute for potable water use. Australia's BlueScope Port Kembla steel plant uses recycled water from Sydney's Wollongong Sewage Treatment Plant, which is less than two miles away. This has resulted in reduced potable water use of 5.2 million gallons/day (Sydney Water, 2009).

Closed Loop Water Cooling System for EAF. The water needed in an EAF with respect to the cooling elements amounts to 12-29 gallons/ft^{2}h (5-12 m^3/m^{2}h). This water can saved by operating closed cooling systems as is done in most modern plants in the EAF and secondary metallurgical sections (IPPC, 2008).

Research commissioned by the European Commission showed that as far as water economy is concerned, integrated circuits, using several treatment stages in cascade, with a single final discharge point, reduce pollutant release to external water bodies (whatever the specific water discharge is) compared to separate circuits with multiple discharge points (European Commission, 1996).

Re-use of Cooling Tower Blowdown. Blowdown water of cooling towers can be recycled as cooling water or rinsing water for steel. Orb Electrical Steels in Australia (a specialty steelmaker) collects the blowdown water from cooling towers and mixes this with collected rainwater to rinse steel, replacing the use of fresh water.

Coke Dry Quenching. Traditionally, coke is quenched by spraying water on the hot coke under the quenching tower. Not only does this result in the use of large amounts of water since part of the water is evaporated, it also results in significant energy losses as well as emissions of particulate matter to the surrounding environment. Coke dry quenching is an alternative technology that is widely used in the steel industry in Japan, Germany and other countries, while its use in China is rapidly increasing to reduce water intake. Net water consumption of coke quenching exceeds 100 gallons/ton of coke, and can be as twice as high or more (see also Chapter 16).

Treatment and Re-use of Water used for Scrubbing of BF Gas. Blast furnace gas is usually cleaned in specially designed hurdle type, venture, or annular gap scrubbers. This generates a contaminated water flow containing suspended solids. Measures can be taken to minimize discharges to water and to minimize water consumption.

To scrub the pollutants from the BF gas, approximately 0.08-1.1 gallons/Nm^3 (0.3-4.0 liter/Nm^3) are needed, corresponding to a gross water consumption of 100-1,920 gallon/ton (0.4-8 m^3/tonne) pig iron. High recycling efficiency of scrubbing water can be achieved with an overflow of only 24 gallons/ton (0.1 m^3/tonne) pig iron. This water is removed from the system with the blast furnace sludge and may undergo further treatment (IPPC, 2001).

Treatment of Wastewater from Wet De-dusting of BOF Gas. In oxygen steelmaking plants, scrubbers can be used to reduce emissions to air from the primary gas flow (BOF gas). This potentially transfers pollution from air to water. A large part of the suspended solids in the scrubbing water circuit can be removed. After pH correction most of the water can be recycled.

The discharge flow from wet de-dusting facilities at oxygen steelmaking plants with a suppressed combustion system can be as low as 0.5 gallons/ton (2 liter/tonne) liquid steel as was the case at LTV Steel Cleveland Works Corus (IPPC, 2001).

Treatment of Wastewater from Continuous Casting. Water is used in continuous casting machines for direct cooling of the slabs, blooms and billets. A contaminated water flow is therefore generated. In many cases this waste water is treated together with waste water streams from the rolling mills. After treatment the water can be recirculated.

The discharge flow from direct cooling systems at continuous casting plants can be as low as 10 gallons/ton (0.04 m^3/tonne) cast steel as was the case at Corus, Ijmuiden (The Netherlands). The recirculation rate can be as high as 99% as was the case at Inland Steel, Indiana Harbor Works (IN) (IPPC, 2001).

24 Summary and Conclusions

In 2008, the U.S. was the third largest steel manufacturing country in the world, producing 7% (103.3 Mtons or 93.7 Mtonnes) of world steel output and ranked fifth for the production of pig iron with a worldwide share of 4% (39.2 Mtons or 35.6 Mtonnes). In total, the sector consumed 1,390 TBtu primary energy (1470 PJ) or 5.1% of the total primary energy consumed by the whole U.S. manufacturing sector. This energy represents about 20% of the total manufacturing costs of steel. Energy efficiency improvement is an important way to reduce costs and increase predictable earnings, especially in times of high energy-price volatility.

Many companies in the U.S. iron and steel industry have already accepted the challenge to improve their energy efficiency in the face of high energy costs and have begun to reap the rewards of energy efficiency investments. Voluntary government programs aim to assist industry to improve competitiveness through increased energy efficiency and reduced environmental impact. ENERGY STAR®, a voluntary program managed by the U.S. Environmental Protection Agency, stresses the need for strong and strategic corporate energy management programs.

This Energy Guide summarizes a large number of energy-efficient technologies and practices that are proven, cost-effective, and available for implementation today. Energy efficiency improvement opportunities are discussed that are applicable at the component, process, facility, and organizational levels. Preliminary estimates of savings in energy and energy-related costs are provided for many energy efficiency measures, based on case study data from actual industrial applications. Additionally, typical investment payback periods and references to further information in the technical literature are provided, when available.

A key first step in any energy improvement initiative is to establish a focused and strategic energy management program, which will help to identify and implement energy efficiency measures and practices across the organization and ensure continuous improvement. Many of the measures discussed have relatively short payback periods and are therefore attractive investments. The degree of implementation of these measures will vary by plant and end use; continuous evaluation of these measures will help to identify further cost savings in ongoing energy management programs. While the expected savings associated with some of the individual measures may be relatively small, the cumulative effect of these measures across an entire plant may potentially be quite large.

For all energy efficiency measures presented in this Energy Guide, individual plants should pursue further research on the economics of the measures, as well as on the applicability of different measures to their own unique production practices, in order to assess the feasibility of measure implementation.

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Any remaining errors in this Energy Guide are the responsibility of the authors. The views expressed in this Energy Guide do not necessarily reflect those of the U.S. Environmental Protection Agency, the U.S. Department of Energy, or the U.S. Government.

Glossary

AC	Alternating current
ASD	Adjustable speed drives
BF	Blast furnace
BOF	Basic oxygen furnace
CDQ	Coke dry quenching
CFD	Computational fluid dynamics
CHP	Combined heat and power
CLB	Combination lance-burners
COG	Coke oven gas
COP	Coefficient of performance
DC	Direct current
DRI	Direct reduced iron
EAF	Electric arc furnace
EBT	Eccentric bottom tapping
ECDT	Electronic condensate drain traps
ESP	Endless strip production
FEM	Finite element method
GCT	Gate communicated turn-off
GHG	Greenhouse gas
GTO	Gate turn-off
HAH	Humidifying air heater
HID	High-intensity discharge
HVAC	Heating, ventilation, air conditioning
KBS	Knowledge base system
LCC	Life cycle costing
LTM	Low-thermal mass
NAICS	North American Industrial classification system
OGB	Oxygen-gas burners
PCI	Pulverized coal injection
PLC	Programmable logic control
PRV	Pressure reduction valve
PVC	Polyvinylchloride
RO	Reverse osmosis
SC	Strip casting
SIC	Standard industrial classification
SSW	Slit segregation wire
TMC	Transport membrane condenser
TRT	Top pressure recovery turbines
TSC	Thin slab casting
UHP	Ultra-high power
ULCOS	Ultra-Low CO_2 Steelmaking
USD	United States dollars
VFD	Variable frequency drive

VSD	Variable speed drive

Organizations

AISE	American Iron and Steel Engineers
AISI	American Iron and Steel Institute
BSC	Bethlehem Steel Corporation
CADDET	Centre for the Analysis and Dissemination of Demonstrated Energy Technologies
CDA	Copper Development Association
CEC	California Energy Commission
CEE	Consortium for Energy Efficiency
CIBO	Council of Industrial Boiler Owners
CIPEC	Canadian Industry Program for Energy Conservation
CMP	Center for Materials Production
CST	Companhia Siderúrgica de Tubarão
EASA	Electric Apparatus Service Association
IPPC	Integrated Pollution Prevention and Control
EPRI	Electric Power Research Institute
IEA	International Energy Agency
IISI	International Iron and Steel Institute
MP&P	Metal Producing & Processing
NEDO	New Energy and Industrial technology Development Organization
NEMA	National Electrical Manufacturers Association
U.S. DOE	U.S. Department of Energy
U.S. DOE-IAC	U.S. Department of Energy - Industrial Assessment Center
U.S. DOE-ITP	U.S. Department of Energy - Industrial Technologies Program
U.S. DOE-OIT	U.S. Department of Energy - Office of Industrial Technologies
U.S. EIA	U.S. Energy Information Administration
U.S. EIA MECS	U.S. Energy Information Administration - Manufacturing Energy Consumption Survey
U.S. EPA	U.S. Department of Energy - Environmental Protection Agency
USGS	United States Geological Survey
WSA	World Steel Association

Gases

CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen
NO_x	Nitrogen oxides
O_2	Oxygen

Units

Btu	British thermal unit
ft	foot
h	hour
hp	horse power
in	inch
J	Joule
lb	pound
m	meter
Nm^3	Normal cubic meter
psi	pounds per square inch
psig	pounds per square inch gauge
ton	short ton (907 kg)
tonne	metric ton (1000 kg)
tcs	tonne cast steel
thm	tonne hot metal
tls	tonne liquid steel

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Appendix A: **U.S. Integrated and Secondary Steel Mills**

Company/Location	**Blast Furnace Name**	**Yr. built or since last rebuild**	**Blast Furnace Age in 2007**	**Production Rate (Mton/year) (2006)**
AK Steel Corp.				
Ashland Works, Ashland KY	Amanda	1963	44	1.93
Middletown Works, Middleton OH	3	1984	23*	2.20
Arcelor-Mittal Steel				
Burns Harbor Division, Burns Harbor IN	C	1972	35	2.12
	D	1969	38	2.22
Cleveland Works, Cleveland OH	C-5	1990	17*	1.37
	C-6	1989	18*	1.30
Indiana Harbor Works, East Chicago IN	IH-3	1988	19*	1.32
	IH-4	1987	20*	1.53
	IH-5			0.85
	IH-6			0.53
	IH-7	1980	27	3.98
Severstal				
Dearborn MI	B	1958	39*	0.95
	C	1959	38*	1.39
Sparrows Point, MD	L	1977	30	2.55
Republic Technologies International				
Lorain OH	4	1962	35*	1.22
U.S. Steel Corp.				
Fairfield Works, Fairfield AL	8	1978	29	2.09
Gary Works, Gary IN	4	1950	57*	0.90
	6	1947	60*	0.97
	8	1943	64*	0.90
	14	2005	2*	2.89
Granite City Division, Granite City IL	A	1956	49	0.88
	B	1961	46	1.22
Great Lakes Division, Ecore MI	B	1951	56	1.33
	D	1952	55	1.43
Edgar Thomson Plant Braddock, Pa.	1	1930	77*	1.10
	3	1978	29*	1.10
WCI Steel Inc.				
Warren OH	1	1980	27*	1.22
Wheeling-Pittsburgh Steel Corp.				
Steubenville, Ohio	5	1995	12*	1.27

Source: I&ST (2007); Worrell *et al.* (1999)
* = age since last major rebuild

Company	Plant Location City	Plant Location State	Year of startup	EAF age in 2003 (years)	Power consumption (kWh/ton)
ABC-Naco	Calera	AL	1972	31	500
			1954	49	500
			1970	33	500
			1970	33	500
AK Steel Corp.	Butler	PA	1969	34	410
	Mansfield	OH	1963	40	400
			1989	14	400
Allegheny Technologies Inc.	Brackenridge	PA	1949	54	500
			1949	54	500
			1949	54	500
			1949	54	500
American Cast Iron Pipe Co. Inc.	Birmingham	AL	1954	49	550-600
			1954	49	550-600
			1954	49	550-600
			2001	2	N/A
Arkansas Steel Associates	Newport	AR	1994	9	440
Atchinson Casting Corp.	Atchinson	KS	1958	45	460
			1940	63	650
			1946	57	520
			1981	22	540
Austeel Lemont Co. Inc.	Lemont	IL	1959	44	465
Bayou Steel Corp.	LaPlace	LA	1981	22	395
			1981	22	445
Beta Steel Corp.	Portage	IN	1997	6	415
Bethlehem Steel Corp.	Coatesville	PA	1985	18	380
	Steelville	PA	1994	9	400
Border Steel Inc.	El Paso	TX	2003	0	420
			1967	36	450
Calumet Steel Co.	Chicago Heights	IL	1967	36	500
Carpenter Technology Corp.	Reading	PA	1955	48	450
			1956	47	450
			1982	21	450
Cascade Steel Rolling Mills Inc.	McMinnville	OR	1991	12	410
Champion Steel Co. , The	Orwell,	OH	1968	35	615
Charter Manufacturing Co. Inc.	Saukville	WI	1991	12	360
CitiSteel USA Inc.	Claymont	DE	1989	14	425
CMC Steel Group	Birmingham	AL	1994	9	385
	Cayce	SC	1992	11	385
	Seguin	TX	1999	4	385
Columbus Steel Castings	Columbus	OH	1965	38	460
			1978	25	470
Corus Tuscaloosa	Tuscaloosa,	AL	1996	7	397
Crucible Materials Corp.	Syracuse	NY	1973	30	490

Electralloy	Oil City,	PA	1968	35	500
Ellwood Quality Steels Co.	New Castle	PA	1985	18	410
Erie Forge and Steel Inc.	Erie	PA	1966	37	400
			1966	37	N/A
			1986	17	N/A
ESCO Corp.	Newton	MS	1979	24	420
			1971	32	420
	Portland	OR	N/A	N/A	515
			N/A	N/A	505
			N/A	N/A	515
Finkl, A., & Sons	Chicago	L	1953	50	500
			1953	50	500
Gallatin Steel Co.	Ghent	KY	1995	8	400
Georgetown Steel Corp.	Georgetown,	SC	1969	34	520
			1969	34	520
Gerdau Ameristeel	Cartersville	GA	1990	13	420
	Charlotte	NC	1989	14	355
	Baldwin	FL	1976	27	385
	Knoxville	TN	2000	3	400
	Jackson	TN	1981	22	390
	Perth Amboy	NJ	1979	24	400
	Sayreville	NJ	1994	9	385
GST Steel Co.	Kansas City	MO	1977	26	465
			1977	26	420
Harrison Steel Castings Co.	Attica	IN	1951	52	445
			1974	29	420
			1992	11	480
Haynes International Inc.	Kokomo	IN	1948	55	N/A
			1963	40	500
Hensley Industries	Dallas	TX	1987	16	510
			1989	14	510
Hoeganaes Corp.	Gallatin	TN	1998	5	420
	Riverton	NJ	1970	33	500
Inmetco	Ellwood City	PA	1978	25	N/A
International Steel Group	Cleveland	OH	1959	44	460
Ipsco Inc.	Montepelier	IA	1997	6	370
	Axis	AL	2001	2	325
Ispat Inland Inc.	East Chicago	IN	1994	9	460
J&L Specialty Steel Inc.	Midland	PA	1980	23	440
Kentucky Electric Steel Inc.	Ashland	KY	1981	22	420
Keokuk Steel Castings Inc.	Keokuk	IA	1976	27	500
Keystone Steel & Wire Co.	Peoria,	IL	1998	5	380
Kobelco Metal Powder of America Inc.	Seymour,	IN	1989	14	440
K.O. Steel Foundry & Machine	San Antonio	TX	1979	24	490
LeTourneau Inc.	Longview	TX	1973	30	450
			1973	30	450
Lone Star Steel Inc.	Lone Star	TX	1976	27	460

MACSTEEL®	Fort Smith	AR	1984	19	392
	Jackson,	MI	1974	29	475
Marion Steel Co.	Marion	OH	1998	5	440
Maynard Steel Casting Co.	Milwaukee,	WI	N/A	N/A	500
			N/A	N/A	500
			N/A	N/A	500
			N/A	N/A	500
National Forge Co.	Irvine	PA	1962	41	470
North Star Steel	Kingman	AZ	1996	7	300
	Wilton	IA	1976	27	450
	Monroe	MI	1980	23	N/A
	St. Paul	MN	1994	9	N/A
	Beaumont	TX	1976	27	370
North Star BHP Steel LLP	Delta	OH	1996	7	338
Northwestern Steel & Wire Co.	Sterling	IL	1971	32	480
			2000	3	390
NS Group Inc.	Beaver Falls	PA	1984	19	440
Nucor Bar Mill Group	Birmingham	AL	1986	17	415
	Kankakee,	IL	1990	13	410
	Jackson	MS	1993	10	430
	Seattle	WA	1995	8	380
Nucor Steel – Auburn	Auburn	NY	1975	28	365
Nucor Corp.	Crawfordsville	IN	1989	14	370
	Darlington	SC	1993	10	330
	Cofield	NC	2000	3	320
	Hickman	AR	1993	10	350
	Jewett	TX	1980	23	360
	Norfolk	NE	1997	6	400
	Plymouth	UT	1981	22	400
	Berkeley County	SC	1996	7	350
	Blytheville	AR	1988	15	325
Nucor Steel – Decatur LLC	Decatur	AL	1997	6	N/A
Oregon Steel Mills Inc.	Portland	OR	1985	18	410
	Pueblo	CO	1976	27	420
			1973	30	420
Republic Engineered Products LLC	Canton	OH	1995	8	385
Roanoke Electric Steel Corp.	Roanoke,	VA	1975	28	480
			1996	7	375
Sheffield Steel Corp.	Sand Springs	OK	1957	46	460
			1970	33	460
Slater Steels Corp.	Ft. Wayne	IN	1942	61	450
			1995	8	540
Standard Steel	Burnham	PA	1962	41	N/A
			1965	38	N/A
	Latrobe	PA	1971	32	N/A
			1971	32	N/A
Steel Dynamics Inc.	Butler	IN	1995	8	410
			1998	5	410
	Whitley County	IN	2002	1	375
Steel of West Virginia Inc.	Huntington,	WV	1979	24	500

TAMCO	Rancho Cucamonga	CA	1996	7	450
Texas Steel Co.	Fort Worth	TX	1923	80	460
			1942	61	450
Timken Co., The	Canton	OH	1985	18	340
			1964	39	490
			1971	32	490
			1976	27	490
	Latrobe	PA	1964	39	500
			1999	4	540
TXI Chaparral Steel	Midlothian	TX	1975	28	400
			1981	22	380
	Dinwiddie	VA	1999	4	315
Union Electric Steel Corp.	Carnegie	PA	1966	37	530
Universal Stainless & Alloy Products Inc.	Bridgeville	PA	1961	42	490
V&M Star	Youngstown	OH	1999	4	395

Source: EAF Roundup, 2003
N/A = not available
* = age since last major rebuild

Appendix B: Basic Energy Efficiency Actions for Plant Personnel

Personnel at all levels should be aware of energy use and organizational goals for energy efficiency. Staff should be trained in both skills and general approaches to energy efficiency in day-to-day practices. In addition, performance results should be regularly evaluated and communicated to all personnel, recognizing high achievement. Some examples of simple tasks employees can do are outlined below (Caffal 1995).

- Eliminate unnecessary energy consumption by equipment. Switch off motors, fans, and machines when they are not being used, especially at the end of the working day or shift, and during breaks, when it does not affect production, quality, or safety. Similarly, turn on equipment no earlier than needed to reach the correct settings (temperature, pressure) at the start time.
- Switch off unnecessary lights; rely on daylighting whenever possible.
- Use weekend and night setbacks on HVAC in offices or conditioned buildings.
- Report leaks of water (both process water and dripping taps), steam, and compressed air. Ensure they are repaired quickly. The best time to check for leaks is a quiet time like the weekend.
- Look for unoccupied areas being heated or cooled, and switch off heating or cooling.
- Check that heating controls are not set too high or cooling controls set too low. In this situation, windows and doors are often left open to lower temperatures instead of lowering the heating.
- Check to make sure the pressure and temperature of equipment is not set too high.
- Prevent drafts from badly fitting seals, windows and doors, and hence, leakage of cool or warm air.
- Carry out regular maintenance of energy-consuming equipment.
- Ensure that the insulation on process heating equipment is effective.

Appendix C: Guidelines for Energy Management Assessment Matrix

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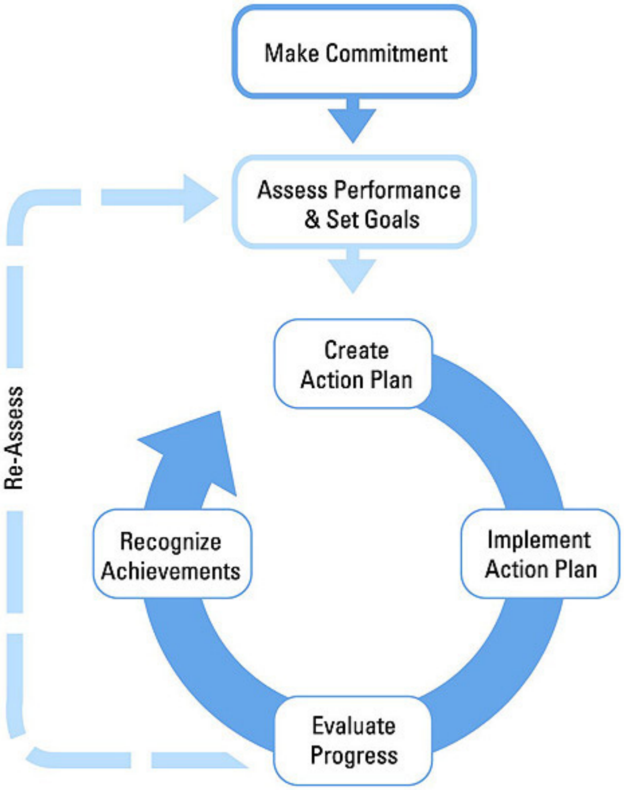
Energy Management Program Assessment Matrix

Introduction

The U.S. EPA has developed guidelines for establishing and conducting an effective energy management program based on the successful practices of ENERGY STAR partners.

These guidelines, illustrated in the graphic, are structured on seven fundamental management elements that encompass specific activities.



This assessment matrix is designed to help organizations and energy managers compare their energy management practices to those outlined in the Guidelines. The full Guidelines can be viewed on the ENERGY STAR web site – http://www.energystar.gov/.

How To Use The Assessment Matrix

The matrix outlines the key activities identified in the ENERGY STAR Guidelines for Energy Management and three levels of implementation:

- No evidence
- Most elements
- Fully Implemented

- Print the assessment matrix.

- Compare your program to the Guidelines by identifying the degree of implementation that most closely matches your organization's program.

- Use a highlighter to fill in the cell that best characterizes the level of implementation of your program. You will now have a visual comparison of your program to the elements of the ENERGY STAR Guidelines for Energy Management.

- Identify the steps needed to fully implement the energy management elements and record these in the Next Steps column.

Energy Management Program Assessment Matrix

	Little or no evidence	Some elements	Fully implemented	Next Steps
Make Commitment to Continuous Improvement				
Energy Director	No central corporate resource Decentralized management	Corporate or organizational resource not empowered	Empowered corporate leader with senior management support	
Energy Team	No company energy network	Informal organization	Active cross-functional team guiding energy program	
Energy Policy	No formal policy	Referenced in environmental or other policies	Formal stand-alone EE policy endorsed by senior mgmt.	
Assess Performance and Opportunities				
Gather and Track Data	Little metering/no tracking	Local or partial metering/tracking/ reporting	All facilities report for central consolidation/analysis	
Normalize	Not addressed	Some unit measures or weather adjustments	All meaningful adjustments for corporate analysis	
Establish baselines	No baselines	Various facility-established	Standardized corporate base year and metric established	
Benchmark	Not addressed or only same site historical comparisons	Some internal comparisons among company sites	Regular internal & external comparisons & analyses	
Analyze	Not addressed	Some attempt to identify and correct spikes	Profiles identifying trends, peaks, valleys & causes	
Technical assessments and audits	Not addressed	Internal facility reviews	Reviews by multi-functional team of professionals	
Set Performance Goals				
Determine scope	No quantifiable goals	Short term facility goals or nominal corporate goals	Short & long term facility and corporate goals	
Estimate potential for improvement	No process in place	Specific projects based on limited vendor projections	Facility & corporate defined based on experience	
Establish goals	Not addressed	Loosely defined or sporadically applied	Specific & quantifiable at various organizational levels	
Create Action Plan				
Define technical steps and targets	Not addressed	Facility-level consideration as opportunities occur	Detailed multi-level targets with timelines to close gaps	
Determine roles and resources	Not addressed or done on ad hoc basis	Informal interested person competes for funding	Internal/external roles defined & funding identified	

Energy Management Program Assessment Matrix

	Little or no evidence	Some elements	Fully implemented	Next Steps
Implement Action Plan				
Create a communication plan	Not addressed	Tools targeted for some groups used occasionally	All stakeholders are addressed on regular basis	
Raise awareness	No promotion of energy efficiency	Periodic references to energy initiatives	All levels of organization support energy goals	
Build capacity	Indirect training only	Some training for key individuals	Broad training/certification in technology & best practices	
Motivate	No or occasional contact with energy users and staff	Threats for non-performance or periodic reminders	Recognition, financial & performance incentives	
Track and monitor	No system for monitoring progress	Annual reviews by facilities	Regular reviews & updates of centralized system	
Evaluate Progress				
Measure results	No reviews	Historical comparisons	Compare usage & costs vs. goals, plans, competitors	
Review action plan	No reviews	Informal check on progress	Revise plan based on results, feedback & business factors	
Recognize Achievements				
Provide internal recognition	Not addressed	Identify successful projects	Acknowledge contributions of individuals, teams, facilities	
Get external recognition	Not sought	Incidental or vendor acknowledgement	Government/third party highlighting achievements	

energy

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Interpreting Your Results

Comparing your program to the level of implementation identified in the Matrix should help you identify the strengths and weaknesses of your program.

The U.S. EPA has observed that organizations fully implementing the practices outlined in the Guidelines achieve the greatest results. Organizations are encouraged to implement the Guidelines as fully as possible.

By highlighting the cells of the matrix, you now can easily tell how well balanced your energy program is across the management elements of the Guidelines. Use this illustration of your energy management program for discussion with staff and management.

Use the "Next Steps" column of the Matrix to develop a plan of action for improving your energy management practices.

Resources and Help

ENERGY STAR offers a variety tools and resources to help organizations strengthen their energy management programs.

Here are some next steps you can take with ENERGY STAR:

1. Read the Guidelines sections for the areas of your program that are not fully implemented.
2. Become an ENERGY STAR Partner, if you are not already.
3. Review ENERGY STAR Tools and Resources.
4. Find more sector-specific energy management information at http://www.energystar.gov/industry.
5. Contact ENERGY STAR for additional resources.

Appendix D: Teaming Up to Save Energy Checklist

The following checklist can be used as a handy reference to key tasks for establishing and sustaining an effective energy team. For more detailed information on energy teams, consult the U.S. EPA’s *Teaming Up to Save Energy* guide (U.S. EPA 2006), which is available at http://www.energystar.gov/.

ORGANIZE YOUR ENERGY TEAM		
Energy Director	Able to work with all staff levels from maintenance to engineers to financial officers. Senior-level person empowered by top management support	
Senior Management	Energy director reports to senior executive or to a senior management council. Senior champion or council provides guidance and support	
Energy Team	Members from business units, operations/engineering, facilities, and regions. Energy networks formed. Support services (PR, IT, HR).	
Facility Involvement	Facility managers, electrical personnel. Two-way information flow on goals and opportunities. Facility-based energy teams with technical person as site champion.	
Partner Involvement	Consultants, vendors, customers, and joint venture partners. Energy savings passed on through lower prices.	
Energy Team Structure	Separate division and/or centralized leadership. Integrated into organization’s structure and networks established.	
Resources & Responsibilities	Energy projects incorporated into normal budget cycle as line item. Energy director is empowered to make decisions on projects affecting energy use. Energy team members have dedicated time for the energy program.	
STARTING YOUR ENERGY TEAM		
Management Briefing	Senior management briefed on benefits, proposed approach, and potential energy team members.	
Planning	Energy team met initially to prepare for official launch.	
Strategy	Energy team met initially to prepare for official launch.	
Program Launch	Organizational kickoff announced energy network, introduced energy director, unveiled energy policy, and showcased real-world proof.	
Energy Team Plans	Work plans, responsibilities, and annual action plan established.	
Facility Engagement	Facility audits and reports conducted. Energy efficiency opportunities identified.	

BUILDING CAPACITY		√
Tracking and Monitoring	Systems established for tracking energy performance and best practices implementation.	
Transferring Knowledge	Events for informal knowledge transfer, such as energy summits and energy fairs, implemented.	
Raising Awareness	Awareness of energy efficiency created through posters, intranet, surveys, and competitions.	
Formal Training	Participants identified, needs determined, training held. Involvement in ENERGY STAR Web conferences and meetings encouraged. Professional development objectives for key team members.	
Outsourcing	Use of outside help has been evaluated and policies established.	
Cross-Company Networking	Outside company successes sought and internal successes shared. Information exchanged to learn from experiences of others.	
SUSTAINING THE TEAM		√
Effective Communications	Awareness of energy efficiency created throughout company. Energy performance information is published in company reports and communications.	
Recognition and Rewards	Internal awards created and implemented. Senior management is involved in providing recognition.	
External Recognition	Credibility for your organization’s energy program achieved. Awards from other organizations have added to your company’s competitive advantage.	
MAINTAINING MOMENTUM		√
Succession	Built-in plan for continuity established. Energy efficiency integrated into organizational culture.	
Measures of Success	Sustainability of program and personnel achieved. Continuous improvement of your organization’s energy performance attained.	

Appendix E: Support Programs and Tools for Best Practices in Industrial Energy Efficiency Improvement

This appendix provides a list of energy efficiency support available to industry. A brief description of the program or tool is given, as well as information on its target audience and the URL for the program. Included are federal and state programs. Use the URL to obtain more information from each of these sources. An attempt was made to provide as complete a list as possible; however, information in this listing may change with the passage of time.

Tools for Self-Assessment

Steam System Assessment Tool

Description:	Software package to evaluate energy efficiency improvement projects for steam systems. It includes an economic analysis capability.
Target Group:	Any industry operating a steam system
Format:	Downloadable software package (13.6 MB)
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/software.html

Steam System Scoping Tool

Description:	Spreadsheet tool for plant managers to identify energy efficiency opportunities in industrial steam systems.
Target Group:	Any industrial steam system operator
Format:	Downloadable software (Excel)
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/software.html

3E Plus: Optimization of Insulation of Boiler Steam Lines

Description:	Downloadable software to determine whether boiler systems can be optimized through the insulation of boiler steam lines. The program calculates the most economical thickness of industrial insulation for a variety of operating conditions. It makes calculations using thermal performance relationships of generic insulation materials included in the software.
Target Group:	Energy and plant managers
Format:	Downloadable software
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/software.html

MotorMaster+

Description:	Energy-efficient motor selection and management tool, including a catalog of over 20,000 AC motors. It contains motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities.
Target Group:	Any industry
Format:	Downloadable software (can also be ordered on CD)
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/software.html

ASDMaster: Adjustable Speed Drive Evaluation Methodology and Application

Description:	Software program helps to determine the economic feasibility of an adjustable speed drive application, predict how much electrical energy may be saved by using an ASD, and search a database of standard drives.
Target Group:	Any industry
Format:	Software package (not free)
Contact:	Electric Power Research Institute (EPRI), (800) 832-7322
URL:	http://www.epri-peac.com/products/asdmaster/asdmaster.html

The 1-2-3 Approach to Motor Management

Description:	A step-by-step motor management guide and spreadsheet tool that can help motor service centers, vendors, utilities, energy efficiency organizations, and others convey the financial benefits of sound motor management.
Target Group:	Any industry
Format:	Downloadable Microsoft Excel spreadsheet
Contact:	Consortium for Energy Efficiency (CEE), (617) 589-3949
URL:	http://www.motorsmatter.org/tools/123approach.html

AirMaster+: Compressed Air System Assessment and Analysis Software

Description:	Modeling tool that maximizes the efficiency and performance of compressed air systems through improved operations and maintenance practices
Target Group:	Any industry operating a compressed air system
Format:	Downloadable software
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/software.html

Fan System Assessment Tool (FSAT)

Description:	The Fan System Assessment Tool (FSAT) helps to quantify the potential benefits of optimizing a fan system. FSAT calculates the amount of energy used by a fan system, determines system efficiency, and quantifies the savings potential of an upgraded system.
Target Group:	Any user of fans
Format:	Downloadable software
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/software.html

Combined Heat and Power Application tool (CHP)

Description: The Combined Heat and Power Application Tool (CHP) helps industrial users evaluate the feasibility of CHP for heating systems such as fuel-fired furnaces, boilers, ovens, heaters, and heat exchangers.
Target Group: Any industrial heat and electricity user
Format: Downloadable software
Contact: U.S. Department of Energy
URL: http://www1.eere.energy.gov/industry/bestpractices/software.html

Pump System Assessment Tool 2004 (PSAT)

Description: The tool helps industrial users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.
Target Group: Any industrial pump user
Format: Downloadable software
Contact: U.S. Department of Energy
URL: http://www1.eere.energy.gov/industry/bestpractices/software.html

Quick Plant Energy Profiler

Description: The Quick Plant Energy Profiler, or Quick PEP, is an online software tool provided by the U.S. Department of Energy to help industrial plant managers in the United States identify how energy is being purchased and consumed at their plant and also identify potential energy and cost savings. Quick PEP is designed so that the user can complete a plant profile in about an hour. The Quick PEP online tutorial explains what plant information is needed to complete a Quick PEP case.
Target Group: Any industrial plant
Format: Online software tool
Contact: U.S. Department of Energy
URL: http://www1.eere.energy.gov/industry/bestpractices/software.html

ENERGY STAR Portfolio Manager

Description: Online software tool helps to assess the energy performance of buildings by providing a 1-100 ranking of a building's energy performance relative to the national building market. Measured energy consumption forms the basis of the ranking of performance.
Target Group: Any building user or owner
Format: Online software tool
Contact: U.S. Environmental Protection Agency
URL: http://www.energystar.gov/index.cfm?c=evaluate_performance.bus_portfoliomanager

Assessment and Technical Assistance

Industrial Assessment Centers

Description:	Small- to medium-sized manufacturing facilities can obtain a free energy and waste assessment. The audit is performed by a team of engineering faculty and students from 30 participating universities in the U.S. and assesses the plant's performance and recommends ways to improve efficiency.
Target Group:	Small- to medium-sized manufacturing facilities with gross annual sales below $75 million and fewer than 500 employees at the plant site.
Format:	A team of engineering faculty and students visits the plant and prepares a written report with energy efficiency, waste reduction and productivity recommendations.
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/bestpractices/iacs.html

Save Energy Now Assessments

Description:	The U.S. DOE conducts plant energy assessments to help manufacturing facilities across the nation identify immediate opportunities to save energy and money, primarily by focusing on energy-intensive systems, including process heating, steam, pumps, fans, and compressed air.
Target Group:	Large plants
Format:	Online request
Contact:	U.S. Department of Energy
URL:	http://www1.eere.energy.gov/industry/saveenergynow/

Manufacturing Extension Partnership (MEP)

Description:	MEP is a nationwide network of not-for-profit centers in over 400 locations providing small- and medium-sized manufacturers with technical assistance. A center provides expertise and services tailored to the plant, including a focus on clean production and energy-efficient technology.
Target Group:	Small- and medium-sized plants
Format:	Direct contact with local MEP Office
Contact:	National Institute of Standards and Technology, (301) 975-5020
URL:	http://www.mep.nist.gov/

Small Business Development Center (SBDC)

Description:	The U.S Small Business Administration (SBA) administers the Small Business Development Center Program to provide management assistance to small businesses through 58 local centers. The SBDC Program provides counseling, training and technical assistance in the areas of financial, marketing, production, organization, engineering and technical problems and feasibility studies, if a small business cannot afford consultants.
Target Group:	Small businesses
Format:	Direct contact with local SBDC
Contact:	Small Business Administration, (800) 8-ASK-SBA
URL:	http://www.sba.gov/sbdc/

ENERGY STAR – Selection and Procurement of Energy-Efficient Products for Business

Description: ENERGY STAR identifies and labels energy-efficient office equipment. Look for products that have earned the ENERGY STAR. They meet strict energy efficiency guidelines set by the EPA. Office equipment included such items as computers, copiers, faxes, monitors, multifunction devices, printers, scanners, transformers and water coolers.
Target Group: Any user of labeled equipment.
Format: Website
Contact: U.S. Environmental Protection Agency
URL: http://www.energystar.gov/index.cfm?c=business.bus_index

ENERGY STAR

Description: As part of ENERGY STAR's work to promote superior energy management systems, energy managers for the companies that participate in ENERGY STAR are offered the opportunity to network with other energy managers in the partnership. The networking meetings are held monthly and focus on a specific strategic energy management topic to train and strengthen energy managers in the development and implementation of corporate energy management programs.
Target Group: Corporate and plant energy managers
Format: Web-based teleconference
Contact: Climate Protection Partnerships Division, U.S. Environmental Protection Agency
URL: http://www.energystar.gov/

Best Practices Program

Description: The U.S. DOE Best Practices Program provides training and training materials to support the efforts of the program in efficiency improvement of utilities (compressed air, steam) and motor systems (including pumps). Training is provided regularly in different regions. One-day or multi-day trainings are provided for specific elements of the above systems. The Best Practices program also provides training on other industrial energy equipment, often in coordination with conferences.
Target Group: Technical support staff, energy and plant managers
Format: Various training workshops (one day and multi-day workshops)
Contact: Office of Industrial Technologies, U.S. Department of Energy
URL: http://www1.eere.energy.gov/industry/bestpractices/training.html

Compressed Air Challenge®

Description: The not-for-profit Compressed Air Challenge® develops and provides training on compressed air system energy efficiency via a network of sponsoring organizations in the United States and Canada. Three levels of training are available: (1) Fundamentals (1 day); (2) Advanced (2 days); and (3) Qualified Specialist (3-1/2 days plus an exam). Training is oriented to support implementation of an action plan at an industrial facility.

Target Group: Compressed air system managers, plant engineers

Format: Training workshops

Contact: Compressed Air Challenge: Info@compressedairchallenge.org

URL: http://www.compressedairchallenge.org/

Financial Assistance

In the following, major federal programs are summarized that provide assistance for energy efficiency investments. Many states also offer funds or tax benefits to assist with energy efficiency projects (see below for State Programs). However, these programs can change over time, so it is recommended to review current policies when making any financial investment decisions.

Industries of the Future - U.S. Department of Energy

Description:	Collaborative R&D partnerships in nine vital industries. The partnership consists of the development of a technology roadmap for the specific sector and key technologies, and cost-shared funding of research and development projects in these sectors.
Target Group:	Nine selected industries: agriculture, aluminum, chemicals, forest products, glass, metal casting, mining, petroleum and steel.
Format:	Solicitations (by sector or technology)
Contact:	U.S. Department of Energy – Office of Industrial Technologies
URL:	http://www.eere.energy.gov/industry/technologies/industries.html

Inventions & Innovations (I&I)

Description:	The program provides financial assistance through cost-sharing of 1) early development and establishing technical performance of innovative energy-saving ideas and inventions (up to $75,000) and 2) prototype development or commercialization of a technology (up to $250,000). Projects are performed by collaborative partnerships and must address industry-specified priorities.
Target Group:	Any industry (with a focus on energy-intensive industries)
Format:	Solicitation
Contact:	U.S. Department of Energy – Office of Industrial Technologies
URL:	http://www.eere.energy.gov/inventions/

Small Business Administration (SBA)

Description:	The Small Business Administration provides several loan and loan guarantee programs for investments (including energy-efficient process technology) for small businesses.
Target Group:	Small businesses
Format:	Direct contact with SBA
Contact:	Small Business Administration
URL:	http://www.sba.gov/

State and Local Programs

Many state and local governments have general industry and business development programs that can be used to assist businesses in assessing or financing energy-efficient process technology or buildings. Please contact your state and local government to determine what tax benefits, funding grants, or other assistance they may be able to provide your organization. This list should not be considered comprehensive but instead merely a short list of places to start in the search for project funding. These programs can change over time, so it is recommended to review current policies when making any financial investment decisions.

Summary of Motor and Drive Efficiency Programs by State

Description: A report that provides an overview of state-level programs that support the use of NEMA Premium® motors, ASDs, motor management services, system optimization and other energy management strategies.
Target Group: Any industry
Contact: Consortium for Energy Efficiency (CEE), (617) 589-3949
URL: http://www.motorsmatter.org/tools/123approach.html

California – Public Interest Energy Research (PIER)

Description: PIER provides funding for energy efficiency, environmental, and renewable energy projects in the state of California. Although there is a focus on electricity, fossil fuel projects are also eligible.
Target Group: Targeted industries (e.g. food industries) located in California
Format: Solicitation
Contact: California Energy Commission, (916) 654-4637
URL: http://www.energy.ca.gov/pier/funding.html

California – Energy Innovations Small Grant Program (EISG)

Description: EISG provides small grants for development of innovative energy technologies in California. Grants are limited to $75,000.
Target Group: All businesses in California
Format: Solicitation
Contact: California Energy Commission, (619) 594-1049
URL: http://www.energy.ca.gov/research/innovations/index.html/

California – Savings By Design

Description: Design assistance is available to building owners and to their design teams for energy-efficient building design. Financial incentives are available to owners when the efficiency of the new building exceeds minimum thresholds, generally 10% better than California's Title 24 standards. The maximum owner incentive is $150,000 per free-standing building or individual meter. Design team incentives are offered when a building design saves at least 15%. The maximum design team incentive per project is $50,000.
Target Group: Nonresidential new construction or major renovation projects
Format: Open year round
URL: http://www.savingsbydesign.com/

Indiana – Industrial Programs

Description: The Energy Policy Division of the Indiana Department of Commerce operates two industrial programs. The Industrial Energy Efficiency Fund (IEEF) is a zero-interest loan program (up to $250,000) to help Indiana manufacturers increase the energy efficiency of manufacturing processes. The fund is used to replace or convert existing equipment, or to purchase new equipment as part of a process/plant expansion that will lower energy use. The Distributed Generation Grant Program (DGGP) offers grants of up to $30,000 or up to 30% of eligible costs for distributed generation with an efficiency over 50% to install and study distributed generation technologies such as fuel cells, micro turbines, co-generation, combined heat & power and renewable energy sources. Other programs support can support companies in the use of biomass for energy, research or building efficiency.
Target Group: Any industry located in Indiana
Format: Application year-round for IEEF and in direct contact for DGGP
Contact: Energy Policy Division, (317) 232-8970.
URL: http://www.iedc.in.gov/Grants/index.asp

Iowa – Alternate Energy Revolving Loan Program

Description: The Alternate Energy Revolving Loan Program (AERLP) was created to promote the development of renewable energy production facilities in the state.
Target Group: Any potential user of renewable energy
Format: Proposals under $50,000 are accepted year-round. Larger proposals are accepted on a quarterly basis.
Contact: Iowa Energy Center, (515) 294-3832
URL: http://www.energy.iastate.edu/funding/aerlp-index.html

New York – Industry Research and Development Programs

Description: The New York State Energy Research & Development Agency (NYSERDA) operates various financial assistance programs for New York businesses. Different programs focus on specific topics, including process technology, combined heat and power, peak load reduction and control systems.
Target Group: Industries located in New York
Format: Solicitation
Contact: NYSERDA, (866) NYSERDA
URL: http://www.nyserda.org/programs/Commercial_Industrial/default.asp?i=2

Wisconsin – Focus on Energy

Description:	Energy advisors offer free services to identify and evaluate energy-saving opportunities, recommend energy efficiency actions, develop an energy management plan for business; and integrate elements from national and state programs. It can also provide training.
Target Group:	Industries in Wisconsin
Format:	Open year round
Contact:	Wisconsin Department of Administration, (800) 762-7077
URL:	http://focusonenergy.com/portal.jsp?pageId=4