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Final Report on Energy Efficiency and Energy Savings in Recycling

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FINAL REPORT ON ENERGY EFFICIENCY AND ENERGY SAVINGS IN RECYCLING

by

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EXECUTIVE SUMMARY

Since World War II, the North American steel industry has been reducing its need for raw materials and energy. In 1970, roughly 145 tonnes of raw materials were required to manufacture 100 tonnes of steel products from an integrated steel mill. By 2000, this number had dropped to 115 tonnes per 100 tonnes of manufactured steel. In terms of energy consumption, the NA steel industry has reduced its requirement by more than 60% since 1950. The majority of the energy savings was realized through the development of Electric-Arc Furnace (EAF) technology. The EAF uses nearly 15 000 million joules (MJ) less energy than the integrated steel mill to produce a tonne of liquid steel. The majority of the energy savings was a direct consequence of using 100% recyclable material as the initial source of iron instead of iron ore. In 2003, approximately 59 million tonnes of ferrous scrap was consumed in North America, 75% of which was used in EAF facilities.

Electric-arc-furnace technology was not always energy efficient, requiring nearly double the thermodynamic limit in the 1970s. In addition, tap-to-tap times were well over three hours making the process very inefficient and costly. Over the last two decades, a number of technological advancements have been made to dramatically reduce energy requirements and charge times. Such practices include the use of a foamy slag, hot heel, and oxy-fuel burners in either the side or the roof of the furnace. In addition, chemical energy – associated with the formation of carbon monoxide and carbon dioxide – was widely used to help maintain the bath temperature. However, the majority of the energy savings was a direct result of improved furnace electrics allowing for better energy control and efficiency.

The combination of post combustion and scrap preheating systems is seen as the future for further reducing the energy requirements of EAFs, but significant research is required to determine the efficiency of both processes before they are implemented in industry. Advancements in blast furnace technology are also expected over the next decade and will most likely focus on gas recycling or recirculation to reduce energy requirements. However other direct reduction processes, in either solid or liquid state, are seen as the future for ironmaking. Over the last decade, several different direct reduction technologies have emerged on both a pilot

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and an industrial scale. For example, direct reduction processing in the U.S. increased from 0.45 million tonnes in 1996 to nearly 6 million tonnes in 2000. This trend is expected to continue over the next decade. Direct reduction processes require, on average, 33% less energy than typical blast furnaces.

The growth of EAF production has also been influenced by the lack of critical environmental issues that are commonly associated with the supporting operations for the integrated steel system. For instance, coke ovens and sinterplants represent two major producers of air-borne pollutants, such as carbon and sulphur dioxide. In addition, EAF mills produce roughly 265 kg less solid waste to manufacture a tonne of steel than their integrated counterpart.

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INTRODUCTION

Almost every literature source covering any aspect of steel, aluminum, or magnesium recycling includes statistics on the amount of raw materials and energy saved by recycling over production of these commodities from primary sources. For instance, producing one metric tonne (t) of steel from ferrous scrap saves roughly 1030 kg of iron ore, 580 kg of coal, and 50 kg of limestone¹. In addition, almost 11 million Btu (MBtu) of energy are conserved, which is enough energy to power almost 20% of the homes (18 million) in the U.S. each year². A typical kilogram of magnesium produced from refined recycled metal would consume 90% less energy than if the material was made from primary sources, and direct energy savings of over 90% can be achieved by using recycled aluminum scrap instead of raw bauxite to produce aluminum metal.

Of the three industries listed above, the North American steel recycling infrastructure is the most mature, encompassing 1800 scrap processors and 12 000 auto dismantlers³. Some sources have reported that steel has been recycled for well over 150 years. In 2003, the U.S. steel industry alone recycled more than 69 million tonnes (Mt) of metal². Over the next decade, this value is expected to climb further as technology drivers push to incorporate more secondary material into the production of primary metal. Energy savings and the environment are two important technology drivers for the 21st century because of various national and international regulations.

The objectives of this report are to present past and current energy statistics for the various avenues of steel production and to outline the technological advancements that have made energy savings possible. Areas for improving energy efficiency in each process will also be discussed. Lastly, greenhouse gas (GHG) emissions and other waste products are also included to show additional environmental benefits of recycling.

Unfortunately literature on energy savings and efficiency in both the aluminum and magnesium industries was not available and could not be included in this report.

STEEL

Scrap Recycling Technologies

In 2002, approximately 81% of all ferrous scrap in the U.S. was first remelted in steel mills. Nearly 75% of this was performed in electric arc furnaces (EAFs), 23% in basic oxygen furnaces (BOFs) and 2% in blast furnaces. Steel mills are defined as manufacturers of pig iron and crude steel. Scrap is used in blast furnaces to improve productivity but only in certain instances because of its inverse affect on the cost of hot metal. For the remainder of this report, the combination of blast furnace and BOF operations will be referred to as an integrated steel system.

Steel and iron foundries represent the next highest consumers of ferrous scrap in the U.S. at 16%. These foundries use either EAFs or cupola furnaces to melt the secondary steel with the latter processing slightly more scrap than the former.

Steel casting manufacturers are the smallest users of ferrous scrap in the U.S. economy at only 3%. Almost all of this scrap was melted in EAFs.

All of the percentages above were calculated directly from Table 1, which illustrates the consumption of iron and steel scrap by furnace type in 2002.

Figure 1 illustrates the different avenues for steel scrap recycling in the U.S.

ENERGY EFFICIENCY AND SAVINGS

Over the last half century, the North American steel industry has reduced its energy consumption by over 60%. While the bulk of the savings occurred prior to 1990, the 1990s alone saw a 9% reduction with another 6% realized in the first five years of the new millennium. The decline in energy consumption over time has been well documented in the U.S. and is graphically illustrated in Fig. 2. The majority of the energy savings have been accredited to various technological advancements and energy conservation measures.

Integrated Steelmaking System

Table 2 provides an overview of the amount of energy required to produce a tonne of liquid steel from an integrated process. The production of iron is by far the number one consumer of energy in this system, representing more than three quarters of the total energy requirement.

Currently in the U.S. two techniques are used for producing iron: blast furnace and direct reduction. The blast furnace is by far the leading technique, producing nearly 48 Mt of iron in 1998 compared with 1.5 Mt from direct reduction facilities⁶. Direct smelting, a third technique, has emerged over the last decade, but it is unknown whether any commercial facilities currently exist. Fruehan⁶ predicted that, over the next decade, the percentage of iron produced from blast furnaces will slowly decline, while direct reduction and smelting processes will likely advance and pick up the slack.

The main drivers for reducing blast furnace production are energy consumption and environmental pollution. Blast furnaces, either old or state of the art, are large consumers of coke and, in turn, enormous producers of CO₂ – a well known GHG. As shown in Table 3, older-type blast furnaces require 130 kg more coke per tonne of liquid iron produced than more recent models⁶. However the state-of-the-art furnaces compensate by using coal injection, at almost double the rate, to make up for the loss of energy from the reduction in coke. Fruehan⁶ estimated that the ratio of coke to coal would decrease over the next decade and most likely reach parity in the newer blast furnaces.

Technological advancements in blast-furnace production are expected in the future and will most likely focus on energy savings and the environment. Reductions in energy use and GHG emissions are expected to be achieved by developments in gas recirculation. It has been stated

that gas recycling could reduce the total fuel consumption rate (coke and coal) by almost 50 kg/t⁶. In addition, top pressure turbines are expected to produce 15-40 kWh of electricity per tonne of metal charged and save 60-70 MJ/t⁶. However before any of these concepts can be realized on an industrial scale, technical challenges need to be overcome in the next decade. Such issues include methods for improving coal combustion (possibly coal oxygen burners) and increasing the strength of the coke agglomerations since less coke is used.

The second portion of the integrated system is the actual steelmaking process, which employs various oxygen furnaces to significantly reduce the metal's carbon content. The most common type of oxygen furnace is the BOF that, according to Table 2, is not very energy intensive because of the extremely exothermic reactions that take place within the furnace during the injection of oxygen. The chemical reactions caused by the blowing oxygen will be discussed in more detail under the EAF section of this report. However, initiatives to make oxygen furnaces more energy efficient have surfaced and have looked mainly at the use of fossil fuels and the post combustion of the off gas to meet such goals. Analysts have reported that capturing the CO from the furnace exhaust gas and subsequently combusting to CO₂ could save the integrated steel manufacturer 500-1000 MJ/t of steel manufactured⁶. The Energy Optimizing Furnace (EOF) is one example of a proposed oxygen furnace that utilizes post combustion to reduce its energy usage. However, many authors do not believe post-combustion systems will benefit the steel industry because of the capital investment needed to install such a system.

Direct Reduction and Smelting

Direct reduction and smelting operations were not discussed in any of the previous recycling project reports since they do not use scrap as a feed material. However, because these two emerging ironmaking processes are seen as important technologies for producing iron in the future, they cannot be overlooked.

Direct reduction is a solid-state process used to convert various forms of iron oxide into iron. The iron produced is more commonly referred to as direct-reduced iron (DRI). Over the last decade, a number of different direct reduction processes have emerged on both a pilot and an industrial scale. Appendix A provides a summary of these processes and their position within the ironmaking industry in 1999.

Direct reduction production in the U.S. has increased from 0.45 Mt in 1996 to 2.72 Mt in 1999⁶. Other hot spots for direct reduction production and growth are in Mexico and Trinidad.

Energy statistics for direct-reduction technologies were not readily available in the literature, but Fruehan⁶ estimated that a metric tonne of DRI consumed an average of 12 000 MJ of energy. In most direct-reduction processes, the two sources of energy are natural gas and electricity. A breakdown of the energy requirements for some of the more common direct-reduction methods is shown in Table 4. Of the processes listed, the FIOR appears to be the most energy intensive. In addition, the FASTMET method inputs coal into the process to substitute for the reduction in natural gas and electricity. The main difference between direct-reduction and blast-furnace technologies is the use of cleaner sources of energy in the former. The combustion of natural gas is the only direct source of GHG emissions. From an energy consumption standpoint, both

concepts are fairly similar with the blast furnace requiring only 1 800 MJ more energy to manufacture a tonne of liquid steel.

In direct smelting, iron is produced from ore using only coal. The main advantage of this process is the elimination of coke, which reduces the initial capital investment associated with coke and agglomeration. Moreover the smelting is typically performed in the molten state increasing the reduction kinetics and making the heat transfer more efficient. Additional benefits of direct smelting are seen in the use of fine ore fractions since surface area is maximized and reaction times are reduced. A list of all the types of direct smelting processes developed is shown in Appendix B along with their corresponding operating status as of 1999. Of the seven processes listed, only the COREX has achieved commercial success. However, as with blast-furnace and direct-reduction processes, smelting is performed in the solid state, which leads to low smelting intensities and high capital costs.

Since direct smelting is relatively new and has found limited industrial success, energy consumption statistics are not readily available in the literature. However, Fruehan⁶ looked at each technique closely and approximated the amount of coal and oxygen required; this is presented in Table 5. It should be noted that the original developers of each process did not supply the data. Moreover, it is unsure why neither the Hismelt nor the Tecored processes show an oxygen value.

Szekely⁵ also summarized a number of new ironmaking processes in 1996 from a variety of literature sources, and the results are shown in Table 6. In this review, the author included the energy output of each process along with its corresponding coal consumption, making it possible to determine the energy efficiency for each technique. From the data in Table 6, it appears that the COREX is the most efficient process, producing the greatest amount of energy for the amount of coal used. The least efficient appears to be the Jupiter technique. Unfortunately, the literature supporting each technique could not be obtained because of poor bibliography referencing in the Szekely⁵ document. In order to make an adequate comparison, Szekely⁵ entered into Table 6 the energy values for a typical blast furnace operation. However, it is unclear whether the energy output in the blast furnace column includes the heat produced from the coal alone or if it includes other forms of energy.

Electric-Arc Furnace

Prior to 1980, EAF tap to tap times were over three hours, and power usage was well over 600 kWh, which was nearly twice the thermodynamic energy needed⁷. Over the last twenty years, a number of major technical advancements in EAF steelmaking have resulted in large decreases in electrical energy requirements. A brief description of the major practices is given below, and Table 7 provides a complete summary of these technologies and their corresponding electrical savings. It should be noted that all of the energy-savings values listed below are from data compiled in 1994. Even though these data are more than a decade old, they still provide a good picture of where energy savings have been realized in EAF steelmaking.

1. Foamy Slag Practice – the arc is encompassed in a foaming slag to help reduce refractory damage and, more importantly, reduce heat loss (radiation) from around the arc region to the side wall of the furnace. This is extremely important as melting starts to occur when the arc

is no longer surrounded by scrap. The foam is created by injecting oxygen through various lance positions and either coal or carbon to produce CO gas.

2. Hot-Heel Production – from each charge, a portion of the molten steel is left in the bottom of the furnace to help melt the next charge of solid steel scrap more quickly. This technique is utilized heavily in the CONSTEEL process, which feeds scrap continuously into a molten heel.
3. Post Combustion – carbon monoxide formed during decarburization is fully oxidized in the furnace by the injection of oxygen through at least one lance and from a variety of positions (top, bottom, etc). The conversion to carbon dioxide produces an enormous amount of heat that can maintain the bath temperature or help heat the feed material. The heat of combustion of CO to CO₂ is three times greater than that associated with the combustion of carbon to CO. Typical EAF operations in the past have fully oxidized the CO at the top of the stack and lost all of the energy associated with this reaction.
4. Oxy-fuel Burners – auxiliary burners, installed either in the side wall and roof of the furnace, and/or in the slag door, have been used to improve melting rates by adding more heat and providing a more uniform heat distribution throughout the furnace. The creation of ‘cold spots’ within the furnace is well documented and can reduce energy efficiency and increase tap-to-tap times.
5. Preheating of Scrap – the ‘hot’ off gas has been used in a number of processes (CONSTEEL and Fuchs shaft) to heat the incoming feed material, which has reduced the amount of heat required to melt the material once placed inside the furnace. The preheating processes derive from either batch bucket or continuous shaft systems. The heat associated with the off gas represents about 20% of the energy losses or approximately 130 kWh/t of steel produced within a typical EAF⁸.
6. Furnace Electrics – the development of power supplies that produce higher operating voltages have vastly improved energy control and efficiency. Many of the EAF operations have installed these new devices, allowing them to run at the theoretical optimum power factor and maximum circuit power. Voltage increases between 60-80% have been reported⁸.

In 1994, the average electrical power consumption for producing a tonne of steel in the U.S. was 480 kWh⁹. By comparing this value with the data in Table 7, it can be shown that better management, maintenance, and control systems (Table 7, items 1, 2, 12 and 13) have resulted in a 26% reduction in the total power requirement for an EAF and therefore have been widely accepted in the steel industry⁷.

In addition, better transformers and power supplies (Table 7, items 3 and 8) accounted for another 22% in electrical energy savings. However, the employment of DC furnaces has not been widespread throughout North America, and some analysts have hinted that the potential energy savings associated with this type of furnace are overstated.

New furnace designs that utilize elongated bottom tapping have only resulted in a 3% decrease in electrical energy consumption but have been implemented in more than 50% of the mini mills in the U.S.⁷.

As of 1994, the installation of gas burners for use during initial melt down, and the use of injection gas stirring and foaming slags, had been implemented in few mini mills. However by 1997, both practices were becoming common in these facilities. This was not surprising given the fact that the combination of these technologies could result in a 16% savings in energy consumption without a large capital cost. The energy reduction associated with foaming slags is also expected to increase since hot-heel operations now allow for the foaming to begin much earlier in the process. Previously a flat bath needed to be obtained before slag foaming could be carried out.

Moreover the incorporation of preheating systems, which alone could reduce energy use by 25%, had gained acceptance in the majority of the EAF operations by 1999⁶. Unfortunately more recent information was not available to better quantify the acceptance of these technologies within the EAF steelmaking industry. However a study conducted from 1990 to 1999 by the International Iron and Steel Institute (IISI) compared a number of EAF operations and showed an average decrease in electrical energy consumption by 13% to 392 kWh/t¹⁰. A study conducted by the U.S. Electric Power Research Institute (EPRI) in 1997 reported that between 360 to 400 kWh of electrical energy was required to manufacture a ton of steel, depending on the power of the furnace⁸. Most of the EAFs in use today are designated as ‘high-power furnaces’, requiring a minimum of 500 kVA per ton of solid-steel scrap. However the trend for future mini mills is towards the implementation of ultra-high-power furnaces with outputs of 900-1000 kVA per ton of furnace capacity⁸.

A direct result of this lower energy requirement or better energy efficiency was a corresponding increase in productivity, rising by 54% to 94 t/h in 1990, because of the shorter tap-to-tap times¹⁰. The majority of the energy losses still occur in the waste-gas stream, followed by the cooling water in the sidewalls and roof of the furnace, and in the slag material¹¹.

In the overall energy picture, one author⁷ estimated that electrical energy only accounted for 60% of the total energy required for a typical EAF; another author¹¹ approximated it to be around 65%, and the EPRI maintained that it lay between the two. The remaining energy requirement is derived from chemical reactions that take place within the furnace. In the EAF, the main source of chemical energy is produced from the partial oxidation of dissolved carbon in molten steel. However, the extreme exothermic behaviour of this reaction has caused some EAF operators to inject solid carbon into the bath to produce additional heat. Both reactions can be expressed by Eq 1 and Eq 2:



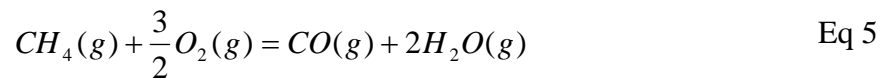
where the underscore indicates that the element is dissolved in steel.

The secondary source of chemical heat results from the oxidation of iron through the injection of oxygen into a semi-molten or completely molten steel bath. In addition the iron oxide can then react with the dissolved carbon to produce CO and pure iron. These two reactions are illustrated in Eq 3 and 4:



These two equations are very well understood from a thermodynamic standpoint and represent an important part of the EAF process because of the amount of heat produced and the recuperation of valuable metallic units. However excess FeO usually results since the kinetics of reaction 4 are slow due to the poor interaction between the slag and the metal.

Other exothermic reactions that occur in the EAF are the combustion of natural gas (Eq 5) and the post combustion of CO (Eq 6).



Brooks⁷ also indicated that it is thermodynamically possible for CO₂ to react back to CO through contact with either solid or dissolved carbon in steel through the following two reactions:



Jepson¹² used industrial data to estimate the efficiency of each reaction in the transfer of heat to either the metal or the slag phase. Almost 100% of the energy generated by the iron oxidation reaction is consumed directly by the metal. The heat-transfer efficiency associated with reactions 1 and 5 is largely dependant on the burner design and furnace configuration. For instance, if the burner flame is in direct contact with the charge during melting, heat transfer is much more efficient. Jepson¹² approximated that the average heat-transfer efficiency for these two reactions was 70% during the initial melting stages but only 25% when the charge was completely molten. It was also reported that post-combustion systems (reaction 6) only resulted in a 50% heat transfer efficiency. Jepson cited two main reasons for such a low efficiency: (1) both the reactants and the product are gases, making them very mobile and impossible to capture within a certain sector of the furnace, and (2) both the reactants are hot causing them to rise in the furnace and react away from the charge material.

The poor heat-transfer efficiencies associated with some of these chemical reactions has led to numerous developments over the last decade to better utilize this energy source. For example, in

order to promote post combustion in the slag layer, oxygen is injected lower in the molten slag bath. However good contact between the metal and slag must be maintained in order for the heat to be transferred to its proper destination. Good contact is achieved through splashing, which will more than likely lead to iron oxidation and the decomposition of CO₂ if carbon is readily available in the system. In addition, post combustion of the gases leaving the furnace through the exhaust could be an excellent source of energy for preheating the charge material before it enters the furnace. This has already been applied to some tunnel kilns and shaft preheating systems, but no mention of their success was found in the literature.

The concept of combining post combustion and scrap preheating should, according to Brooks⁷, be the major focus of many mini mills' research projects over the next decade to further reduce electrical energy requirements. However, some key questions that need to be answered first are:

- a) How is the preheating efficiency affected by the scrap size and shape?
- b) What is the best configuration for conveying heat from post-combusted gases to the feed materials?
- c) What is the optimum amount of post combusting that should be carried out in the furnace relative to the preheating unit?
- d) How does preheating scrap and/or DRI affect melting times?

Many authors believe that, in order to further reduce the energy requirements of EAFs, their shape and configuration need to be altered. This is because the original design of the EAF was strictly for electrically melting scrap material and was optimized to directly expose the majority of the charge to the arc. This causes much more energy to be used initially to melt the material than once the material is molten which, in turn, causes greater heat losses through the walls and roof of the furnace. By replacing the arc as the main source of heat for melting the feed material, additional energy savings can be realized. This could be achieved by feeding the starting material directly into a molten hear and utilizing the thermal mass of the molten material. In addition, a foaming slag practice could be used right from the start of processing to further reduce energy requirements by limiting heat losses. This concept is the essence behind the CONSTEEL and the proposed ECOARC processes¹³. However these processes are contrary to normal EAF processing since they represent continuous operations. Therefore they will have difficulty gaining acceptance in the steelmaking industry until the batch processing philosophy is changed.

Outside of energy losses to the waste gas stream (which is starting to be recaptured by the use of various scrap-preheating systems), almost 17% of the energy input (either electrically or chemically) is being lost to the water-cooling system of the furnace⁸. The slag consumes an additional 10% of the total energy⁸.

GREEN-HOUSE GAS (GHG) EMISSIONS

The number one producer of CO₂ is the blast furnace. This is because the main source of energy is coke that, when fully oxidized, produces CO₂. In order to reduce CO₂ emissions, natural gas could be substituted for coke; however the price of natural gas has risen exponentially over the last couple of years, and adequate supply is based on location.

Coke manufacturers are also major producers of air-borne pollutants and probably have a more negative effect on the environment than the blast furnace itself. For example, sinter plants release NO_x and SO_x emissions, while coke ovens are notorious ‘volatile organic compound’ polluters. Tougher environmental laws have been implemented since the mid 1970s and have resulted in a 95% reduction in SO_x emissions, representing almost 198 000 tons⁵. In the same time frame, CO₂ emissions have dropped 28% on a yearly basis and have removed nearly 1.5 million tons of CO₂ from the environment⁵.

However, the reduction in NO_x and SO_x emissions still do not meet current ‘clean air’ regulations because of the associated cost of reaching total compliance. Szekely⁵ estimated the cost to be close to that required to build a brand new mini-mill with a capacity comparable to the integrated system.

On the other hand, recycling steel in an EAF system does not cause the same environmental consequences as the integrated steel mill despite concerns over the possible formation of dioxine at high frequencies.

OTHER STEEL PLANT WASTES

Recycling steel scrap in a typical mini-mill also reduces the amount of plant wastes that are normally produced using an integrated system. For instance Szekely⁵ reported that, for every ton of steel produced in an integrated steel plant, 420 kg of various by-products are produced. The breakdown of these waste streams is shown in Table 8. This is well over 2.5 times the amount of by-products produced from a standard mini-mill. It should be mentioned that the blast furnace slag, dust, and sludge are now being recycled into a number of other industries. For example, blast furnace slags are now added to commercial cement, while steelmaking slags are used for roadfill. However, the low intrinsic value of these types of materials makes it uneconomical to ship them over a large distance, which is becoming a problem in North America. For example, in the U.S the critical or ‘break even’ distance is around 80 km⁵.

CONCLUSION

The EAF uses nearly 15,000 million joules (MJ) less energy than an integrated system to produce a tonne of liquid steel. This is a direct reflection of the different sources of feed material used between the two processes and the number of technological advancements in EAF processing over the last decade. Such technologies include the use of oxy-fuel burners, hot heels, and a foamy slag practice. In addition, better furnace electricians have been achieved and greatly improved energy control and efficiency.

Future energy savings in EAF processing are also expected over the next decade, and these mostly surround the implementation of post combustion and scrap preheating systems. As for integrated steel mills, it is also expected that energy savings will occur through the incorporation of gas recycling equipment. In addition, other direct-reduction processes that require less energy are starting to gain commercial acceptance and are expected encompass a larger share of ironmaking in the U.S. over the next decade.

REFERENCES

1. M.D. Fenton, "Iron and Steel Recycling in the United States in 1998", U.S. Geological Survey, 1999, Circular 1196-G.
2. Steel Recycling Institute, "A Few Facts about Steel – North America's #1 Recycled Material", Fact Sheet, 1999, www.recycle-steel.org/fact/.
3. Steel Recycling Institute, "The Inherent Recycled Content of Today's Steel", 2004, www.recycle-steel.org/pdf/inherent_04.pdf.
4. M.D. Fenton, "Iron and Steel Scrap," Minerals Yearbook, 2002, http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_scrap/fescmyb02.pdf.
5. J. Szekely, "Steelmaking and Industrial Ecology – Is Steel a Green Material", Journal of the International Steel Institute, 1996, pp. 121-132.
6. R. Fruehan, "Future Iron and Steelmaking in the USA," Scandinavian Journal of Metallurgy, Vol. 28, 1999, pp. 77-85.
7. G. Brooks, "Developments in Electric-Arc Furnace Steelmaking", Innovative Technologies for Steel and other Materials, COM, 2001, pp. 81-91.
8. P. Roberts, "Understanding Electric-Arc Furnace Operations: Commentary", EPRI Center for Materials Production, 1997, pp. 1-6.
9. N. Martin, I. Price and E. Worrel, "Energy Efficiency Opportunities in Electric-Arc Steelmaking", Iron and Steelmaker, Vol. 26, No. 1, 1999, pp. 25-32.
10. S. Kohle, "Improvements in EAF Operating Practices Over the Last Decade," 57th Electric Furnace Conference, Iron and Steel Society, Warrendale, PA, USA, 1999, pp. 3-14.
11. P. Berger, "Methods and Aims of Improved Electric-Arc Furnace Steelmaking", SEAIISI Quarterly, 1990, January, pp. 48-57.
12. S. Jepson, "Chemical Energy in the EAF: Benefits and Limitations", 58th Electric Furnace Conference, Iron and Steel Society, Warrendale, PA, U.S.A, 2000, pp. 3-14.
13. H. Ao, T. Maki, H. Mizukami and R. Yamaguchi, "'ECOARC' Technology", 58th Electric Arc Furnace Conference, Iron and Steel Society, Warrendale, Pa., U.S.A, 2000, pp. 325-336.

Table 1 – U.S. scrap consumption by furnace in 2002 (Mt)⁴.

Furnace type	Steel mills	Foundries	Steel castings	Total
Blast furnace	1	0	0	1
BOF	13	0	0	13
EAF	42	5.4	1.7	49
Cupola	0	5.9	0.1	6
Total	56	11	1.8	69

Table 2 – Energy consumption in North America in 1999 to produce a tonne of liquid steel using an integrated steelmaking system⁶.

Integrated stage	Energy (MJ)	Percentage of total energy required (%)
Ironmaking (blast furnace)	13 800	76
Steelmaking (BOF)	200	1
Hot rolling	2 100	11.5
Cold rolling	1 200	6.5
Losses and other	920	5.0
Total	18 220	100%

Table 3 – Comparison of coke and coal requirements for past and future blast furnace systems.

Average fuel rate (kg/t)	1998	2015
Older models		
Coke	430	320
Coal	100	200
State-of-the-art		
Coke	300	240
Coal	180	240

Table 4 – The energy requirements for various direct reduction processes.

	MIDREX	HYL III	FIOR	AREX	FIOR II	Iron carbide	FASTMET
Iron source	Lumps/pellets	Lumps/pellets	Fines	Lumps/pellets	Fines	Fines	Fines
Type of reactor	Shaft	Shaft	Fluid bed	Shaft	Fluid bed	Fluid bed	Rotary heart
Gas preparation	Reforming	Reforming	Reforming	Self-reforming	Reforming	Reforming	No gas/coal
Pressure	Atmospheric	5 bars	10 bars	Atmospheric	10 bars	-	Atmospheric
Typical plant capacity (Mt/y)	1	1	0.4	0.5	1	0.32	0.45
Investment cost (\$/T.a.c)	250	250	300	200	300	200	150
Energy input (Gcal/t)	2.5	2.7	4.0			3.0	3.0
Natural gas [GJ/t]	10	10.9	18	8.7	13	13	2.5
Coal [kg/t]	-	-	-	-	-	-	380
Elect. [kWh/t]	125	85	200	70	150	230	60
Product carbon content (%)	1-2	1-4	0.5	2	1.5	<6 (Fe ₃ C)	95%

*t – metric tons; **Mt/a – million metric tons per year

Table 5 – Amount of coal consumed in various direct smelting processes⁶.

Process	Coal (kg)	Oxygen (m ³)
COREX	880	525
AISI/Pellets	850	650
AISI/Cyclone	850	650
DIOS	900	680
Hismelt	830	0
Tecnored	720	0

Table 6 – Energy requirements for standard blast furnace and emerging smelting reduction processes⁵.

	Unit	Coke + sinter + BF	Core x	DIOS	Hlmelt	AISI	Jupiter	CCF (Hoogovens and Iliva)
Annual capacity	(Mt/a)*	4	0.7	N.P.	1	N.P.	N.P.	0.3
Investment cost	(\$/T.a.c.)	320	370	N.P.	N.P.	160	N.P.	170
Main energy inputs								
Coal	(Mt/thm**)	0.62	1.1	0.8	0.7	0.75	0.57	0.64
Oxygen	(Nm ³ /thm)	50+hot blast	540	500	Hot blast	510	435	550
Energy output	(GJ/thm)	4	15	7.8	3	7.4	2.6	4
Stop and go ability		Poor	Fair	Poor	Poor	Fair	Poor	Good
Environmental evaluation		Poor	Good	Good	Fair	Good	Good	Good

*Mt/a – million metric tons per year; ** N.P. = Not Published; ***thm – metric tons of hot metal

Table 7 – Electrical energy savings for various EAF energy efficiency technologies developed in the last twenty years⁹.

Technology	Electricity savings (kWh/t)
1. Improved process control	30
2. Flue gas monitoring and control	14
3. UHP transformers – improved efficiency	17
4. Bottom stirring and gas injection	19
5. Foamy slag practice	19
6. Oxy-fuel burners	39
7. Eccentric bottom tapping	14
8. DC arc furnace	89
9. Scrap preheating tunnel (CONSTEEL)	61
10. Scrap preheating with post combustion (Fuchs)	119
11. Twin shell DC with scrap preheating	19
12. Preventive maintenance	67
13. Energy monitoring and management system	17

Table 8 – By product and waste comparison between integrated and mini mills⁵.

By product and waste	Integrated (kg/t)	By product and waste	Mini mill (kg/t)
BF slag	250	EAF slag	116
BF dust and sludge	25	EAF dust	18
BOF slag	135	Metallic wastes	11
Metallic wastes	7	Refractory wastes	10
Refractory wastes	5.5	Other	5
Total	423	Total	160

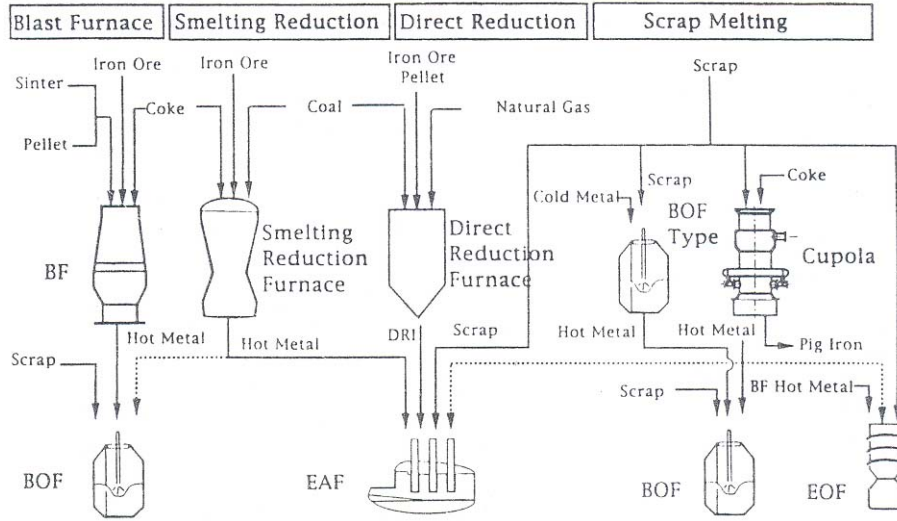


Fig. 1 – Various avenues for steel scrap recycling.

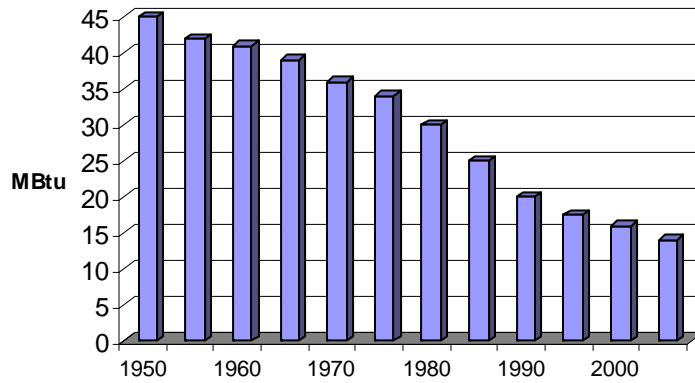


Fig. 2 – Energy consumption per ton of steel shipped.

APPENDIX A – ADVANCED DIRECT REDUCTION PROCESSES AS OF 1999

Process	Production (mt/yr)	Comments
Gas/Shaft		
Midrex	25	Proven Technology; requires pellets or lump ore and large scale to be economical
HyLI and III	10	Similar to Midrex
Gas/Fluid Bed		
Fior	0.33	Proven technology
FINMET	0	Improved FIOR plants being built in Australia and Venezuela; expected production of 2.5 Mt at Australian facility in 1999
Iron Carbide	0.1	Nucor plant in Trinidad closed in 1999; Qualitech plant planned to open in 1999, but many economic and technical problems were incurred
Cicored	0	In 1999, plant in Trinidad was supposed to begin production
Coal/RHFFor RKF		
FASTMET	0	Pilot plant facility opened in Japan
INMETCO	0.06	Waste oxide plant operating; ore based plants planned
Iron Dynamics	0	Combined reduction with coal on an RHF with a submerged-arc melter; 0.45 Mt/a plant began operation in 1999
COMET	0	Uses layers of coal and ore for separating gangue; in 1999 pilot plant in Belgium was operating
SL/RN	1.02	Uses high coal rates
Coal/Fluid Bed		
Cicofer	0	Only in development stage

APPENDIX B – DIRECT SMELTING PROCESSES FOR MANUFACTURING MOLTEN IRON AS OF 1999

Process	Feed	Status
Corex Shaft furnace Melter gasifier	Coal/pellets or lump ore	4 plants in operation, several others planned
DIOS Smelter	Coal/fine ore	JISI pilot plant closed in 1996; pilot plant reopened in 1997 by NKK to prove long-term operations however, not operating in 1999
Fluid bed prereducer	Coal/pellets or waste oxide	Smelter tests complete
Hlsmelt Smelter	Coal/fine ore	Pilot facility operating; various types of feed material were tested; converted to vertical vessel and oxygen, now similar to AISI and DIOS
Fluid bed prereducer		
ROMELT Smelter	Coal/ore or waste oxide	Semi-commercial Plant
No prereducer		
CCF Smelter	Coal/fine ore	Cyclone furnace tested however was not linked to smelter; Hoogovens for a 300 000 t/a, semi commercial plant suspended in 1999
Cyclone prereducer		
Tecnored Shaft furnace	Fine ore/coal and coke/air	Semi-commercial plant operating in Brazil 20 000 t/a scale up tests complete