Saving One Barrell of Oil per Ton (SOBOT)

A New Roadmap for Transformation of Steelmaking Process

American Iron and Steel Institute

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Introduction

Currently, energy represents about 20% of the total cost of producing steel and is rising. The increasing cost of energy and even its current and future availability have led to the need to refocus attention on energy intensity in steel production. To address this issue long-term, American Iron and Steel Institute (AISI) members are proposing the "Saving One Barrel of Oil per Ton", or SOBOT, Research Program.

Using today's process routes and technology, the steel industry [integrated and EAF steelmakers] uses 12.6 million BTU per ton shipped, or 2.07 barrels of oil per ton shipped [2003 data].

Table 1: Steel Industry Energy Use [2003 Data]

Integrated Steelmakers	19.55 MMBTU	3.22 Barrels of Oil/t
Electric Steelmakers	5.25 MMBTU	.86 Barrels of Oil/t
Total Industry [49% EAF]	12.6 MMBTU	2.07 Barrels of Oil/t

Our goal is to develop new steelmaking technologies which, when in commercial use, will take steel production from 2.07 barrels of oil/ton today [2003] to 1.2 barrels of oil/t in 2025, ***approximately one barrel of oil less to produce a ton of steel***:

Table 2: SOBOT Energy Use Goal [projected 2025]

Integrated Steelmakers	2.0 Barrels of Oil/t
Electric Steelmakers	.56 Barrels of Oil/t
Total Industry [55% EAF]	1.2 Barrels of Oil/t

Energy savings of this type cannot be made by only incremental changes although they are often important enabling technologies. It requires transforming the steelmaking process. In addition to dramatically lowering energy consumption, this program would advance the sustainability of steel production, reducing its environmental impact by lowering the production of carbon dioxide.

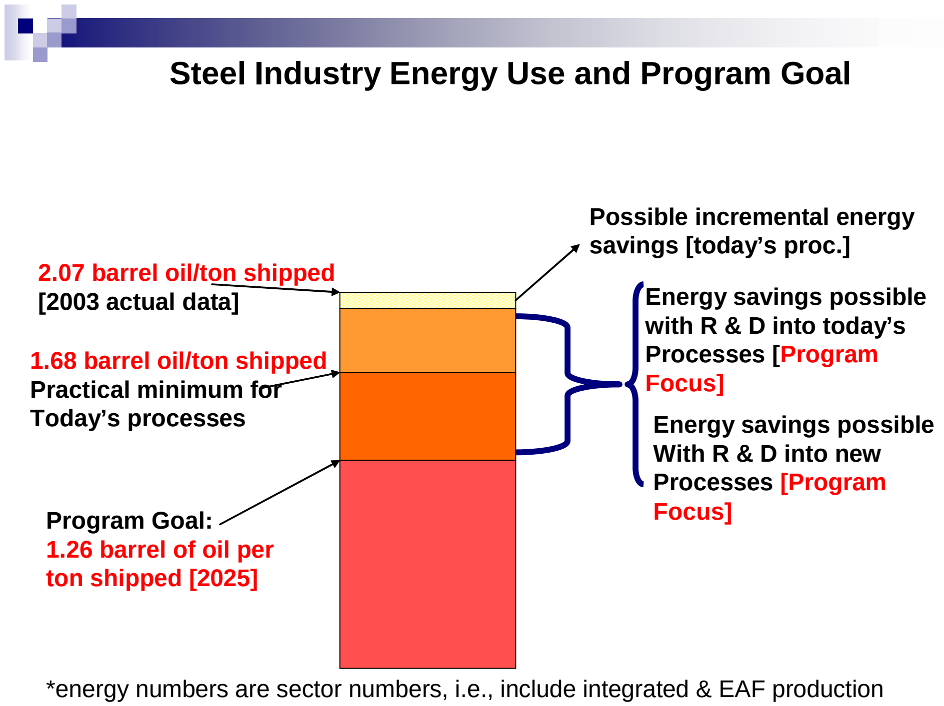


Figure 1: R & D investment in new technology is needed to meet the Program Goal

Only a small portion of this energy gap could be bridged by the implementation of best practices [yellow area]. Best practices implementation will continue to be the focus of AISI members through benchmarking activities undertaken in AISI manufacturing committees. *Moving toward and beyond the practical minimum energy to make steel will require the development of new transformational technologies. The intent of this program is the development of these new transformational technologies [areas shown by blue brackets].*

Background

The steel industry is the largest energy-consuming industry in the world. In North America, iron and steel production represents approximately two percent of energy consumption. The steel industry as a sector [integrated and EAF producers] reported 12.6 million BTUs per ton of steel shipped in 2003. This means it takes the equivalent of 2.07 barrels of oil to produce a ton of steel [using 6.09 MMBTU per barrel of oil].

The North American steel industry has achieved tremendous improvements in energy performance in recent decades (Figure 3). This has been achieved through a variety of technological transformations such as continuous casting and thin-slab casting to name just two, so there is a clear precedent for the type of transformational change envisioned in this program.

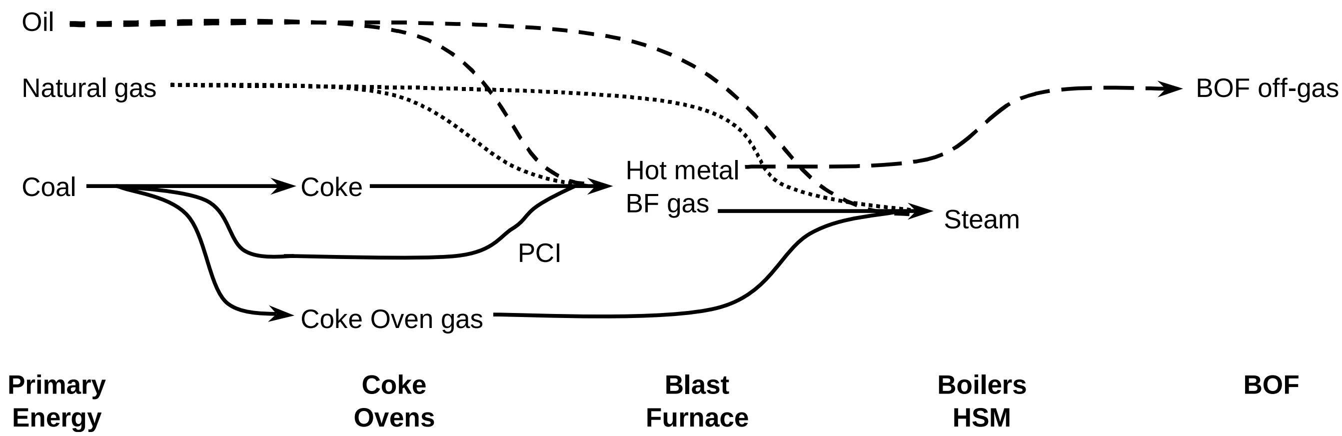
Energy consumed directly by steelmakers includes materials used as reductants in ironmaking, as well as other types of energy (Table 3). Energy is also consumed indirectly for the mining, preparation, and transportation of raw materials, such as: coal, iron ore pellets, scrap and lime; and in the production of process gases such as oxygen.

Table 3. Applications of Sources of Energy in Steel Production

Sources of Energy	Application as Energy	Application as Reductant
coal		coke production, BF pulverized coal injection; DRI production
natural gas	furnaces	BF injection, DRI production
electricity	EAF, rolling mills and various other motors	
oil	steam production	BF injection

It should be noted that in many cases, energy is transformed through a series of synergistic processes within the steel plant.

Figure 2. Energy Transformations in Steel Production

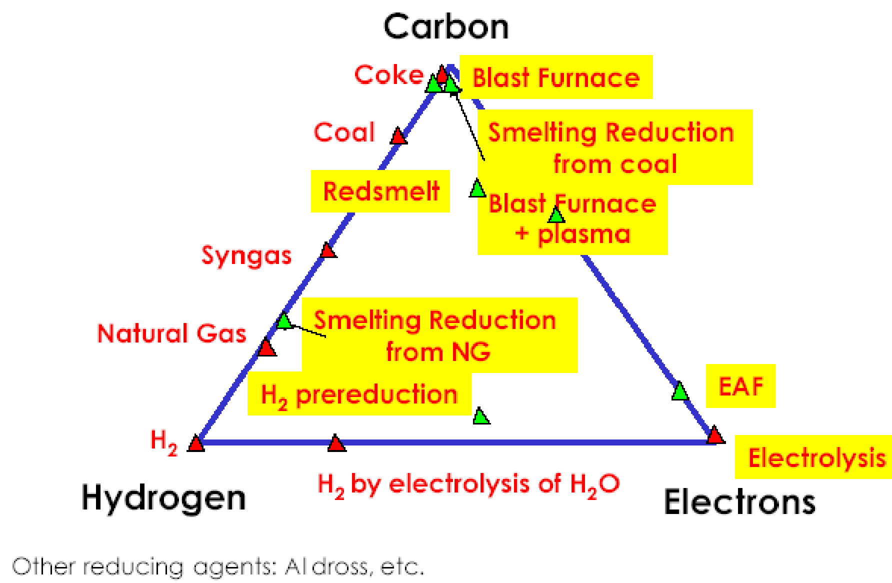


The energy employed directly by the steel industry ultimately results in the production of steel products, and various by-products and process losses:

- steel (consisting of metallic iron and other elements)
- gaseous by-products (Blast Furnace gas, Coke Oven gas or BOF gas)
- molten by-products (Blast Furnace slag or BOF/EAF steelmaking slag), with sensible heat losses subsequently dissipated through cooling
- liquid by-products (coal tar and benzene)
- solid by-products (coke breeze or Blast Furnace dust & sludge)
- process product yield losses (scrap, scale or iron oxides)
- stack gas sensible heat, cooling, friction and other losses.

All of the sources of energy used in steel production are factors in the generation of carbon dioxide to various degrees, with coal resulting in the highest CO_2 generation and electricity the lowest (depending on the extent of electrical energy that is sourced from nuclear versus hydroelectric power). The International Iron and Steel Institute (IISI) has initiated the CO_2 Breakthrough Program with the objective of dramatically reducing CO_2 emissions. Several of the initiatives in the CO_2 Breakthrough program have the potential to be the type of transformational technologies sought. AISI member companies are participants in this research.

Figure 3. Conceptual Representation of Various "Breakthrough" Production Routes



Approaches towards lowest energy steel production (low-carbon ironmaking and steelmaking) could involve:

- Developing new processes having lower energy intensity, or new technologies that enable improved energy performance for existing processes. This includes technologies that can take advantage of the energy currently lost in existing processes. Alternative approaches may include:
  - avoiding a heating/cooling step
  - reducing the temperatures required
  - recovering and applying heat at high temperatures
- Coupling ironmaking and steelmaking processes to energy generation and thereby making maximum use of the chemical energy and thermal energy by-products of iron and steelmaking (the perspective of "the energy plant that produces a steel by-product").
- Developing processes having lower carbon intensity or that use renewable forms of carbon.

The steel industry can also develop technologies to transform the industry so it generates its own fuels or uses alternative fuels as they are developed by others. *Such strategies can greatly reduce the use of natural gas an important national and industry goal.*

This requires making better use of the hydrocarbon fuels that are already in use, weaning itself away from its dependence on hydrocarbon fuels, and finding ways to sequester the greenhouse gases produced. In all likelihood, there will be no single technology that will accomplish all that is needed, but a combination of technologies

Alternative fuels that could be substituted into the steelmaking process:

1. Charcoal from trees, silage, and sawmill wastes could be used as a fuel and as a replacement for coke in the blast furnace.
2. Hydrogen, as it becomes available could be used to reduce iron ore or as a fuel in furnaces and transportation equipment. The steel industry is a producer of hydrogen in its cokemaking facilities and blast furnaces.
3. Electrolytic winning of iron from iron ore and electro-refining of iron is a possible alternative to the blast furnace and BOF and EAF furnaces.
4. Biometallurgical processes may become feasible.
5. Consumer waste products such as garbage, plastics, waste oils, tires, auto fluff, etc. show promise as fuel substitutes.
6. Coal Gasification technologies which should be explored to manuyfacture syngas from coal on site at a steel plant

The Paired Straight Hearth Furnace is an example of a high-productivity, low energy intensity ironmaking process. It uses no natural gas and the flow sheet below shows the relationship of the Hearth Furnace and Oxygen Melter working in synchronization energy-wise, i.e., the off-gas from the Oxygen Melter is used to fire the Hearth Furnace. This technology exemplifies the type of transformational project envisioned in the SOBOT Program.

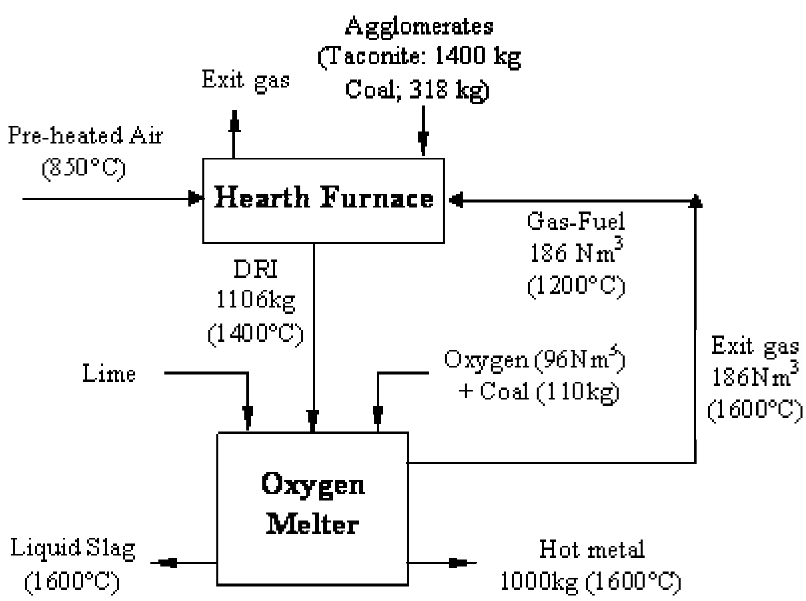


Figure 4: Flow Sheet of the new Paired Straight Hearth Ironmaking Process

In summary, changing the energy footprint of the steel industry is a daunting task. But the rewards are large as well—consider that the steel industry in the US produces approximately 107 million tons of steel annually— so meeting our goal would save the energy equivalent of approximately 100 million barrels of oil annually in 2025. As with all R & D there will be early adoption opportunities that will put some of the new technologies into use well before 2025, and any head start in energy efficiency is a "win" for industry and DOE.

To be successful requires the continued commitment and focus that the steel industry and DOE have displayed in prior collaborative projects managed by AISI. To achieve the goal of SOBOT Program, i.e., Saving One Barrel of Oil per Ton, three research pathways will be pursued simultaneously, 1) energy savings, 2) energy substitution and 3) energy recovery. Each is described in the subsequent chapters.

Chapter 1 - ENERGY SAVINGS

This portion of the *Saving One Barrel of Oil per Ton* roadmap addresses the energy savings aspect of the program. The steelmaking process has undergone continuous optimization and re-invention over the past decades. Reasonable and obtainable energy efficiency improvements in the steel plant are on the order of 0.7 % per year. AISI recently reported that the United States steel industry has achieved a new milestone in energy efficiency by reducing its energy intensity per ton of steel shipped by approximately seven percent in 2003 compared to 2002 [Figure 1], thus extending its drop in energy intensity to 23 percent since 1990. Because of the close relationship between energy use and greenhouse gas emissions, the industry's aggregate carbon dioxide (CO_2) emissions per ton of steel shipped were reduced by a comparable amount during the same period.

AISI 2005 Chairman John P. Surma, president and CEO of United States Steel Corporation, said. "As part of our industry's Climate VISION agreement with the Department of Energy, we set a goal to improve energy intensity per ton of steel shipped by 10 percent by 2012 compared to the 1998 baseline. The 2003 data show we are making solid headway toward achieving that target."

Figure 5

U.S. Steel Industry Energy Intensity 2003

	Production (tons)	Shipments (tons)	Utilization [S/P]	Energy Intensity (million BTUs/ton Shipments) 2003	2002
BOF	49,690,889	48,294,778	97.2%	19.55	21.23
EAF	32,991,563	31,727,682	96.2%	5.26	5.23
TOTAL	82,682,452	80,022,460			

Adjust to/AISI Reported Production Data (apply S/P factor)

	Production (Reported)	Shipments (Adjusted)
BOF	50,941,708	49,510,454
EAF	48,750,861	46,883,254
TOTAL	99,692,569	96,393,708

	2003	2002	1990
COMPOSITE ENERGY INTENSITY	12.6	13.6	16.4

Since 1990, Energy Intensity is DOWN 23.2%!

Since 2002, Energy Intensity is DOWN 7.4%!

The goal of this program is to far surpass the energy savings conceived under CLimateVISION. This section provides a roadmap for maximizing energy savings in steel production operations by drawing upon the findings compiled in the document "Steel Industry Marginal Opportunity Study" (SIMOS) prepared by Energetics, Inc. for

DOE. The term “energy savings” is considered equivalent to a reduction in energy consumption and accordingly would include energy recovery methods where potential energy losses are ultimately recovered and reused directly in the steel production process, e.g., scrap preheating by hot off-gases and post combustion.

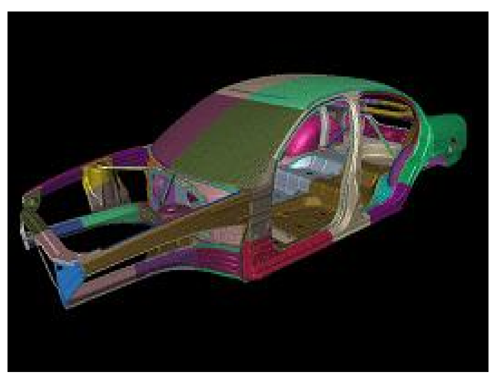
This chapter follows the general layout of the SIMOS document by considering energy saving opportunities through the sequential phases of the steel production process. Likewise, the scope of this chapter has been restricted to considering only steel production in North America. While this chapter includes a qualitative discussion regarding related reductions in the consumption of consumable items employed in steel production (e.g., refractories, electrodes, ferroalloys), the energy employed in the production of these consumables is not quantitatively considered.

When one looks beyond the steel plant into the entire value chain, a compelling rationale for energy and environment-focused projects is often found. For example, the development of advanced high strength steels (AHSS), now being adopted by automakers, is resulting in tremendous energy and environmental benefits as a result of dramatic improvements in fuel savings. The following benefits are based on a market penetration of only 7% of AHSS- type vehicles, a low hurdle given the rapid adoption already evidenced:

Table 4. There are significant energy savings opportunities in the Steel Value Chain

Item	Savings per year	Savings per yr per federal $ spent	Dollar savings per year at $50/barrel
Barrels of oil	4,071,429	0.84 barrel	$203,571,450
CO_2 emissions reduction (tons)	2,100,000	0.5 ton	N.A.

ULSAB_AVC



Another way to look at this example is a lightweight steel vehicle of the type designed under AISI’s Ultra Light Steel Auto Body – Advanced Vehicle Concepts [ULSAB-AVC] Program saves 21.2 MMBTU per year over a vehicle operating at today’s mileage standard of 27.8 mpg and driving 10000 miles per year. Even when applied to only 1 million vehicles per year, about 6% of the new vehicles built and entering service each year, the energy savings is 2.12 X 10^{13} BTU/Yr. *Savings throughout the steel value chain should not be ignored and may impact heavy equipment, trucks, cars, machinery and buildings.*

Steelmaking Processes

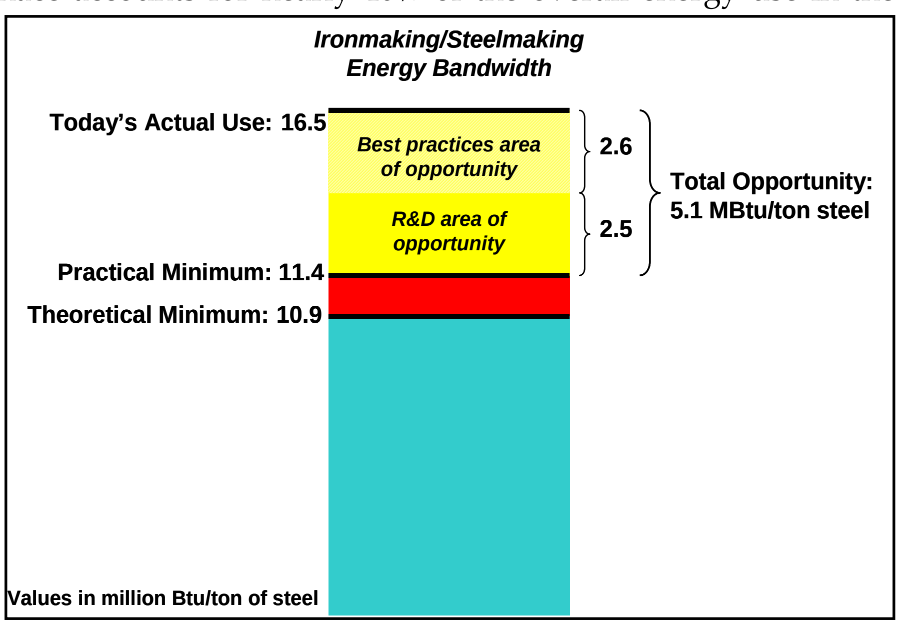
Since the majority of energy consumption in the production steel occurs during the respective ironmaking and steelmaking (including melting, refining and casting) processes, consideration of these process steps should provide the most significant opportunities for energy savings. Many of these energy savings opportunities are generally applicable to both ore-based and scrap-based steelmaking processes. Some of these are listed below along with possible relevant technologies included in parentheses.

- improved energy management (sensors, post-combustion)
- increased yields (near-net shape casting)
- reduced refractory consumption (improved refractory, slag splashing)
- reduced flux consumption

Integrated Steelmaking

The integrated steelmaking process, as defined in SIMOS, is the ore-based manufacture of steel and combines hot metal production and BOF steelmaking. The document goes on to identify a possible energy saving of just over 30%. Since the vast majority of the total integrated steelmaking energy expenditure (about 98%) occurs in the production of hot metal, the majority of readily accessible energy savings (about 65% of the gap) is directly attributable to the ironmaking process. Most of the remaining energy savings are categorized as general, (e.g., preventive maintenance, improved variable speed drives for pumps and fans, etc.)

Today's modern blast furnace is the product of decades of technological improvements. Energy consumption in blast furnace ironmaking has decreased by more than 50% since 1950. Still, the blast furnace accounts for nearly 40% of the overall energy use in the steel industry[4] and significant energy opportunities remain. However, a review of the SIMOS document reveals that about ½ of the bandwidth falls outside the realm of energy savings (captureable predominately as latent energy recovery/co-generation .



While modest improvements in blast furnace efficiency still continue to be found (through optimized injection technologies and better sensors/process control), any major gains may have to be achieved via alternative ironmaking technologies. However, it should be recognized that environmental concerns (primarily associated with the production of coke and sinter for the blast furnace process) have been the primary drivers for the development of these new processes, not reduced energy consumption. Thus R & D efforts directed to decrease/optimize overall energy consumption in new alternative ironmaking processes are an appropriate focus for this program.

The BOF process itself is not a major energy consumer. It is the inherent energy of the charge materials that impact the overall energy intensity of this steelmaking path. Given the high energy cost in the production of hot metal, any technologies that allow an increased scrap/hot metal ratio in the BOF charge would provide a clear benefit and accordingly deserve some consideration.

EAF Based Steelmaking

Data in the SIMOS report indicates that transitioning from the integrated ore-based steelmaking to scrap-based EAF steelmaking provides the single most effective means of lowering energy requirements for steel production. Driven by this and other associated benefits (e.g., lower capital cost, reduced CO_2 generation, increased flexibility) the percentage of EAF produced steel has gradually increased over the past 50 years. The introduction of low cost EAF/Continuous Casting based technology in the 1970's quickly displaced integrated producers in the long products market. The rate of increase in EAF-produced steel has risen dramatically in the 1990's with the introduction/proliferation of thin slab casting and the corresponding penetration into the flat products market. The growth of EAF based steel tonnage is expected to continue. However, a number of factors will start to have an impact on this trend, the most prominent being future limitations on scrap availability.[†] Developing a means to overcome some of these barriers (e.g. improved processes for low-grade scrap recovery) could represent research opportunities.

Within the EAF steelmaking process, the SIMOS document indicates an energy gap comprising over 45% of the industry average. This is split 2/3 from implementation of "best practices" opportunities and 1/3 from current and future R&D opportunities. Most of the "best practice" opportunities are related to energy savings, primarily achieved through improvements in furnace design, process control, scrap preheating/charging practices and post combustion.

[†] Home scrap availability will decrease as further gains in yield are made. Furthermore, based on 1997 data, 89% of discarded automobiles, 80% of discarded appliances, and 60% of discarded steel cans were already being recycled.

Some of the process control improvement efforts include striving for increased electrical energy transfer efficiencies (e.g. current carrying conducting electrode arms), reduced tap-to-tap times, and increased percentage of power-on time.

R&D opportunities could include sensible heat recovery from slags, fumes and off-gases.

Casting

The major energy savings obtained in the casting processes have been achieved as a result of the transition from ingot casting to continuous casting product, the elimination of soaking pit cycles for ingot reheating, and from the significant additional yield improvements in the continuous casting process. The transition from ingot to continuous casting is virtually completed for flat products. However, some ingot making capacity still exists in the production of long products. The primary barrier to the complete conversion to continuous cast long products is perceived differences in quality, especially steel cleanliness. A concerted effort has been underway to eliminate this particular barrier.

Near-net shape casting provides the opportunity for energy reduction in the subsequent rolling process by reducing the number of forming steps required to produce a final product. Thin slab casting is probably the most significant form (in terms of tonnage) of near-net shape casting. Strip casting is still in the early stages of commercialization and needs to overcome some quality and productivity concerns before it can achieve widespread acceptance and provide any significant impact on steel industry energy savings objectives. Beam blank casting is a growing near-net shape process in the long products category.

Rolling and Finishing

The primary means of energy savings in rolling operations is the elimination/minimization of reheating steps. This may be achieved to a certain extent through new casting and rolling technologies including near-net shape casting (discussed above) and direct rolling. Fruehan et al.[3] has estimated that direct charging decreases energy consumption of the rolling process by about 80%. (The actual energy savings would depend on the charging temperature of the slab/bloom.) Most of the perceived barriers to direct rolling are based on either logistical or quality issues. Logistical barriers include plant layout and product mix/order size impact on scheduling. The quality barriers are predominately tied to the multi-stage inspection and conditioning requirements currently necessary to meet increasing customer expectations on surface quality.

Energy is also consumed in the deformation of the steel during rolling/forming processes (i.e. energy for mill motors and drives). This amount of energy consumed tends to be small in comparison to the energy consumed for reheating. Still there are opportunities for reducing the energy consumption, perhaps through appropriately applied casting of near-net shape forms requiring less deformation and less energy.

The issue of mechanical vs. thermal processing needs to be studied. Such a study will discover opportunities to replace thermal processing with less energy intensive mechanical processing.

Table 5: Barriers & Opportunities to Achieving Energy Savings in Steelmaking

	Opportunities	Barriers
Steelmaking	- Improved energy management (sensors, post-combustion) - Increased yields (near-net shape casting) - Reduced refractory consumption (improved refractory, slag splashing) - Reduced flux consumption	Return–on-Investment as a rationale for Capital Investment
Integrated	possible energy savings (bandwidth) of just over 30%. Transition BOF to EAF steelmaking	
BOF Steelmaking	Increased scrap/hot metal ratio in charge	
EAF Steelmaking	Electrical energy transfer efficiency	
Casting	Net shape casting	Development and maintenance cost
Rolling	Net shape casting	Development and maintenance cost

Chapter 2 - ENERGY SUBSTITUTION

Worldwide economic and population growth have caused the demand for energy to increase dramatically. During the period 1990 to 2001, global energy usage increased by approximately 15%.[1] Inevitably, this has been a significant factor in causing energy prices in North America to rise during that period by over 75%. Furthermore, energy prices have always been very volatile. These trends are expected to continue and even worsen in future years. Additionally, many fear that the increasing concentration of greenhouse gases in the atmosphere from human activities is contributing to global climate change. These trends create pressure and opportunities in the steel industry to seek new technologies for the generation, conservation, and substitution of fuels, and ultimately the development of new steelmaking processes.

Energy substitution has near, medium and long-term aspects. In the short term, the steel industry has the opportunity to avail itself of or maximize its use of alternative fuel technologies already extant.

Near Term

In the near term, the steel industry must continue to implement the latest energy saving technologies. This implies the need for worldwide benchmarking of best practices. We must also look to expand the use of known energy saving and fuel substitution strategies. For example, blast furnace coal injection avoids the losses inherent in the cokemaking operation and facilitates retaining that portion of the energy value of coal in the blast furnace process that would otherwise be lost to form coke by-products. We must also strive to maximize the yield from our operations. Minimizing the generation of scrap and oxides also saves energy.

Medium Term

The steel industry is already a substantial generator of fuels in the form of by-product off-gases: coke oven gas, blast furnace gas, BOF gas, and EAF gas. In the medium term, the industry can perform R&D on existing fuel and process technologies that maximize the use alternative fuels. Gas reforming technologies utilizing natural gas and the sensible heat and small CO and H_2 fractions contained in steelmaking off-gases could yield substitute fuels for use in steel plants.

Coke oven gas [COG] is generated at 1100^{o}C and further processed in a coke by-product plant where its heavy hydrocarbon constituents are removed. Considerable thermal energy is dissipated through this process. Subsequently, COG at ambient temperatures, containing about 500 BTU/ft^3 is reused by the industry to fire the coke ovens and elsewhere in the mill. However, much of its energy value has been lost in the recovery

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[1] World Energy Use & Carbon Dioxide Emissions 1980-2001, May 2004, page 14 – www.eia.doe.gov/emeu/cabs/carbonemiss/energycarbon2004.pdf

process. This is because the by-product process separates many energy-bearing components as products for the chemical industry (although it should be noted that these are high-value applications of these materials). Technologies that substitute COG for other fuels could be of great value. COG also contains significant quantities of hydrogen that could be separated and recovered.

Blast furnaces generate large volumes of off-gases. These gases are high pressure, low temperature, low calorific value, and are high in nitrogen. As coal or natural gas injection increases, the fraction of hydrogen in the off-gas increases considerably to as much as 20%. Cleaned for reuse, blast furnace gas contains 90 - 110 BTU/ft^3 (3-4 GJ/NM^3). However, this low BTU concentration in blast furnace off-gas is a result of high concentrations of nitrogen in the gas. R&D almost certainly could improve its fuel value. Research in gas reformation might make it possible to create a radically new blast furnace process that employs oxygen, very low amounts of air, and partially substituting its own off-gases for coal and coke.

Off-gases from the BOF and EAF are at a very high temperature [greater than 1650^oC], low pressure, and can approach 6 GJ/NM^3, although they have a low fuel value during much of the steelmaking cycle. Unfortunately, they are generated intermittently, vary greatly in temperature, CO and nitrogen concentration, and are very dirty. Nevertheless, R&D could focus on eliminating these barriers and the energy value of these off-gases could be recovered. Currently, foreign steelmakers (outside North America) capture and reuse BOF gases; rising energy prices may make this economically feasible in North America.

Long Term

In the long term, the steel industry can develop technologies to transform the industry so it generates its own fuels or uses alternative fuels as they are develop by others. The steel industry must perform R&D that will radically transform the way steel is made.

Furthermore, the steel industry must radically reduce its energy intensity and hence the amount of greenhouse gases that it generates. This requires making better use of the hydrocarbon fuels that are already in use, weaning itself away from its dependence on hydrocarbon fuels, and finding ways to sequester the greenhouse gases produced. In all likelihood, there will be no single technology that will accomplish all that is needed, but a combination of technologies

Alternative fuels that could be substituted into the steelmaking process:

1. Charcoal from trees, silage, and sawmill wastes could be used as a fuel and as a replacement for coke in the blast furnace.

2. Hydrogen, as it becomes available could be used to reduce iron ore or as a fuel in furnaces and transportation equipment. The steel industry is a producer of hydrogen in its cokemaking facilities and blast furnaces.
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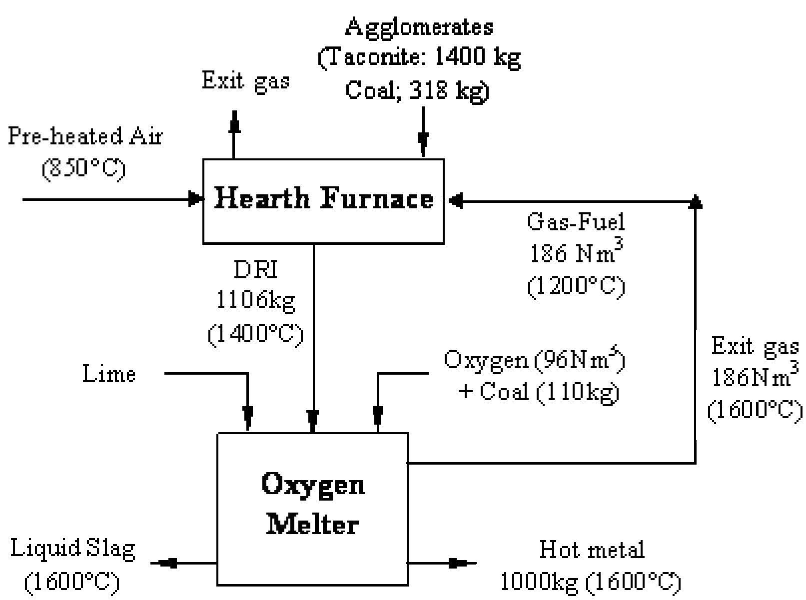

Figure 6: Flow Sheet of the new Paired Straight Hearth Ironmaking Process

Longer term R & D planning also needs to consider CO_2 sequestration technologies. Such technologies, especially those utilizing by-products from the steelmaking process, will reduce greenhouse gas generation and landfill requirements. Many have the potential to create valuable products that can be substituted for other manufactured goods, thus saving energy elsewhere in the economy.

Chapter 3 - ENERGY RECOVERY

The *SOBOT* Program goals are intended to both reduce the primary steelmaking industry's reliance on energy sources as well as reduce the volume of greenhouse gases it introduces to the environment. The other chapters of this roadmap discuss opportunities to reduce energy consumption by developing more energy efficient steelmaking practices, and to replace traditional energy inputs with ones that are more efficient and less harmful to the environment. This chapter considers technologies to recover energy contained in the by-product outputs of the steelmaking process and reallocate that otherwise wasted energy for use elsewhere in the steel production process. The intent here is to replace these currently unproductive modes of energy consumption, thereby eliminating the need to capture these by-products as well as to eliminate the potentially environmentally harmful effects of their initial generation.

To illustrate this concept, consider the simplified mass/energy balance diagram shown below.

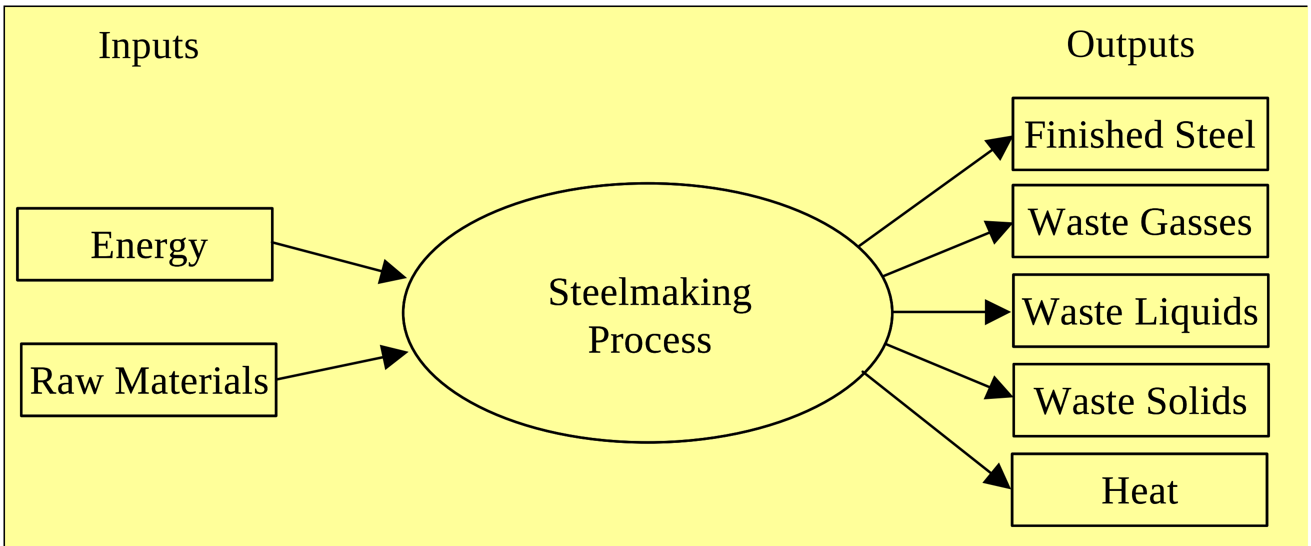

Figure 1. Simplified steelmaking process mass and energy balance diagram.

Inputs to the process include raw materials such as iron ore, limestone, scrap and alloys, and energy such as coal, coke, natural gas, and electricity. Outputs include both the finished steel product (the "product"), as well as by-products in the form of gases, liquids, solids, and heat ("by-products).

In a 100% efficient process, all of the inputs, both raw materials and energy, would be converted to finished product at ambient temperature (the basis of the theoretical minimum energy requirement calculations); but obviously, this level of efficiency is unattainable. Even in the most ideal case, the process of making steel requires heating the raw materials to a temperature above the liquidus of the final steel composition, processing it, and returning it to ambient temperature. For cold rolled products, processing requires yet another temperature excursion to the annealing/heat treating temperature and again, cooling to ambient. Even if the raw materials and energy conversion were 100% efficient, there would still be a substantial loss of heat to the environment, heat which contains potentially usable energy. Since iron ore sources are less than 100% pure iron, there will inherently be by-products representing the undesirable components of the raw material inputs, as well as remnants from the additional inputs required to extract impurities from the input ore.

This chapter encourages researchers to examine the by-product outputs of the steelmaking process, consider the energy content of these outputs, and develop useful and practical means to extract energy from these outputs for use in other applications, either within the steel plant or externally.

An excellent illustration of this concept is embodied in the non-recovery cokemaking process example below.

Example – Non-Recovery Cokemaking Processes

Coke is a major input to the conventional blast furnace ironmaking process. Coke, intermixed with iron ore and fluxes in the shaft of the blast furnace, is combusted to provide reducing gases for reduction of iron oxides, produce energy for the iron oxide reduction process, and melt theiron and slag to allow casting of the furnace iron. Coke is made from coal by heating it to drive off volatile materials and sinter the remaining carbonaceous material into a solid mass capable of remaining relatively intact through the blast furnace process. In traditional recovery cokemaking processes, the volatile coal off-gases are further processed into other valuable materials, such as coke oven gas, tar, ammonia, and other chemicals. In the non-recovery cokemaking process, these off-gases are combusted to generate steam which, in turn, are used to generate electricity in a steam turbine generator. The electricity thus produced can be used within the steelmaking plant, or sold externally through the connected power grid. In this example, the by-product outputs (volatile coal off-gases) are converted into electrical energy, which offsets electricity that would otherwise be generated elsewhere.

The research community is thus challenged to examine all of the by-product outputs of both conventional and emerging steelmaking processes for other opportunities to recover and redistribute energy. Several other potential by-product energy sources will be discussed subsequently to start the thought process in this regard.

Cokemaking Process Energy Recovery Opportunities

Traditional cokemaking processes include coal as the major raw material input and use coke oven gas and electricity as the primary energy inputs. Outputs include: solid coke, which is charged to the blast furnace; off-gases from the coking reaction; and heat, much of which is converted to steam during the coke quenching operation. The off-gases include a mixture of H_2 and CO, and a mixture of hydrocarbons and other volatile compounds released from the coal during heating. Minor amounts of CO_2 are also produced due to infiltrated air.

Potential energy recoveries from the cokemaking process include: combusting the off-gases to produce electricity in a steam turbine (as illustrated in the non-recovery coke making process example cited earlier); extracting the hydrogen from the coke oven gas for use in hydrogen-powered vehicles or equipment; recovering the heat in the steam from the quenching process for lower temperature heating or power generation processes; or as is currently done, using these off-gases in blast furnace stove heating and in the blast furnace itself via tuyere injection. Technologies that can allow the recovery of sensible heat of the coke oven gas prior to ammonia liquor quenching should be investigated. The steam from the quenching process or produced by utilizing the latent heat in the off-gases could be captured and filtered for use in steel plant processes that require steam, such as heating process baths (pickle tanks, strip cleaning tanks) and steam equipment (steam ejector based vacuum degassers). Improvement to current dry quenching technology must also be investigated.

Blast Furnace Ironmaking Process Energy Recovery Opportunities

Major blast furnace process inputs include: iron ore; fluxes, such as limestone to extract the gangue oxides from the ore and to absorb impurities; coke; natural gas, fuel oils, and directly injected coal to add carbon units; electricity; and combustion air and natural gas or coke oven gas to fire the hot blast heating stoves. Major outputs include: liquid pig iron; molten slag containing the impurities in the input ore; furnace off-gases consisting primarily of CO and CO_2 from the combustion of coke and the reduction of iron oxide; and stove off-gases consisting of CO_2 and water from the combustion of natural gas, blast furnace gas and coke oven gas. The furnace off- gases also contain a quantity of fines from the furnace. Major sources of waste-heat include that released from the molten slag while cooling to ambient, combustion gases from the stove, and heat losses through the furnace shell.

Opportunities for energy recovery include: combusting the blast furnace off-gases in the hot blast stoves; the cokemaking process[2], or hot mill reheating furnaces (as is common practice currently); extracting hydrogen from the furnace gases for use in hydrogen powered vehicles or equipment; CO_2 removal from the top gas to possibly enhance its calorific value; and recovering the latent heat from the molten slag, stove off-gases, or steam captured in slag granulation systems. Modern high top pressure furnaces have energy recovery turbines. Higher turbine conversion efficiencies and more economical designs for medium top pressure furnaces could be investigated.

Pelletizing and sintering are two ways by which iron bearing materials are engineered for superior performance in modern-day blast furnaces.[3] In a pelletizing plant, iron ore feed is ground, impurities are partially removed, and the purified ore is converted into balls which are then heated at high temperatures. The pelletizing operation has recirculating combustion gas streams that allow for recovery of sensible heat. Improved heat exchanger designs would allow for increased energy recovery, primarily from the off-gases in the first preheating zone.

Direct-reduced Ironmaking Process Energy Recovery Opportunities

Modern direct-reduced ironmaking (DRI) processes convert iron oxide directly to solid sponge iron. The reactions occur at elevated temperatures, requiring heat input to and heat liberation from the process. Reductions are driven either by $CO–CO_2$ reactions, starting from coal, or H_2/CO - H_2/CO_2 reactions using natural gas. Any DRI process generates waste heat that could be subsequently recovered and redistributed. The processes also either generate CO/CO_2 off gases, which could be further combusted to generate electricity or other power/heat; or $H_2/CO/CO_2$, from which hydrogen could be extracted for use in hydrogen-powered vehicles or equipment.

Steelmaking/Casting Process Energy Recovery Opportunities

The steelmaking/casting process stage includes several individual processes that are used in multiple combinations – electric arc furnace (EAF) melting or BOF steelmaking, ladle or AOD refining, desulphurization, argon stirring, vacuum degassing, and continuous casting. Major raw material inputs include: molten pig iron (from the blast furnace), solid scrap at ambient temperature, ferroalloys, oxygen, slag fluxes, and equipment cooling water. Major energy inputs include chemical energy (contained within the molten pig iron) and electricity. Major by-product outputs include: molten slag, hot iron fines and oxides, CO/CO_2 resulting from decarburization processes

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[2] *The viability of this needs to be further investigated due to the very non-luminous flame.*

[3] *While their may be opportunities for heat recovery from sintering operations, the low use of sintering in North America limits such opportunities*

(including both the BOF, AOD, VOD and vacuum degasser), spent cooling water, non-recovered heat from the cooling water, heat lost to the ambient environment, and heat in the slabs which exit the caster at temperatures around 1100^{o}C.

Perhaps the most significant energy recovery opportunity in the steelmaking/casting process is the off-gases from the BOF process in integrated plants. Both sensible heat and chemical energy of the contained gases must be considered. While technologies currently exist for this purpose, they have not been economically viable for implementation in North America. Technology that can prove to be viable in the North American market would be of tremendous importance.

The heat remaining in the slabs as they exit the caster is another potential area for heat recovery. Some of the heat generated in the ironmaking and steelmaking process must be extracted to cool the steel to a solid form that is amenable to subsequent hot rolling processes. Typically, the steel is cooled to a temperature of approximately 1100^{o}C prior to exiting the caster. The heat lost during cooling from temperatures above the liquidus to an 1100^{o}C exit temperature is typically dumped directly into the environment and lost.[4]

Currently, some steelmaking shops are configured to hot charge the cast slabs to the reheating furnaces at the hot mill, thereby reducing the energy that would otherwise ultimately be required to heat the slabs to the hot rolling temperature. Unfortunately, not all shops are favorably configured, and steelmaking shop/hot mill scheduling often prevents scheduling slabs for hot rolling immediately as they exit the caster. It would be of great value to develop technologies that better facilitate hot charging, or otherwise recapture and recover the latent heat energy contained in the slabs as they cool before reheating for hot rolling.

Hot Rolling Process Energy Recovery Opportunities
Major raw material inputs at the hot rolling process include slabs from the caster and equipment/process cooling water. Major energy inputs include: latent heat in slabs that can be hot charged; natural gas, coke oven gas, and/or blast furnace gas for the reheat furnaces; and electricity. Major by-product outputs include heat lost by the steel slab/strip during cooling from the reheating temperature to ambient, reheat furnace off-gases, spent equipment and process cooling water, and a small amount of iron oxide generated by oxidation in the reheat furnaces and during hot rolling.

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[4] *Given the exit water temperature either from mold or spray cooling, the temperature difference may be too low for meaningful exploitation. Any significant opportunity to recover heat energy from this application would need to consider a different solidification methodology.*

The energy potential of input gases at the reheat furnaces is generally completely consumed by the combustion process. Generally, the greatest energy recovery opportunity in the hot rolling process is from the heat remaining in the strip after exiting the finishing stand and again after exiting the cooling table. Upon exiting the reheating furnace and through the final finish rolling stand, heat is continuously lost from the slab/strip to the environment. This heat is generally unrecoverable, although technical developments are targeting methods to keep as much heat in the strip as possible as it proceeds through the rough and finish rolling processes (e.g. transfer table covers, coil boxes, etc.). Thermal energy could potentially be recovered after finish rolling at two stages – during cooling from the finishing temperature to the coiling temperature on the run-out table, and subsequently during cooling of the finished coils from the coiling temperature to ambient temperature in preparation for subsequent cold processing. Such thermal energy recovery techniques would need to take into account the need to maintain controlled cooling rates consistent with those necessary to achieve the appropriate metallurgical properties of the specific product.

Finishing Process Energy Recovery Opportunities

There are considerably fewer opportunities for recovering and redistributing energy from the by-product outputs of processes subsequent to the hot rolling step. The one possible exception is the annealing process. In this step, cold rolled steel is heated to temperatures up to around 820^{o}C to anneal the cold rolled structure, and subsequently to provide controlled cooling to impart desired structure and metallurgical properties. Annealing processes include batch and continuous annealing for cold rolled strips, and continuous annealing as part of the continuous hot dip galvanizing process.

Potential energy recovery opportunities in this process include energy contained in off-gases from heating processes using combustion, and from the heat liberated from the steel strip during controlled cooling from the annealing temperature to ambient. In addition, many annealing processes use protective atmospheres containing from 5 to 100% hydrogen; these off-gases are not normally recovered and represent a potential source for hydrogen recovery and redistribution. The research community is encouraged to examine other by-product outputs in the finishing stage for other energy recovery opportunities not recognized here.

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