ENERGY EFFICIENCY AND ADVANCED TECHNOLOGIES IN THE IRON AND STEEL INDUSTRY

Ernst Worrell, Department of Science, Technology & Society, Utrecht University, Utrecht, The Netherlands
Curtis Moore, Curtis Moore and Associates, McLean, Virginia, USA

ABSTRACT
The iron and steel industry is one of the largest energy-consuming and energy-intensive industrial sectors in the world. In the U.S. it consumes approximately 8% of total manufacturing energy consumption. The development of energy efficiency and penetration rate of various technologies, e.g. BOF steelmaking and continuous casting is discussed and compared. Between 1980 and 1991 energy intensity of the US steel industry has declined by 17%, of which 11%-points are due to efficiency improvements. Considerable potential for energy efficiency improvement can be realized by applying currently best available technology (the so-called 'technical potential'). For the US the technical potential is estimated to be 43±8%, taking the current industrial structure (mix of raw materials used and products produced) into account and the best available technology. The economically profitable potential is estimated to be 10-15%-points lower. The potential for energy efficiency improvement in the U.S. is higher than that in other OECD countries, despite the improvements since 1980. Advanced technologies, such as smelt reduction and near net shape casting, present major opportunities for further reduction in energy consumption at potentially lower costs, as well as environmental benefits. Thin slab casting has first been introduced in the U.S. by mini-mills to compete on the steel sheet markets. Since the first commercial introduction in 1989 the technology has shown rapid development and capacity growth. Smelt reduction on the other hand does not yet show such a rapid development. We discuss the status of smelt reduction, as well as the potential opportunities for the U.S. integrated steel industry.

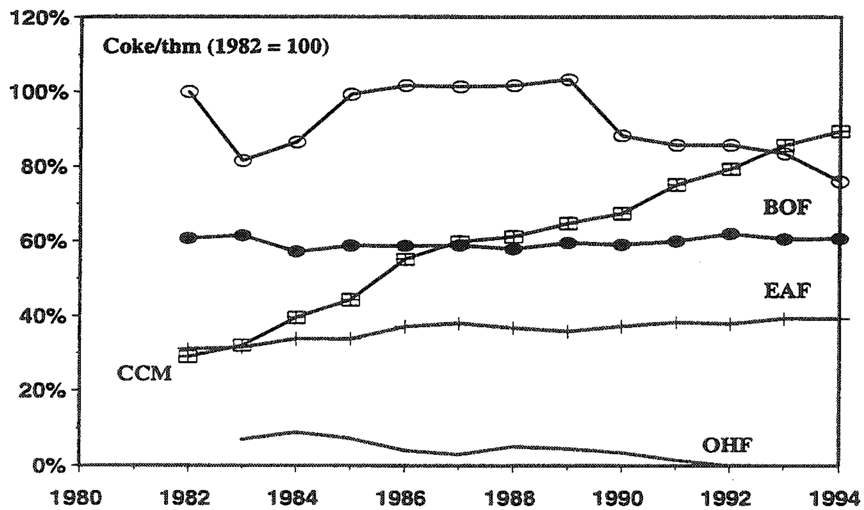
INTRODUCTION
The U.S. steel industry produces annually about 90 Million tonnes from iron ores and scrap, using large amounts of energy and processing large material streams. Losses are associated with handling large streams of materials and energy, which result in leakage to the environment in various forms. The large material streams within the iron and steel industry make the industry important from an environmental point-of-view. Traditionally, environmental legislation aimed at emission standards for a number of substances, i.e. criteria pollutants. Currently, new forms of environmental policy and emission reduction target setting are discussed. This enables an integrated assessment of environmental impact and technology development directions. We will concentrate on energy use, as this is related to important emissions of acidifying pollutants (NOx, SOx), greenhouse gases (CO_2)) and various criteria pollutants.

The technology of ironmaking and steelmaking is no status quo, but subject to continuous change. Today, several new technologies are developed that could drastically change the picture of steelmaking. We will discuss these new technologies from an energy and environmental perspective, but also indicate the major opportunities offered by these technologies, in an increasingly competitive global steel market. We will start with a short discussion of the U.S. industry, also within an international perspective. We will describe some important technological developments in the iron and steel industry, and their possible impact on energy use and environmental performance. This is followed by a discussion of the opportunities for environmentally sound steelmaking technologies, and implementation strategies for the various parties, highlighting the prospects and potentials.

THE U.S. IRON AND STEEL INDUSTRY

We will discuss the (structural) development of the U.S. iron and steel industry since the early 1980's, limiting the discussion to the main trends and important indicators. We will compare it to developments in other OECD countries. The production of steel in the U.S. shows large variations in volumes of steel produced, from a low of 68 Mtonnes in 1982 to a high of 91 Mtonnes in 1994.[1] These variations are larger than in other OECD countries. In the early 1980's the low production volumes are mainly due to the economic crisis in the industrialized countries, leading to a reduced demand for steel.

Figure 1. The changing structure of the iron and steel industry in the United States between 1980 and 1994. The production shares of steelmaking processes (OHF, BOF and EAF) are depicted, as well as the continuous casting ratio and the relative coke input in the blast furnaces (relative to the 1980 input).

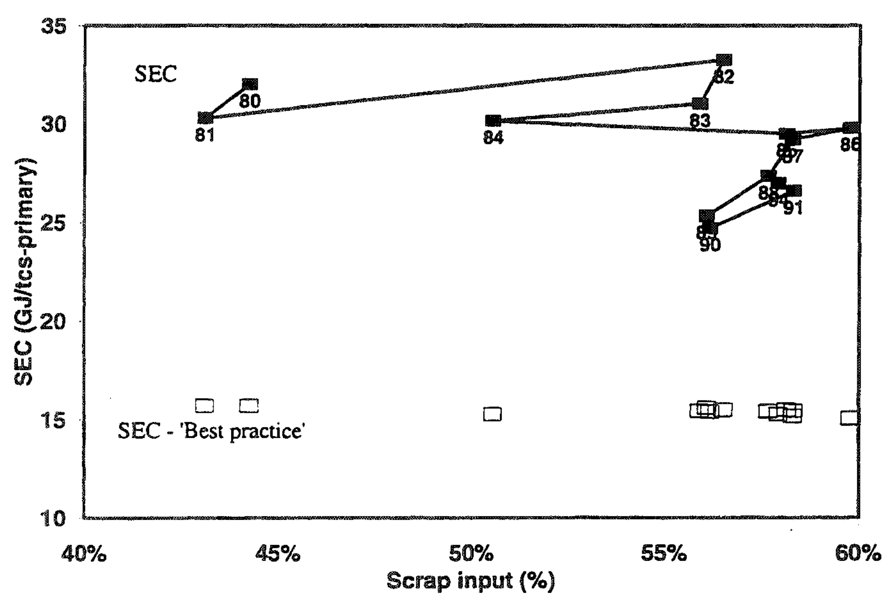


Compared to the iron and steel industries in other OECD countries the U.S. steel industry has a relative high share of electric arc furnaces (EAF), as separate furnaces in mini-mills or as part of integrated mills. Figure 1 shows that the share of EAF in steel manufacture has slightly increased in the past 10 years. In recent years this share has even increased more rapidly through the construction of several 'green field' mini-mills and the closure of a few integrated mills (e.g. Bethlehem, PA in 1995). The introduction of thin slab casting by Nucor in 1989 in the U.S. has made the important sheet steel market accessible for mini-mills. The production costs of hot rolled sheet from a mini-mill with a thin slab caster are estimated at 250 US$/tonne by the analysts Paine Webber (NY). For comparison, an estimate of the production costs of an integrated steel plant in the "lower lake" area is estimated at 330 US$/tonne (1992). Since the first machine in 1989 now a total thin slab casting capacity of 8.5 Mtonnes has been constructed or ordered in the U.S. This development has lead to increased imports of direct reduced iron (DRI) from Latin-American countries, e.g. Venezuela, and to the construction of a new process, i.e. the iron carbide process by Nucor, in Trinidad. These processes make use of cheap natural gas reserves in these countries. In the U.S. there is one domestic DRI steel producer (Georgetown Steel), one new plant under construction in Mobile, AL (based on a "mothballed" plant shipped from Scotland) and other plants planned (Louisiana, Texas).

The overall energy intensity can be defined by the specific energy consumption (SEC). The SEC is defined as the amount of energy (in enthalpy) needed to produce a tonne of a certain steel product, expressed as tonne crude steel (tcs). The SEC is influenced by three main factors: type of products made, type of production process (which is partly related to the type of resources or feedstock used in the process, e.g. primary or secondary resources) and the efficiency of the current production processes. The type of primary energy carrier used can also affect the energy efficiency (for instance in boilers). We will not consider the variety of fuels available since most iron and steel industries are assumed to have (market) access to most types of energy carriers in the U.S., and coal (and coke) is the most important fuel in this sector.

It is necessary to assess the major input and output factors that influence the composite SEC of the sector. The most important input-factor influencing energy consumption in the iron and steel industry is the feedstock: iron ore and scrap for primary steel or scrap only for secondary steel. Direct reduction is not taken into account because it makes only a very small contribution to the iron production in the U.S.[1] The production of primary steel consumes more energy, but produces a higher steel quality. In the BOF-process the amount of scrap used varies by plant and over time. The main output-factor is the product type. We have aggregated the various products to three categories, e.g. ingots and slabs, hot rolled steel (including plates, strip, wire (rod) and long steel products) and cold rolled products (cold rolled sheet and strip), representing the most important product categories, from the perspective of energy consumption. Production is defined as the total output of usable ingots, continuously cast semi-finished products and liquid steel for castings.[2] Finishing (e.g. galvanizing, annealing) has not been accounted for in the analysis. This introduces an uncertainty (of approximately 1%) in the calculations, dependent on the share of finished product and the SEC of annealing or galvanizing.[3]

Figure 2. Actual and 'Best Practice' specific energy consumption between 1980 and 1991 in the U.S., relative to the share of scrap consumption as input for steelmaking.



In the U.S., both structural change and efficiency improvement have contributed considerably to the decreasing SEC between 1980 and 1991.[3] The most important change in product mix is the growing share of EAF steelmaking from 27% to 38% of total steel production. Crude steel production in the U.S. decreased dramatically in the beginning '80s, and remained constantly at around 80 Mtonnes, with an upswing between 1988 and 1990 to around 90 Mtonnes. Efficiency improvement can be explained mainly by the increasing continuous casting ratio (from 20% in 1980 to 75% in 1991), and the closing of inefficient OHF steelmaking (the production share decreased from 12% to 2% in the period 1980-1991). The use of scrap in the BOF has decreased slightly from 27 to 25%.[4] In the same period Germany demonstrated a higher reduction of the SEC, while other OECD countries, e.g. France and Japan have reduced the SEC only moderately. However, these major steel producers were in 1991 generally more efficient than the U.S.,[3] despite a less scrap use in the BOF.[4]

A specific analysis of the efficiency of the blast furnaces showed that these are generally less efficient in the U.S. compared to other OECD countries. The net fuel use (coke, injected fuels, steam) in the U.S. was estimated at 15.3 GJ/tonne hot metal in 1994.[5] The 1994 net fuel consumption in other OECD countries was 13.1 GJ/thm in France, 12.7 GJ/thm in Germany, 12.3 GJ/thm in Japan, 13.3 GJ/thm in The Netherlands and 15.0 GJ/thm in the UK.[6] The relative high energy consumption seems to be due to the relative small scale and old age of U.S. blast furnaces, a high coke consumption, low fuel injection rates, and no power recovery (due to low pressure differences). Also, the low U.S. energy prices influence the energy consumption of the U.S. industry. Recently, fuel injection is increasing and some blast furnaces have been taken out of production. Replacing coke by injected fuels saves energy in the production of coke. Coke production is one of the most polluting processes in the production of primary steel. Emissions of coke production can sometimes exceed air emission standards, and more strict emission standards may lead to closing of the coke ovens and to increased imports of coke.

Figure 1 shows that steel production with the open hearth furnace has been reduced to zero by 1992. In Western-Europe and Japan OHF-capacity has closed since the late 70's.[1] That the OHF process has played a role in the U.S. steel industry, so long after European and Japanese industries phased OHF out, is an indicator of the innovative environment of integrated steel mills in the U.S. The slower penetration of continuous casting compared to other OECD countries is another example. Ingot casting leads to higher material losses and to a higher energy consumption to reheat the steel. Continuous casting share in the U.S. was equal to 89% of the production in 1994, which is lower than other OECD countries. In the EU-12 the average was 93% in 1994, and in Japan it was equal to 96%.[1] The decommissioning of ingot casting was relatively slow compared to most OECD countries, where over 90% continuous casting was reached as early as 1985 (Japan), 1986 (France) or 1989 (Germany).[1]

Boyd et al.[7] studied the energy intensity of mini-mills (using EAF) in the U.S. over time. Electricity use declined over time, approximately with 7 kWh/tonne annually, although the decline was influenced by capacity utilization. The study showed that new equipment is more efficient, and that some savings are the product of energy saving measures. They showed that the average electricity consumption for mini-mills was 718 kWh/tonne in 1988.[8] Because this includes electricity use for other purposes, the average electricity consumption in the EAF is estimated at 530 kWh/tonne. Please note that since 1988 new EAF-capacity has come on-line, so that the current average will be more efficient.

CONVENTIONAL ENERGY EFFICIENCY IMPROVEMENT AND ENVIRONMENTAL MEASURES

A large number of measures are available for improving the performance of existing steel plants. For each unit operation various measures are available. Due to space constraints we will refer to literature for a description of the measures.[9, 10, 11, 12] Based on Figure 2 it is possible to estimate the potential for energy efficiency improvement using 'best practice' technology. The 'best practice' technology is based on existing plants operating in 1988.[3] The 'best practice' integrated steel plant, casting and rolling is based on a plant in The Netherlands[11] and for the EAF on a plant located in Germany.[10] Table 1 presents the estimated energy efficiency improvement potentials for the U.S. and selected OECD countries.

Table 1. Technical potential for energy efficiency improvement (in %) using 'best practice' technology in the steel industry for several countries, expressed as primary energy. The uncertainty range given in the table is estimated on the basis of the uncertainties in the data. Between brackets the reference year of the analysis is given. The estimated potential energy savings exclude coke production. Electricity production efficiency is assumed to be 40%.

Country	Share World Steel production 1994 (%)	Savings Primary energy (%)
France	2.5%	33±7% (1991)
Germany	5.6%	9±2% (1991)
Japan	13.5%	24±5% (1991)
U.S.	12.5%	43±8% (1994)

Comparison to 'best practice' is an indication of the potential that can be reached under economic constraints. However, the economic potential for efficiency improvement can be lower (generally 10-15%-points) due to high (capital) costs of some retrofit measures.[12] In practice, some expensive energy efficiency measures are implemented for other reasons than energy efficiency improvement, e.g. dry coke quenching to reduce dust emissions in Germany and Japan. Also a large number of technologies can be implemented to reduce other environmentally hazardous emissions, although most are end-of-pipe measures, reducing the emissions after the formation. Retrofit of existing facilities might remain expensive, stressing the need for synergetic approaches. A more efficient way to reduce emissions is to internalize the environmental performance by reducing or blocking the formation of the pollutants, reducing costs as well as improving performance. In the next section we will describe some important developments, e.g. smelt reduction and near net shape casting. Especially smelt reduction is an important development as it will integrate several unit-operations in one plant, reducing capital costs, while leap frogging the environmental problems associated with cokemaking.

ADVANCED TECHNOLOGIES AND ENERGY EFFICIENCY IMPROVEMENT

High costs of end-of-pipe environmental control equipment might strongly influence the economics and implementation of retrofit measures. We assess the potentials of advanced technologies that show various inherent advantages, including lower capital costs, more efficient use of energy and environmental emissions, compared to state-of-the-art processes. The new technologies can 'leap-frog' the problems associated with current production technologies in steelmaking. The new technologies have to be viewed in the perspective of ongoing developments in the sector. Integrated and EAF steelmaking will converge more and more, as developments in convertor steelmaking aim at increased quality control and use of scrap. Currently, scrap input in the BOF plant is limited by the sensible heat from the hot pig iron and the heat released from the oxidation of the carbon in the pig iron. Fuel injection can reduce the pig iron input further, typically from over 75% to 50% in primary steel.[13] EAF steelmaking sees increasing use of iron products (DRI, iron carbide), fuel and oxygen injection rates. New technologies include the use of plasma-furnaces, oxy-fuel burners (reducing the electricity demand), new furnace designs like K-ES and DC-arc furnaces.[14] Best-practice electricity consumption of EAF furnaces is estimated at 350 kWh/tonne (both for K-ES and DC-arc), while using some natural gas, injected coal and oxygen.[14] New EAF technologies will also enhance productivity (decreased tap-to-tap times), reduce electrode consumption[10] and improve product quality.[14] These developments will maintain the pressure on integrated steelmakers for market shares, and hence drive innovation. We will start to discuss the use of thin slab casting in the U.S., which has taken off rapidly after the first introduction. This is followed by discussing the opportunities for smelt reduction emphasizing the implications for energy intensity and the U.S. steel industry.

Near Net Shape Casting

Near net shape casting implies the direct casting of the metal into (or near to) the final shape, e.g. strips or sections, replacing hot rolling. In conventional steelmaking, steel is first cast and stored. The cast steel is reheated and treated in the rolling mills to be reshaped. Near net shape casting integrates casting and the first rolling steps. The technology was originally proposed back in the previous century by Bessemer. The current status of this technology is so-called thin slab casting. Instead of slabs of 120-300 mm thickness produced in a continuous casting machine (CCM), slabs of 30-60 mm thickness are cast. The cast thin slabs are reheated in a coupled furnace, and directly rolled in a simplified hot strip mill. Technology is currently supplied by German constructors, SMS (Compact Strip Plant, CSP) and Mannesmann-Demag (In-line Strip Plant, ISP) and by Voest-Alpine from Austria. Ten plants are in operation worldwide with a total capacity of over 7 Mtonnes, of which most in the U.S.

Energy savings using thin slab casting are estimated by comparing the energy required for the slabbing furnace and the driving energy of the hot strip mill, to energy required for thin slab casting. In the CSP plants, energy used for casting and rolling is reduced to 0.6 GJ/tonne rolled steel (primary energy), equivalent to savings of 75% relative to current best practice using conventional technology. The capital costs of strip casting plants are much lower than that of a conventional CCM and hot rolling mill. Estimates for the reduction of capital cost differ from over 30%[15] to 60%,[16] depending on the capacity of the rolling mill. This reduced capital requirement made it possible for smaller (e.g. mini-mills) to enter the sheet steel markets. The application of CSP technology by Nucor in the U.S. led to a successful entry and expansion of Nucor in this market, now producing nearly 10% of the U.S. production. The reduction of operating costs is estimated to be 20-25%.[15,16] Thin slab casting is now finding it's way into the integrated mills (i.e. Acme Steel in the U.S., Hanbo Steel in Korea), reducing the production costs of hot strip by 77 US$/tonne.[17] In Europe several integrated producers have announced plans to build large thin slab casting facilities. The example of thin slab casting shows that innovative technology can penetrate rapidly in the U.S. steel industry, after the economic advantages were successfully demonstrated by an innovative producer.

Table 2. Commercial thin slab casting machines in the world (summer 1995). Thin slab casters are delivered by Schloemann-Siemag Aktiengesellschaft (SMS, Compact Strip Plant; CSP) or by Mannessmann-Demag (In-line Strip Plant; ISP).[15,16]

Location	Capacity (tonnes/year)	Slab Thickness (mm)	Start-up
Nucor Steel (CSP), Crawfordsville, USA	900,000	40-50	1989
Nucor Steel (CSP),Hickman, USA	1,000,000	50	1992
AST (CSP), Terni, Italy	n.a.	50	1992
Arvedi (ISP), Cremona, Italy	500,000	30-60	1992
Nucor Steel (CSP), Crawfordsville, USA	900,000	40-50	1994
Nucor Steel (CSP), Hickman, USA	1,000,000	50	1994
HYLSA (CSP), Monterrey, Mexico	900,000	50	1994
Hanbo Steel (CSP), Asan Bay, Korea	1,000,000	50	1995

Smelt Reduction

Smelt reduction processes, currently under development, combine coal gasification with the direct reduction of iron oxides. In this way, production of coke is abolished and the demand of ore preparation reduced, integrating three processes in one. Coke making and ore preparation are responsible for the largest part of emissions in the primary steelmaking route. Various pilot-plants exist worldwide, and the first commercial applications are operating. Table 3 gives an overview of the currently developed technologies and stage of development.

The average age and relative small scale (compared to modern large volume units) of blast furnaces in the U.S. makes the adoption of smelt reduction attractive, even if only coke plants or ore preparation facilities need to be replaced. It is difficult for old coke plants to reduce emissions further, without large investments. Tightening environmental legislation for coke making might lead to closure of coke plants and increased imports, also because construction of new coke plants due to environmental legislation in the U.S. seems very unlikely.[18] Under these circumstances the construction of new smelt reduction plants might be attractive. Meijer *et al.*[19] studied six scenarios for revamping existing equipment in the blast furnace route. Depending on the type and investments for the smelt reduction installation, constructing a smelt reduction plant might be cost-effective in the case of building a new coke plant, rebuilding coke batteries or construction of a new blast furnace (for conditions in Germany or The Netherlands). Only relining of an existing blast furnace would be less costly.[19] In case of large volume blast furnaces (capacities over 2 Mtonnes/year) smelt reduction might currently be economically less attractive.

The COREX process is the only commercial smelt reduction process, CCF, DIOS and HIsmelt are advanced projects. First commercialization of the more advanced smelt reduction processes is expected around the turn of the century.[20] The principals of the smelt reduction processes have been proven on large scales, and the construction of large sized demonstration plants is planned for the near future. The principals of all processes are similar, although differences occur, especially in the pre-reduction phase where ores and coal are mixed. CCF, DIOS and HIsmelt use ore fines, abandoning both coke making and ore preparation. DIOS and CCF use oxygen,[19, 23] while the HIsmelt does not need oxygen production but uses hot blast stoves.[20] COREX plants are in operation in South Africa, and at POSCO (two) in South-Korea.[24] An interesting project is currently under construction in South Korea integrating many advanced technologies. Hanbo Steel is constructing a new green field steel plant at Asan Bay. The plant will incorporate two COREX-units, using the flue gases in a direct reduction unit (Midrex) to produce 800,000 tonnes DRI annually. The total iron production capacity will be around 2.3 Million tonnes.[24] The plant incorporates two compact strip plants by SMS with a total annual capacity of 2 Mtonnes. The Asan Bay complex is a very compact integrated steel plant with drastically reduced capital costs, energy consumption and environmental impact, and is a model for future integrated facilities. A similar unit is on order for Saldanha Steel in South Africa (at the Sishen ore port near Cape Town). At Saldanha Steel one COREX C-2000 unit (capacity of 650,000 tonne hot metal) will be coupled to a Midrex unit producing 800,000 tonnes DRI, using a feed of 100% lump ore for the COREX and 70% lump ore for the Midrex.[24] A Russian smelt reduction process, Romelt, is marketed in the U.S. as a mill dust recycling process but is very energy intensive.

Table 3. Current status of major development programmes of smelt reduction processes.[19, 20, 21, 22, 23] Electricity conversion efficiency is assumed to be 40%. The SECs should be compared to 17.8 GJ/thm for a modern large scale blast furnace[12] and an estimated capital costs of 330 US$/thm for a modern large scale blast furnace (including coke oven and sinter plant), derived from Meijer et al.[19] The 1994 U.S. energy use for ironmaking is estimated at 21.7 GJ/thm.[5]

Process	Developers	Status	Estimate SEC - primary (GJ/thm)	Estimated Investments ($/thm capacity)
CCF	Hoogovens (Netherlands), Ilva (Italy)	Experience at 175,000 thm/yr. Pilot-plant planned (350,000 thm/yr)	15	150-180
COREX	Voest-Alpine (Austria, Germany)	Commercial operation in South Africa and Korea	17-20	210-250 (new plant)
DIOS	JISF (Japan)	Integrated pilot plant is under construction (180,000 thm/yr)	?	750 actual costs small scale pilot plant
HISmelt/KSG	CRA (Australia) Klöckner (Germany)	Pilot plant (100,000 thm/yr)	16-17 (pilot plant)	?

In the U.S. the AISI-Project (American Iron and Steel Institute) aimed at the development of a smelt reduction process, and the start-up of a pilot-plant was planned in 1994/1995.[25] The AISI-plant was designed to have a higher productivity than the COREX-process, with much smaller reactors, and hence lower capital costs. AISI research has concentrated on the bath melting step. AISI changed the process development towards recycling of zinc-containing mill wastes, and recovering the zinc (50% of zinc consumption is imported in the U.S.) for recycling. A recent patent exchange has given AISI the rights of the cyclone convertor (CCF) developed by Hoogovens, so that both developers possess the full rights on the total process. Hoogovens is pursuing further development, and is searching for risk sharing partners.

Due to the different reaction conditions and the full integration, the theoretical energy demand of smelt reduction is lower than that of a blast furnace.[22] Previous studies estimated the energy consumption to be 20-30% lower than that of the conventional blast furnace route. Smelt reduction plants generally have a higher coal input than current blast furnaces, but export larger quantities of fuel gas. The exported offgas of the COREX-process has a heating value of approximately 7 MJ/Nm^3 (LHV) and is relatively clean (sulphur content of 10-70 ppm).[22] Currently operating plants already show energy consumption levels comparable to the blast furnace routes, *but* at much smaller scales. The first commercial COREX plant operating in South Africa (capacity of 300,000 thm/year) shows an estimated net SEC of 17 GJ/thm.[22, 26] Since the figure is valid for a small first-of-a-kind plant, lower SECs may be expected, to be reached through increased capacities, optimization of the carbon monoxide/ore-interaction, and optimization of fuel gas use. In the near future net fuel use of second generation plants is estimated to be 20.4 GJ/thm with a net electricity production of 2.1 GJ$_e$/thm (595 kWh$_e$),[19] equal to a net primary energy consumption of 15.1 GJ/thm (assuming 40% electricity generation efficiency). Smelt reduction replaces coke making, ore preparation and the blast furnace. The second generation smelt reduction technology would reduce energy use in ironmaking by 30% relative to the 1994 situation in the U.S. (blast furnace net consumption is 18.6 GJ/thm, incl. ore preparation, and coke production net consumption is 3.1 GJ/thm (6.93 GJ/tonne coke, 445 kg coke/thm)).[5] In the long term further reductions leading to a net SEC of 11 GJ/thm may be expected.[27]

Coke plants need high grade coking or metallurgical coal types, which are more expensive than steam coal. Smelt reduction technology makes it possible to use steam coal, thereby reducing fuel costs. Based on experience with the COREX-process in South Africa suitable coal types are determined by the ratio of volatile compounds to fixed carbon, ash and sulphur contents.[22] Ash content should not exceed 25%, and coals with a sulphur and phosphor content of 0.7-0.9% and up to 0.07% respectively have been used.[26] The U.S. is a net importer of metallurgical coke and coal.[28] Because in the U.S. large fields of suitable coal types can be found, smelt reduction will reduce the need for importing and using expensive metallurgical coal. Capital costs of modern blast furnace-based plants are high. The investments involve coke plants, ore preparation (sintering, pelletization) and the blast furnace. Economies of scale typically result in large scale primary steel plants. Blast furnace plants are estimated to cost approximately 330-350 US$(1990)/thm annual capacity.[19] The capital required for a commercial sized CCF plant are estimated to be 150-180 US$/thm annual capacity.[19] The investments required for the COREX-process are estimated to be 210-250 US$/thm capacity (excluding ore agglomeration plant).[19] Also compared to the costs of rebuilding coke batteries (70 US$/thm), or replacement of a coke battery (120 US$/thm) a second generation smelt reduction is attractive. The operating costs of a smelt reduction plant will be significantly lower due to the abandoned processes. The reduction of operation and maintenance costs for the CCF process in Western-European conditions is estimated to be 18 US$/tonne pig iron.[19]

Smelt reduction has environmental advantages. Various environmentally hazardous compounds (e.g. sulphur compounds, poly aromatic hydrocarbons, ammonia) are released in cokemaking, making extensive gas clean-up at the coke plant necessary. Coke making and ore preparation also release large amounts of dust. Inherent to the smelt reduction processing route is the absence of the formation of most of the problematic compounds in coke making, while the fuel gas produced has much lower sulphur content than coke gas. In smelt reduction, hydrocarbons are not condensed,[22] but combusted at the high reactor temperatures. Integration, abandoning coke quenching, and reduced ore handling will reduce the dust emissions. The HIsmelt pilot plant showed relatively low dust rates, and the dust can be recirculated into the process.[20] Another possibility, demonstrated with the CCF, is the use of zinc-containing wastes (dust from secondary steelmaking and blast furnace sludge), as most of the zinc is captured in the gas clean-up, leaving clean iron.[19]

IMPACTS AND OPTIONS FOR THE U.S. INDUSTRY

In the future the industry will continue to face competitive pressures, stressing the need for strategic technology development, as is recognized by the industry.[29] Technology development should take into account both economic and strategic issues, as well as environmental issues. Policy initiatives by DOE ("Industries of the Future") and EPA ("Common Sense Initiative") stress the need for synergetic technology developments. The discussed technologies, i.e. strip casting and smelt reduction, fit in a strategic technological development path with regard to competitive and environmental issues. We will focus on the integrated producers, that are faced with the largest challenges. With respect to *competitiveness* there will be a drive to increase productivity and flexibility. Future steel plants might be smaller, dedicated to certain products, and more flexible. Domestic competition of mini-mills will grow because of strip casting, and the increased use of high quality iron inputs as DRI and iron carbide. Also, increased international competition will put pressure on national and international markets, because of the end of "voluntary import restraints" and increased global trade under WTO (and NAFTA). Where mini-mills have low costs and are competitive, integrated mill products might be especially sensitive to international market changes. Therefore, further cost reductions are needed in integrated steelmaking to compete in future markets. Despite strong improvements, energy efficiency of integrated steelmaking is still low in comparison to other OECD countries, leading to higher energy costs (despite lower energy prices). Capital costs of integrated plants are high compared to mini-mills, stressing the need for low cost production equipment. Also, excess electricity production in smelt reduction makes it possible to reduce the amount of purchased electricity or sell electricity to the grid, which is important in light of the restructuring U.S. power market.

With respect to *environmental* issues the steel industry will be faced with increased demands to reduce the environmental impact. Using conventional technologies this might lead to increased environmental compliance costs. Integrated producers in most industrialized countries are facing similar emission limits [30] and future developments. Major issues are hazardous emissions, from e.g. coke making, ore preparation, and hazardous wastes from e.g. scrap processing. Coke production facilities in the U.S. are generally old, and improving performance may not be cost effective. Future environmental legislation will increase the pressure on coke making facilities, or might lead to increased coke imports, increasing dependence and (possibly) costs, as well as increasing emissions in the producing countries, e.g. China. On the short term increased coal injection rates will reduce the demand for coke, but this is (still) limited to a practical limit of 200 kg/thm for many blast furnaces. Mill dusts (containing various heavy metals) are also recognized as a major problem, and the industry is faced with developing technologies to recover and recycle the materials.

New smelt reduction technology is able to deal with these challenges in a strategic way. Capital cost of smelt reduction technologies are lower than today's technology. Traditionally, capital costs of coke making and the hot strip mill determined the large size of integrated steel plants. The new technologies abandon some processes or dramatically reduce the capital cost by integrating various processes. This enables the design and construction of smaller, more flexible integrated steel plants. Productivity of small plants will be higher due to lower capital costs, lower maintenance costs, as well as lower energy costs. Also, dependence on imported coking coal will be reduced. Smelt reduction makes it possible to abandon coke production and ore preparation, hence abandoning the most important environmental hazardous process stages, reducing the environmental risks of integrated steelmaking. The new technology will reduce the material losses, and makes it possible to recycle iron containing wastes, e.g. mill dusts and sludges, and recover both iron and other metals. Hence, the new technologies will "leap-frog" the current environmental and economic problems faced by the industry. Development and implementation of these new technologies will put the U.S. iron and steel industry ahead of new environmental standards and reduce capital needs for end-of-pipe technology (which can be very expensive, e.g. dry coke quenching).

Barriers to be overcome are the reduced R&D expenditure of the U.S. steel firms, a conservative investment climate at 'big steel', as well as the relative high costs of capital. Over the past 20 years U.S. steel industry's research budgets have been decreasing, and are generally not more than 0.5% of sales.[31] The budgets are much lower than that of major European, Japanese or Canadian steel companies, that spend 1% of sales or more on R&D.[31] The EAF producers have only very limited R&D budgets, and depend more on technology suppliers. The small R&D capabilities of the U.S. steel industry stress the need of national and international cooperation in this field, like the European and Japanese industries do. The U.S. industry also seems to prefer short term investments[31] over more strategic technology developments. The major step in the U.S. steel industry of the past decade is the introduction of thin slab casting by the mini mills to compete "big steel" in a very important market segment. Earlier thin slab casting projects by integrated producers were all canceled in early stages. Currently, all major R&D activities are taking place outside the U.S., despite the interests of the U.S. industry. Capital is expensive in all countries, but it seems that U.S. firms use high "hurdle rates" for investments, also because of low energy prices. Capital rationing is often used as an allocation means for investments within firms, leading to even higher hurdle rates, especially for small projects, that are much higher than the cost of capital on the market.[32] Current growth in the steel market might generate more capital, that can be used strategically to increase competitiveness in the medium to long term.

CONCLUSIONS AND RECOMMENDATIONS

Between 1980 and 1991 energy intensity of the U.S. steel industry has declined by 17%, of which 11%-points are due to efficiency improvements. Considerable potential for energy efficiency improvement can be realized by applying currently 'best available technology'. For the U.S. the technical potential is estimated to be 43±8%, taking the current industrial structure (mix of raw materials used and products produced) into account and the best available technology. The economically profitable potential is estimated to be roughly 10-15%-points lower. The potential for energy efficiency improvement in the U.S. is higher than that in other OECD countries, despite the improvements since 1980. Advanced technologies, such as smelt reduction and near net shape casting, present major opportunities for further reduction in energy consumption at potentially lower costs, as well as environmental benefits. New technologies will "leap-frog" the current environmental and economic problems faced by the industry. Development and implementation of these new technologies will put the U.S. iron and steel industry ahead of new environmental standards and reduce capital needs for end-of-pipe technology. Energy savings for ironmaking are estimated at 30%, while the total energy savings using 'best practice' and new technologies in the total industry are higher. Barriers to be overcome are the reduced R&D expenditure of the U.S. steel firms, a conservative investment climate at 'big steel', as well as the relative high costs of capital. Over the past 20 years U.S. steel industry's research budgets have been decreasing, and are generally not more than 0.5% of sales. The budgets are much lower than that of major European, Japanese or Canadian steel companies, that spend 1% of sales or more on R&D. Technology development by the iron and steel industry should emphasize the major new technologies, also in light of future environmental standards. The industry can take a pro-active position. However, this would need a stronger emphasis on cooperation, increased R&D funds, as well as cooperation with the government (DOE, EPA). Policymakers could press the development of these new technologies, by internalizing environmental and energy efficiency criteria in economic and technology development policies.

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