GREENHOUSE GAS EMISSIONS FROM MAJOR INDUSTRIAL SOURCES – III
IRON AND STEEL PRODUCTION

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Title:	**Greenhouse Gas Emissions From Major Industrial Sources - III Iron and Steel Production**
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Other remarks:

Background to the Study

The IEA Greenhouse Gas R&D programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. The first phase of this Programme concentrated on emissions of carbon dioxide from power generation. In the second and third phase, attention has also been given to other greenhouse gases, notably methane, and a broader range of industrial processes.

Greenhouse gases are produced from a variety of industrial activities. The main industrial sources, other than power generation, are those energy intensive industries that chemically or physically transform materials from one state to another. During these processes many greenhouse gases (carbon dioxide, methane and nitrous oxide) are released. One notable example is the iron and steel industry where considerable amounts of CO_2 are produced. This study is the third in a series to look at greenhouse gas abatement and mitigation options for the energy intensive industries.

The study was undertaken by ECOFYS of the Netherlands.

Iron and steel production overview

The two principal types of steelmaking technology in use today are the primary integrated steel mills and the scrap based mini-mill. These two-production technologies account for 90% of world steel production, 60% in integrated steel mills and 30% in the scrap based mini-mills.

Integrated steel plants typically consists of a coke making facility, ore agglomeration plants, blast furnace(s), basic oxygen furnace plants, continuous casting and rolling and finishing operations. All operations are located at one site. The typical capacity of these plants is 3-5 Mt per year of finished steel. Investment costs for a complete integrated steel plant with a capacity of 5 Mt are estimated at \$2.5-5 billion. However, it is more common that specific operations are replaced instead of building a complete new plant. World-wide the specific primary energy consumption for this process route ranges from 19 to 40 GJ/t product, with the average energy consumption in developing countries of 23 GJ/t product.

In the scrap based mini-mills, steel production processes consists of one or more electric arc furnaces (EAF) and casting, rolling and finishing operations. Scrap is the traditional input, but with the recent shortage of high-quality low-price scrap, scrap substitutes such as direct reduced iron (DRI), are increasingly being used. The typical capacity is 0.5-1.0 Mt crude steel per year. Investment costs for a 1.0 million tonnes plant are estimated at \$50-250 million. The power consumption of state of the art furnaces is 300-350 kWh/t product. Other energy inputs are for oxygen production, carbon powder, electrode consumption and natural gas..

Production from mini-mills has grown, especially in the United States for a number of reasons, which include:

- Their relatively low capital requirements compared to integrated steel plant
- Their flexibility of location compared with integrated steel mills which are dependent on main transportation routes for iron ore and coal.

Results and Discussion

The following areas are described in the report:

- The sources and emissions of greenhouse gases from the iron and steel industry.
- The opportunities identified to reduce greenhouse gas emissions
- The costs of abatement of greenhouse gas emissions
- Projections of future greenhouse gas emissions from the iron and steel industry
- Barriers to the introduction of technology

The sources and emissions of greenhouse gases from the iron and steel industry

The iron and steel industry is the largest energy consuming manufacturing sector in the world. In 1990, the global energy consumption was estimated to be 18-19x10^9 GJ, or 10-15% of the annual industrial energy consumption. The principal greenhouse gas emitted from iron and steel production is CO_2. The associated CO_2-emission is estimated to be 1425 Mt. In 1995 this amount had increased to 1442 Mt CO_2, equalling roughly 7% of global anthropogenic CO_2-emissions. When mining and transportation of ore are included, this share is expected to be near 10% of total emission.

The CO_2-emission associated with the production of one tonne of steel varies depending on the production route, see Table 1 below.

Production Process	**CO_2 Emission (tonnes per tonne product)**
Integrated steel mill	1.6-2.2
Scrap based production in a mini-mill	0.6-0.9
Scrap substitutes (DRI) in a mini-mill	1.4-2.0

Table 1 CO_2 Emissions from Steel Production Processes

In integrated steel plants, the majority of CO_2 emissions (70%) arise from iron production in the blast furnace. Smaller but still significant CO_2 emissions come from rolling and finishing of products (12%), ore preparation (12%) and oxygen and power production (7%). By contrast in scrap based mini-mills the main emissions are from the electric arc furnace (45%), finishing and rolling (36%) and oxygen/power production (16%).

The opportunities identified to reduce greenhouse gas emissions

Several options to abate the emission of CO_2 were identified in the study. These are summarised below:

- *Improvement of the energy efficiency by the introduction of available techniques*. For integrated steel mills 16 separate techniques were identified to improve energy efficiency and 12 for mini-mills. Details of the individual energy efficiency improvements that can be made are given in the main report. The technical potential for energy-efficiency improvement averaged over the world was 23% of the projected unabated CO_2-emission in 2010, which equals about 400 Mt of CO_2. Of this potential emission reduction, approximately 90% may be achieved in integrated steel mills and the remaining 10% in mini-mills.

- *Improvement of the energy efficiency by the introduction of new and emerging techniques.* The main techniques in this category are smelt reduction and near net shape casting techniques. Commercial introduction of smelt reduction is not expected before 2010. The specific energy consumption of an integrated steel mill incorporating all new technologies can be up to 45% lower than current energy consumption.
- *Shift from primary to secondary steel.* The CO_2 emission factor for secondary steel is about 35% that of primary steel production. During recent decades the usage of secondary steel has stagnated, due to technological developments in smelting, casting and processing that led to a decline of amounts of plant and circulating scrap. Primary steel is likely to remain the preferred material for many high-quality products due to its lower content of undesirable residual metals. Furthermore, a shortage of high-grade scrap may limit further growth of the mini-mill capacity. Plants that produce scrap-substitutes (e.g. DRI) will partly fill this gap while exhibiting CO_2-emission factors marginally lower than from integrated steel plants. Due to the complexity of steel product categories and different scrap qualities the reduction potential of a shift from primary to secondary steel was considered to be too hard to project by the consultant.
- *Carbon dioxide recovery from blast furnace gas*. The study has shown that in an integrated steel plant 70% of the CO_2 emitted comes from the blast furnace off gas. It would be technically feasible using available capture technology to decarbonise the blast furnace gas before it is used for heat recovery. It has been estimated that this can be undertaken at costs of \$35/t CO_2 abated. Applying CO_2 capture could add some 15-20% to the cost of steel production. If this technique were applied across the industry it has been estimated that, by 2020, CO_2 emission reductions could be as high as 290 Mt annually. The captured CO_2 could not be utilised within the steel process and would need to be transported away from the site possibly for subsequent geological storage. Mini-mills were not considered since they use electricity for the EAF's and the CO_2 emitted from the power plant would be generated outside the steel plants boundary.
- *Charcoal-based blast furnaces*. This technology is used in Brazil, but this was considered to be a niche operation. Worldwide the potential is limited because of the large land areas required for growing wood for producing charcoal to replace fossil fuel use in iron and steel production.
- *Iron ore reduction with hydrogen*. Direct reduction of iron ore to a low carbon product for use in steel manufacture is already practised. Reduction normally takes place in natural gas or a coal derived reducing gas containing CO, CO_2 and H_2. Direct reduced iron (DRI) has been developed as a low-cost high-quality alternative to scrap steel. DRI is physically similar to iron ore and contains the minerals present in the ore. The low carbon content of DRI means that it cannot be used as the sole raw material in the basic oxygen furnace of an integrated steel plant, and is typically melted in an EAF. A number of DRI processes have been developed although currently their share of the world market is small (6% of world iron production), but this is expected to grow.
- Iron oxide can be reduced by hydrogen alone. A new process has been developed in which hydrogen and iron oxide are injected into a hot plasma and the iron oxide reduced. The technology is still under development and not expected to be commercially available before 2020. A demonstration plant was planned to be constructed in Ireland in 1994 -1996, but the status of this plant is unknown. However, the potential for ore reduction by hydrogen, produced from fossil fuels combined with capture and storage of CO_2, may offer a future route to produce primary steel with very low CO_2-emissions. More research is required to determine the potential of this route and the associated R&D-needs.

Costs of CO_2 abatement

The costs for CO_2 abatement in the iron and steel industry and potential emission abatement are given in Figure 1 overleaf.

The study has indicated that some 20 Mt/y of CO_2 can be abated with net savings of \$310/t CO_2 abated, a further 40 Mt/y at savings of \$150/t CO_2 abated and 60Mt/y at savings of 60/t CO_2 abated. These net savings are achieved principally through efficiency improvements in electric arc furnaces.

A further 220 Mt/y of CO_2 can be abated at savings of between $0 to $60 per tonne, through energy efficiency improvements in finishing and rolling operations, and in the blast furnace. Another 300 Mt/y of CO_2 can be abated at costs between $0 and $50 per tonnes principally by addition of top gas turbines to blast furnaces. A further 30 Mt/y is potentially achievable at costs up to $100/t of CO_2.

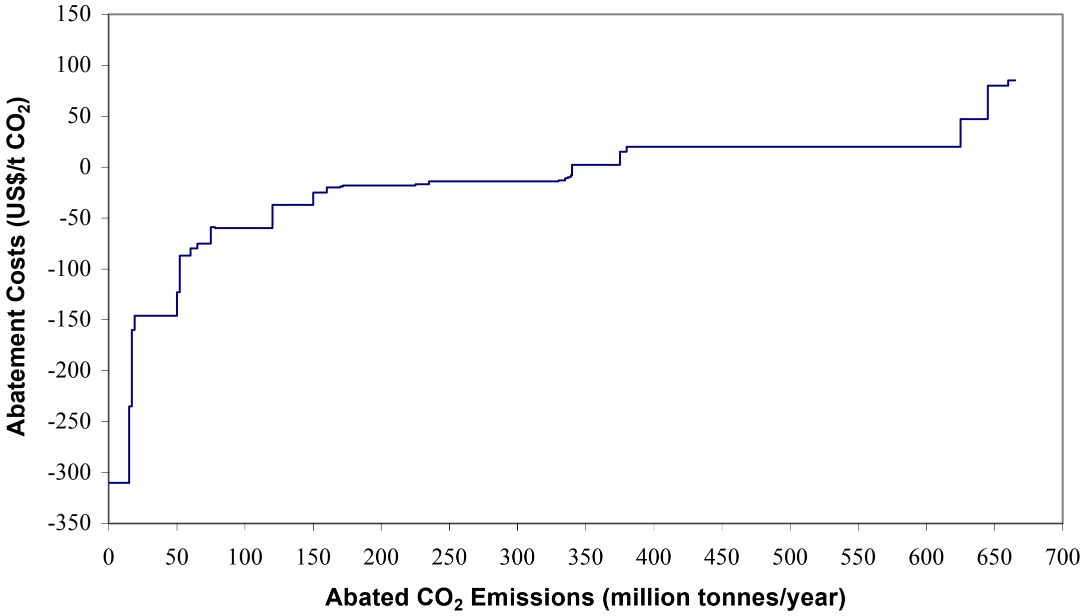

Figure 1 **Greenhouse Gas Abatement Cost Curve for The Iron and Steel Industry**

Projections of future greenhouse gas emissions

Estimates of energy use and emissions until the year 2020 were developed by the consultant for four scenarios. Each scenario assumes a 30% growth in global iron and steel production. The scenarios developed were:

- *Frozen Technology* - this scenario assumes that the industry's energy efficiency levels and emission factors are fixed at 1985-1995 levels in each region. It ignores current industry trends toi improve energy efficiency and reduce emissions and represents a "worst case" scenario.

- *Moderate Change* - or business as usual scenario, assumes that the existing energy efficiency measures now underway are taken up by the industry principally within Europe and no diffusion of new technology even for new capacity overseas.

- *Accelerated Change* - this scenario assumed increased implementation of energy efficiency measures in the developed countries and the introduction of new and emerging production techniques for all new capacity in China Russia and Eastern Europe and a reasonable percentage of older less efficient plant are closed.

- *Wonderful World* - the fourth scenario assumes a rapid transition of plant in developing countries to meet Western best practise efficiency standards through accelerated introduction of new and emerging technologies and closures of old plant, the introduction of CO_2 capture on blast furnces worldwide and a larger world market for scrap steel.

The projected CO_2-emissions from these scenarios are given in Figure 2 overleaf.

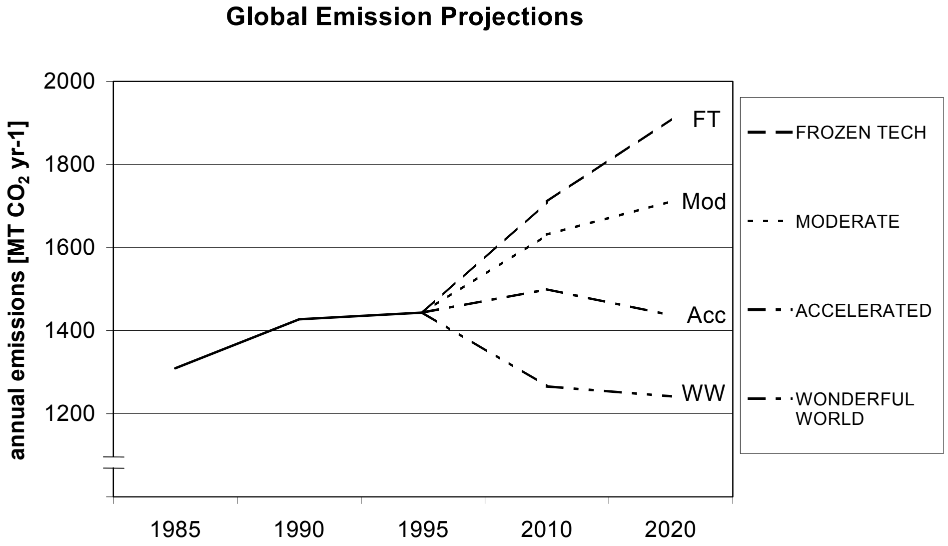

Figure 2 **Projected Global Emissions for the Iron and Steel Industry.**

In the Frozen Technology scenario it was estimated that by 2020 the global emissions of CO_2 would rise by 440 Mt per annum. In the "Moderate Change" scenario (designed to resemble business-as-usual) emission increases by 2020 will be some 250 Mt per year. This rise is largely due to increased production in China, Russia and Eastern Europe. In the more radical scenarios "Accelerated Change" indicates that emissions will be stabilised at 1995 levels by 2010 and only the "Wonderful World", indicates potential emission reductions of 200 Mt/y by 2020 compared to 1995 base levels

Barriers to the introduction of new technology

A number of non-technological barriers that affect the uptake of CO_2-abatement options in the iron and steel industry were identified, these are:

- *Environmental legislation*. Especially for sinter plants and coke ovens, environmental standards force integrated steel manufacturers to look for alternatives. Since smelt reduction is an option that avoids the use of both sinter and coke, the uptake of this technology may be accelerated by more stringent environmental standards.
- *Capacity development*. It is not expected that new primary steel making capacity will be built in developed countries. CO_2-abatement in these countries should, therefore, come from retrofit options. In developing countries new capacity is expected. Technology transfer through Joint implementation and CDM[1] actions could be used to ensure that the latest technologies would be used.
- *Market and product development*. Primary steel manufactures are constantly developing their products to keep a commercial edge over secondary steel production. Technological developments are directed at steel cleanliness, surface appearance and gauge control. In the automotive industry, steel has a competitor in aluminium. Although the discussion on the effect on CO_2-emission is still ongoing, it forces the steel industry to pay considerable attention to product innovation.
- *Cost reduction*. Processes in an integrated steel mill are very expensive. Eliminating one or more processes is therefore very attractive. This is a major driver for the development of smelt reduction and near-net-shape-casting techniques. Increased levels of pulverised coal injection can also avoid new coke making capacity.

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[1] Clean Development Mechanisms

- *Investment risks*. The development of new and emerging processes often involves large investments. Steel companies are not always willing to take the financial risk alone. At least in one case this has led to a postponement of the development of a new reduction technology

Expert Group Comments

The expert reviewers who assisted in the review were drawn largely from the iron and steel industry. The comments drawn from the experts were generally complimentary of the study. A large number of Comments received were editorial. A number of the reviewers questioned the cost data and emission data given for certain technologies. A significant number of technical points relating to the discussions on technologies for steel manufacture were made particularly by the industry representatives and in a number of places supplementary data was supplied. One reviewer questioned the use of a 5% discount rate, which was considered to be too low from an industry perspective. This point was accepted but IEA GHG standard practice is to use a 10% discount rate in all studies so that the abatement costs are comparable. All the points made have been reconciled and corrected.

Major Conclusions

The study has shown that the iron and steel industry is the largest energy consumer of the manufacturing industries. The iron and steel industry is also a significant emitter of greenhouse gases, principally CO_2. In 1995 the iron and steel industry emitted 1442 Mt of CO_2, equivalent to 7% of global anthropogenic CO_2 emissions. The CO_2 emission per tonne of product varies considerable depending on the production process, however the majority (70%) of emissions comes from iron production in the blast furnace of an integrated steel plant.

A number of abatement opportunities were identified within the steel plant to reduce CO_2 emissions which include energy efficiency improvements introduction of new more efficient technology and increased use of scrap. CO_2 emissions from scrap based mini-mills are about one third of those from integrated steel plants. However, the introduction of this technology is limited by the availability of high quality scrap. Costs of abatement vary considerably. The study has indicated that some 20 Mt/y of CO_2 can be abated with net savings of \$310/t CO_2 with a further 40 Mt/y at savings of \$150/t CO_2 and 60 Mt/y at savings of \$60/t CO_2. A further 220 Mt/y of CO_2 abated at savings of \$0 to \$60 per tonne, whilst another 300 Mt/y of CO_2 can be abated at costs between \$0 and \$50 per tonnes.

Deep reductions in CO_2 emissions from iron and steel plants could be achieved by applying CO_2 capture technology to the blast furnace off gases at a cost of \$35/t. Utilisation of the captured CO_2 is not feasible in the iron and steel plant and would therefore need to be transported outside the plant boundary for storage. Alternately a new technology for ore reduction by hydrogen, provided that it is produced from carbon free sources, may be a route to produce primary steel with very low CO_2-emissions. However, more research is required to determine the potential of this route and the associated R&D-needs.

Recommendations

The study has indicated the potential for reduction in greenhouse gas emissions from the iron and steel industry through the transfer of more energy efficient technology. Technology transfer from the western countries to countries such as Russia and China and Eastern Europe might be assisted by mechanisms such as Joint Implementation and the Clean Development Mechanism.

The study has highlighted the potential use of hydrogen for iron ore reduction in the iron and steel industry. As determined in other IEA GHG studies, the generation of hydrogen from fossil fuels can be combined with decarbonisation and storage of CO_2. The potential for using fossil fuel based hydrogen in the steel industry could be considered in detail in a further study, since it offers the potential for deep reductions in CO_2 emissions in an industry which is currently a significant emitter of greenhouse gases. This study should focus on the potential for hydrogen reduced iron in steel manufacture, the status of current technology developments, the future R&D needs to introduce this technology as well as the potential CO_2 reduction attainable globally by the introduction of such technology.

Greenhouse Gas Emissions from Iron and Steel Production

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October 2003

By order of the IEA Greenhouse Gas R&D Programme

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EXECUTIVE SUMMARY

In this report an assessment of the greenhouse gas emissions arising from the production of iron and steel and of ways to abate these emissions is presented. The report is prepared by order of the IEA Greenhouse Gas R&D Programme which is systematically evaluating the costs and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels.

The iron and steel industry is the largest energy consuming manufacturing sector in the world. In 1990, its global energy consumption was estimated to be 18-19 exajoule (EJ), or 10-15% of the annual industrial energy consumption. The associated CO_2-emission is estimated to be 1425 Mtonne. In 1995 this amount had increased to 1442 Mtonne CO_2, equalling roughly 7% of global anthropogenic CO_2-emissions. When mining and transportation are included this share is expected to near 10% of total emission.
In the last decade considerable changes occurred in the division of the CO_2-emissions of the iron and steel industry over world regions. This is due to a decline in production and emissions in the countries of the former Soviet Union and Eastern Europe on the one hand, and due to a rapid increase of production and emissions in China and other dynamic developing countries on the other hand.

Currently, two processes dominate the global steel production: (a) the integrated steel mill in which steel is made by reducing iron ore in a blast furnace and subsequent processing in an oxy-steel plant; (b) the minimill in which steel is made by melting scrap or scrap substitutes in an electric arc furnace. Other process that are in use are either outdated, e.g. the open-hearth furnace, or so new that their share in the world steel production is still small, e.g. direct reduction and smelt reduction processes.

The CO_2-emission associated with the production of one tonne of steel varies strongly depending on the production route. The CO_2-emission of one tonne of steel made in an integrated steel mill is 1.6-2.2 tonne. This is two and half times the emission of one tonne of steel made out of scrap in a minimill (0.6-0.9 tonne). The CO_2-emission of one tonne of steel made through direct reduction and a minimill is 1.4-2.0 tonne and in through a blast furnace and an open hearth furnace 2.5-3.1 tonne.

There are also large differences between CO_2-emission factors of steel making between world regions. This is due to differences in efficiency of the processes and fuel input and due to a different pace of penetration of new technologies. The outdated open hearth furnace has been completely replaced by the oxy-steel process (first introduced in the 1950s) in the developed countries. In the former Soviet Union, however, this process is still in operation. China also still operates open hearth furnaces, but intends to have them all closed by 2000. At the moment, the CO_2-emission factor for steel of China is a factor 2 higher than in the European Union and Nafta-countries.

Several options exist to abate the emission of CO_2. These are:

- *Improvement of the energy efficiency by the introduction of available techniques*. For integrated steel mills 16 techniques have been identified and for minimills 12. The technical potential for energy-efficiency improvement averaged over the world is 23% of the unabated CO_2-emission in 2010, which equals about 400 Mtonne of CO_2. Of this potential emission reduction, approximately 90% may be achieved in integrated steel mills. The remaining 10% has to be realised in minimills.
- *Improvement of the energy efficiency by the introduction of new and emerging techniques.* The main techniques in this category are smelt reduction and near net shape casting techniques. Commercial introduction of smelt reduction is not expected before 2010. The specific energy consumption of an integrated steel mill incorporating all new technologies can be 45% lower than the current world average. If a penetration rate of new technologies of 1% per year can be achieved, the abated CO_2-emission will be about 95 Mtonne in 2020.
- *Shift from primary to secondary steel.* The CO_2 emission factor of secondary steel is about 35% of that of primary steel. During recent decades the usage of secondary steel has stagnated. This was due to technological developments in smelting, casting and processing that led to a decline of amounts of plant and circulating scrap. Primary steel is likely to remain the preferred material for many high-quality products due to its lower content of undesirable residual metals. Furthermore, a shortage of high grade scraps may limit further growth of the minimill capacity. Plants that produce primary iron scrap-substitutes (e.g. direct reduced iron) are partly filling this gap while exhibiting CO_2-emission factors similar to the conventional blast furnace route. Due to the complexity of steel product categories and different scrap qualities the reduction potential of a shift from primary to secondary steel is hard to project.
- *Carbon dioxide recovery from blast furnace gas*. Decarbonising blast furnace gas before use can be done at costs of US\$35/tonne CO_2. Transportation and storage of CO_2 will add US\$8-20/tonne CO_2 (at a transportation distance of 100 km). In 2020 this could contribute 290 Mtonne to the CO_2-emission abatement.
- *Charcoal-based blast furnaces.* A technology being used in Brazil. However, the potential is limited because the large surface area required for growth of wood for producing charcoal.
  - *Iron ore reduction with hydrogen*. Iron ore can be reduced by hydrogen. This is already done in direct reduction processes. A new process, that was tested, is based on plasma technology. This process is still under development and not expected to be commercial before 2020. However,

ore reduction by hydrogen, provided that it is produced from carbon free sources, may be a route to produce primary steel with very low CO_2-emissions. More research is required to determine the potential of this route and the associated R&D-needs.

Non-technological aspects that affect the uptake of CO_2-abatement options are:

- *Environmental legislation*. Especially for sinter plants and coke ovens environmental standards force integrated steel manufacturers to look for alternatives. Since smelt reduction is an option that avoids the use of both sinter and coke, the uptake of this technology may be speeded by more stringent environmental standards.
- *Capacity development*. It is not expected that new primary steel making capacity will be built in developed countries. CO_2-abatement in these countries should therefore come from retrofit options. In developing countries new capacity is expected. Joint implementation can be used to ensure that the latest technologies will be used.
- *Market and product development*. Primary steel manufactures are innovating their products to keep an edge over secondary steel. Technological development is directed at steel cleanliness, surface appearance and gauge control. In the automotive industry steel has a competitor in aluminium. Although the discussion on the effect on CO_2-emission is still ongoing, it forces the steel industry to pay attention to product innovation.
- *Cost reduction*. Processes in an integrated steel mill are very expensive. Eliminating one or more processes is therefore very attractive. This is a major driver for the development of smelt reduction and near-net-shape-casting techniques. Increased levels of pulverised coal injection can also avoid new coke making capacity.
- *Investment risks*. The development of new and emerging processes often involves large investments. Steel companies are not always willing to take the financial risk alone. At least in one case this has lead to a postponement of the development of a new reduction technology.

Four scenarios were developed to assess the possible CO_2-emission in 2010 and 2020. These scenarios are called: Frozen Technology, Moderate Change, Accelerated Change, Wonderful World. The scenarios differ in the development of energy efficiency per world region. This reflects differences in assumed diffusion of technologies over world regions. The CO_2-emission projected according to this scenarios is depicted in Figure S.1.

We can reflect the potential emission abatement that can be attained by implementing the options described in this report against the Frozen Technology scenario. The economic potential, using a discount rate of 5% (the standard in IEA Greenhouse Gas Programme studies) and a technical lifetime that differs per option, is estimated at 440 Mtonne CO_2 in 2010 and at 590 Mtonne CO_2 in 2020. These emission reductions correspond to 25% and 31% of the CO_2-emission in 2010 and 2020 respectively according to the Frozen Technology scenario. When CO_2-removal from blast furnace gas is also taken into account, these percentages increase to 40% and 46% respectively. However, CO_2-removal costs about US$40-60/tonne CO_2.

A scenario “Moderate Change” is designed to resemble business-as-usual. According to this scenario the CO_2-emission in 2020 will be 1,700 Mtonnes, equalling a 10% reduction compared to a “Frozen Efficiency Scenario” with 1,900 Mtonnes. In the “Moderate Change” scenario the CO_2-emission factors are reduced by 10% in the European Union and Nafta-countries and the difference in energy efficiency of the other regions with EU/NAFTA is reduced by 35%. The more radical scenarios “Accelerated Change” and “Wonderful World” assume that by 2010 the energy efficiency gap between further improved EU/NAFTA values and other world regions is reduced by 65% and completely disappears, respectively. The projected global emission levels for 2020 are 1,400 and 1,200 Mtonnes per year equalling reductions by 15% and 25% against business-as-usual and 25% and 35% against the “Frozen Efficiency Scenario.”

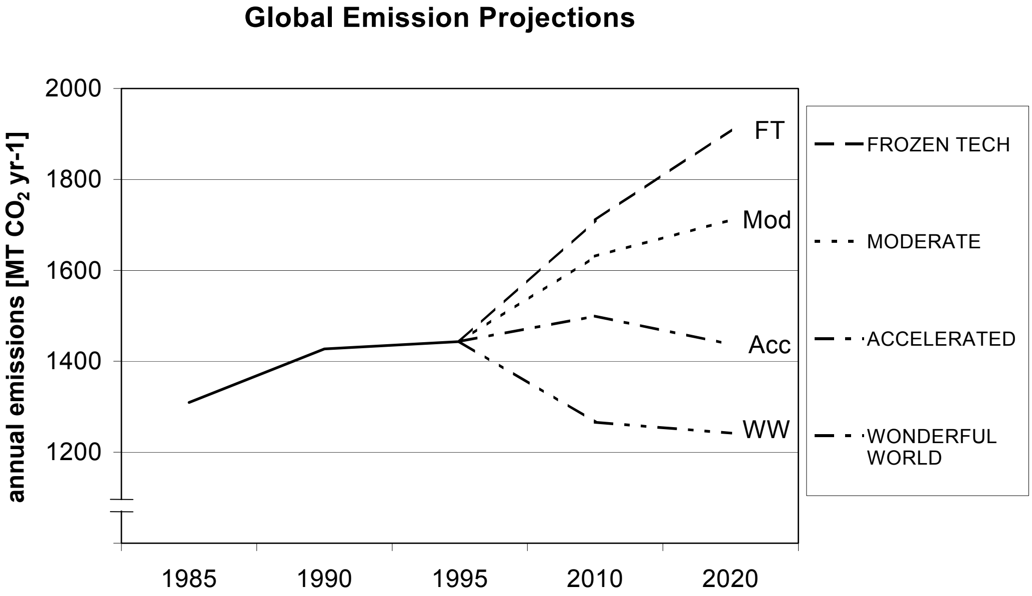

Figure S1: Projected global emission for the four scenarios.

CONTENTS

ABBREVIATIONS

thm	tonne of hot metal
tcs	tonne of crude steel
tpi	tonne of pig iron
ths	tonne of hot rolled steel
tls	tonne of liquid steel
EU15	The 15 members states of the EU
Nafta	
OTH EUR	European countries, not member of EU
FSU	Countries of Former Soviet Union
EET	Eastern Economies in Transition
ROW	Rest of the World
RC or Remco	Remaining countries
EAF	Electric arc furnace
BF	Blast furnace
CO	Coke oven
BOF	Basic oxygen furnace
SR	Smelt reduction
DR	Direct reduction
EJ	Exajoule (= 10^{18} Joule)
PJ	Petajoule (= 10^{15} Joule)
TJ	Terajoule (= 10^{12} Joule)
GJ	Gigajoule (= 10^{9} Joule)
MJ	Megajoule (= 10^{6} Joule)
Mtonne	Million metric tonnes

1. INTRODUCTION

The IEA Greenhouse Gas R&D Programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. The first and second phase of this program were directed at power generation and non-CO_2 greenhouse gases. The third phase deals with a broader range of industrial processes.

In this report an assessment of the green house gas emissions arising from the production of iron and steel and of ways to abate these emissions are presented. The iron and steel industry is the largest energy consuming manufacturing industry in the world. In 1990, its global energy consumption was estimated to be 18-19 exajoule (EJ), or 10-15% of the annual energy consumption [WEC, 1995]. The associated CO_2-emission is estimated at 1425 Mtonne of CO_2[1] (see later in this report). The annual steel production increased from about 100 million tonnes in 1945 to about 770 million tonnes in 1990 [IISI, 1996a]. Global steel production is expected to grow further, by about 1.7% a year, mainly because of an increase in steel production in developing countries [WEC, 1995; Tilton, 1990]. The apparent steel consumption per capita in these countries is only one seventh of that in OECD-countries, but this situation is likely to change [WEC, 1995]. Whereas the crude steel production in OECD-countries has remained fairly stable at 320-370 million tonnes since 1980, the production in developing countries is growing steadily at a rate of more than 6% annually to reach about 240 million tonnes in 1993 [WEC, 1995]. This growth is expected to continue. As a result, global steel production might rise to 1280 million tonnes in 2020, assuming a business-as-usual scenario. In this scenario the global energy consumption of the iron and steel industry is projected to increase to more than 25 EJ in 2020 [WEC, 1995]. The associated CO_2-emission might rise to about 1700 Mtonnes.

Currently, two processes dominate the global steel production: (a) the integrated steel mill in which steel is made by reducing iron ore in a blast furnace and subsequent processing in an oxy-steel plant; (b) the minimill in which steel is made by melting scrap or scrap substitutes in an electric arc furnace. Other processes that are in use are either outdated, e.g. the open-hearth furnace, or so new that their share in the world steel production is still small, e.g. direct reduction and smelt reduction processes. To be able to put all these technologies into perspective, a brief historical development of iron and steel making is given in Chapter 2. All currently employed steel making routes will be described in more detail in Chapter 3.

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[1] In this report carbon dioxide emissions are expressed in million metric tonnes of CO_2 (Mtonne CO_2). To obtain Mtonne of C multiply by 0.273.

In Chapter 4 the specific energy demand and the associated CO_2-emission of four steel making routes are determined. Besides the two aforementioned routes, the integrated steel mill and the minimill, a route consisting of a direct reduction process and a minimill and a route including an open hearth furnace are considered.

Chapter 5 presents an estimate of the emissions of CO_2 from the operations in iron and steel production per world region. The world regions are composed on the basis of comparative penetration and efficiency of processes. A method was developed that is based on a bottom-up analysis using available national data. The guiding principle was to use a consistent method that would treat all countries uniformly and avoid discrimination because of unavailability or availability of country specific studies on this topic.

Chapter 6 deals with options to reduce the CO_2-emission from iron and steel production. Options that will be discussed are: improvement of the energy efficiency, shift from primary to secondary steel, alternative fuels and reducers (charcoal, hydrogen) and CO_2-recovery and storage from blast furnace gas. Improvement of the energy efficiency is an important option in this context. Available techniques to improve the energy efficiency of integrated steel mills and minimills are described. Details on improvement potential and costs are given. The information is used to construct so-called CO_2-abatement curves. New and emerging techniques are also described.

Chapter 7 deals with other non-technological issues that affect the deployment of options to reduce the emissions of greenhouse gases. These issues are categorised into economic and organisational factors, current and future environmental legislation, flexible measures for climate change policy (clean development mechanism, joint implementation and emission trading), market trends and drives and product development.

To get insight into the possible development of the emission of CO_2 up to 2010 and 2020 from iron and steel production scenario modelling is used. Chapter 8 describes four scenarios that differ in assumptions regarding the development of technologies and the diffusion of technologies over world regions.

Finally, in chapter 9 the key findings of the study are summarised.

2. HISTORICAL DEVELOPMENT AND CURRENT STATUS

2.1 HISTORICAL TRENDS IN IRON AND STEEL PRODUCTION

In this section a brief history of the major iron and steel making processes is presented. The aim is to place these processes in a historical perspective and to describe energy-efficiency improvement in the past. We first discuss the main processes involved in the making of pig iron, which is reduced iron ore that still contains impurities, mainly carbon. Then, we deal with the main processes used to improve the quality by removing impurities, with an emphasis on steel making processes.

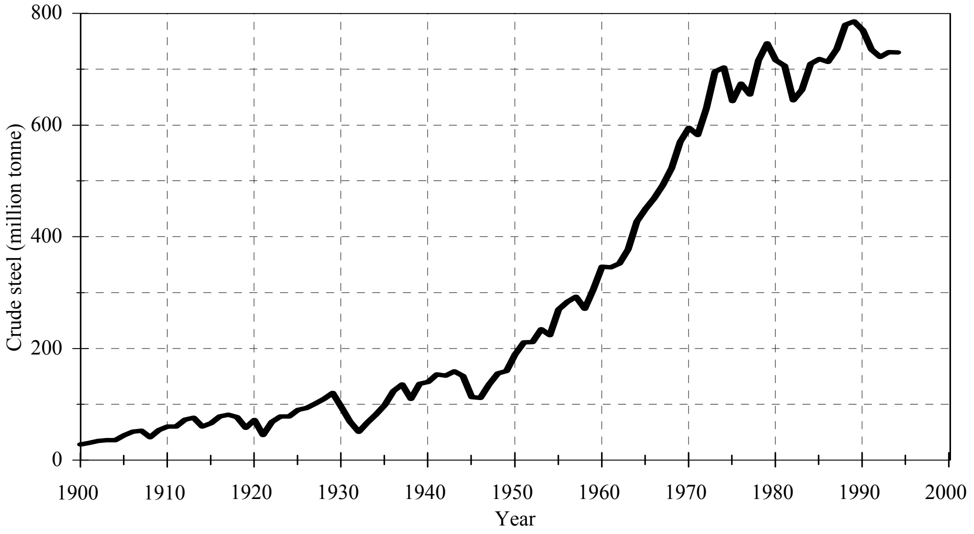

Figure 2.1: Development of the world crude steel production from 1900 to 1994 [IISI, 1993, 1996a].

2.1.1 History of iron making

The first record of the use of iron goes back to 2500-2000 BC [Chatterjee, 1996]. It is believed that in that period iron was not produced deliberately but was obtained from natural resources, e.g. meteorites [Kirk-Othmer, 1981]. Deliberate production of iron began in about 1300 BC with the use of charcoal as fuel and reducer, in small furnaces that made use of cold air. Evidence for the existence of such furnaces has been found in Africa, Asia and in Central Europe [Kirk-Othmer, 1981; Juleff, 1996]. The temperature that could be achieved in these furnaces was probably below the melting point of iron. The product had to be hammered for it to be freed from slag and to make wrought iron. When better blowing devices were introduced, the temperature could be raised, and liquid, high-carbon iron was formed. In 1300 AD the Stuckoven was introduced in Germany. Although the Stuckoven was only 3-5 m high and 1-1.2 m in diameter [Ottow *et al,* 1994], its design was essentially the same as that of the modern blast furnace. Charcoal was used as fuel. Based on data on the use of charcoal to produce pig iron and bar steel in the United Kingdom in the period 1540-1760 [Jeans, 1882; Hammersley, 1973] we can make an estimate of the reduction in the energy demand in this period. The charcoal consumption to make pig iron decreased from 5.5 to 2 loads[2] of charcoal per tonne of pig iron in this period. This is an improvement in energy efficiency of about 0.5% a year. Pig iron was converted to bar steel in the finery process. Between 1540 and 1760 the energy demand for the finery process decreased from 16 to 4 loads per tonne of bar steel, or a decrease of 0.6% a year [Hammersley, 1973]. Because both the demand for charcoal used for steel making and the amount of pig iron needed per tonne of steel decreased, the overall energy efficiency improvement is greater than 0.6% a year [Hammersley, 1973].

Because of the weak structure of charcoal, the height, thus the capacity of the blast furnaces was limited. This is because the coal in the mix forms the supporting structure of the furnace charge. Coke is much stronger and does not have this disadvantage. Coke was first used around 1718, but its application in the United Kingdom remained limited to one site until the 1750s [Hyde, 1977]. Before 1750 charcoal was cheaper than coke, but this situation changed in the period 1750-1790. In addition, the amount of coke required for pig iron reduction decreased markedly in this period [Hyde, 1977]. In 1750 coke pig iron made up 5% of the total UK pig iron production; by 1790 it made up 90% [Hyde, 1977]. The development of the average coke consumption for pig iron production from the time when coke-fired blast furnaces were introduced is shown in Figure 2.2 [Heal, 1997; IISI, 1996b] Three main periods of energy efficiency improvement can be distinguished. First, in the period of the first diffusion of the process, between 1760 and 1800, a reduction in the coke demand of almost 2% a year was achieved, mainly by the introduction of steam engines, which permitted the use of higher blast pressures [Heal, 1975]. Second, in the 19th century the coke demand declined further, by an average of 1% a year. The use of regenerators to preheat the blast accounted for much of this reduction. Finally, in the period 1950-1990, reduction of demand for coke was 3.4% a year on average 3.4%. This reduction in demand was achieved by, for instance, increasing the iron content of the ore, using ore agglomeration, raising the temperature of the hot blast, and the use of blast furnaces with a larger inner volume. On average an improvement in the energy efficiency of iron making of 1.4% a year was achieved in the period 1760-1990.

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[2] At that time charcoal was delivered in cartloads to the ironworks. A “load” did not have a standard measure. Hammersley [Hammersley, 1973] gives a range of 13.5-17.5 hundredweight (cwt) (1 cwt is about 50 kg) for a load of charcoal. Assuming an average lower heating value of 29.5 GJ/tonne [Rossillo-Calle *et al.*, 1996], 1 load of charcoal equals 20-26 GJ.

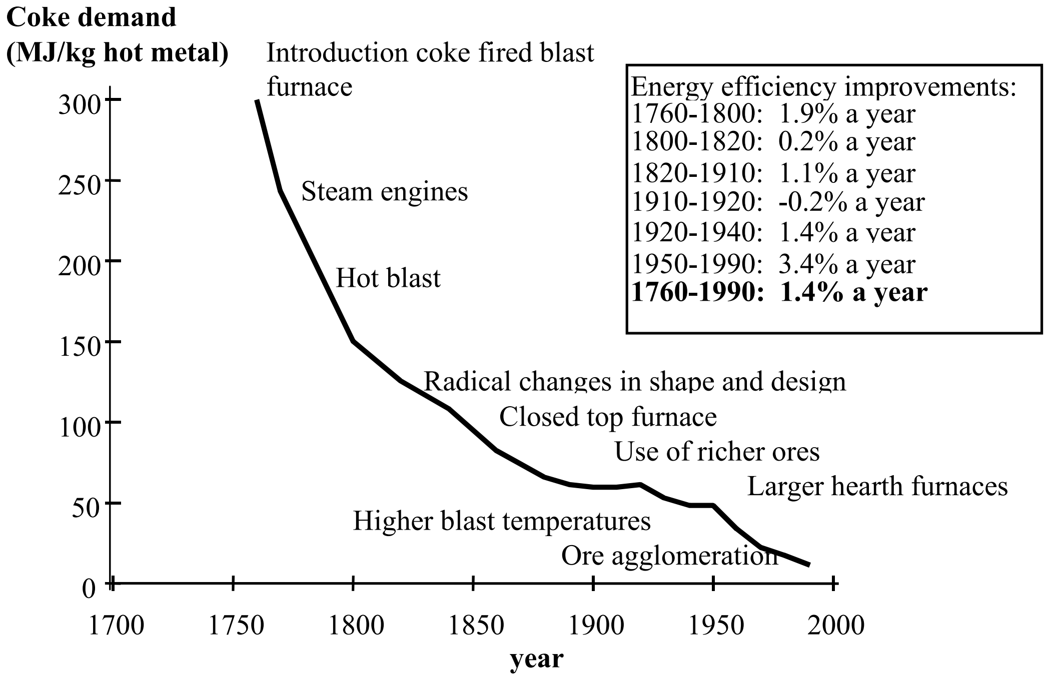

Figure 2.2: Development of the coke demand for pig iron making [Hammersley, 1973; IISI, 1996b]. It is also indicated when new technologies were introduced.

Up to the 1960s the blast furnace was the main process for reducing iron oxide. Direct reduction processes have been in use since ancient times, but gained renewed interest in the 1960s. Several direct reduction processes have been developed and are now in use. From a more recent date are the smelting reduction processes, which are still under development. These two processes are discussed later in this report.

2.1.2 History of steel making

Table 2.1 gives an overview of the history of processes to upgrade the quality of pig iron and steel making processes. Three lines of development are distinguished: (a) refining processes, (b) (re)melting processes, and (c) processes that both refine and melt. In refining processes, carbon and other impurities present in pig iron, like silicon and manganese, are removed. In this line of development we also consider processes that free the pig iron from slag. The product is not steel but is, for instance, wrought iron. Melting processes are processes whereby the steel is melted only to be cast steel. Because no refining takes place, the composition of the feed should equal the composition of the desired product.

Table 2.1: History of steel-making processes[a]. Approximate dates of first industrial application are shown in parenthesis.

Year	Refining processes	Refining and melting processes	Melting processes
	Finery (from 12th century)[b]		Crucible (18th century)[b]
	Puddling (1785)[b]		
1850	Bessemer (1860)	Open Hearth Furnace (1864)	
	Thomas (1878)		
1900			Electric Arc Furnace (1900)
1950		Basic oxygen furnace (1952)	
		Oxygen bottom blowing (1967) Combined blowing (1970)	UHP-EAF (1970) DC-EAF (1985)
2000			

[a] Based on [Faure, 1993] and [Kudrin, 1985].
[b] Based on [Kudrin, 1985].

The oldest process for refining iron is the inefficient, charcoal-fuelled, finery process, which was widely used in the 11th and the 12th centuries [Kudrin, 1985]. The product was wrought iron rather than steel. At the end of the 18th century the puddle process was introduced. First it was used to make iron, but around 1850 it was converted to make steel by refining pig iron on the hearth of a reverberatory furnace. The product of a puddle process was semifluid steel, which had to be forged. However, the technique had limited success.

In 1855 Bessemer obtained a patent on a new process, at present known as the Bessemer converter. In 1860 the first Bessemer process went into operation [Rosenberg, 1982; Kudrin, 1985]. The principle of the Bessemer converter is still followed: The oxidation of carbon and other impurities provides enough heat to melt the metal. In the Bessemer converter cold air was blown from the bottom through a refractory-lined vessel. In theory, no additional fuel was required. In practice, about 1 tonne of coal per tonne of steel was consumed [Rosenberg, 1982], equal to about 30 GJ/tonne steel. Other advantages were the reduced refining time and investment costs. However, there were several disadvantages: It was impossible to remove sulphur and phosphor; the product became brittle after some time because of the large quantities of nitrogen dissolved in the steel; and the process of oxidation was so fast that is was very difficult to control the product quality [Rosenberg, 1982].

In 1878 an adapted version of the Bessemer process, the Thomas process, was introduced. This process allowed the production of low-phosphorus steel from high-phosphorus pig iron. The Thomas process used a basic refractory lining instead of the acid refractory lining of the Bessemer process; it is therefore also called the Basic Bessemer process [Kudrin, 1985].

In the meantime the Open Hearth Furnace (OHF) (or the Siemens-Martin furnace) was developed in France. In an OHF pig iron and scrap are melted on a hearth of a reverberatory furnace by the heat of a flame. The OHF resembles the puddle process; the difference is that in the OHF air and gaseous fuel are preheated by heat exchanging with the combustion gases in what was called a regenerative gas furnace [Siemens, 1873]. With the regenerative gas furnace it was possible to attain temperatures sufficiently high to melt steel. The process had two main advantages over the Bessemer process: (a) pig iron and scrap of any composition could be melted and (b) good control of the steel quality was possible. The price paid for this was higher investment, higher energy consumption and longer refining time.

In 1952 another new process for steel making was introduced: the Basic Oxygen Furnace (BOF). The process is also know as the Linz-Donawitz (LD) process, named after the two cities where the Austrian steel company VOEST built the first two BOFs. A BOF is an improved version of the Bessemer process. Oxygen is blown through a water-cooled lance from the top into the converter. The advantages of using pure oxygen instead of air are that the gas volume to be heated and compressed is smaller, no nitrogen can dissolve in the metal, and the heat generated by the oxidation of impurities is greater and adequate to melt 20-30% additional scrap. The BOF had a far better energy efficiency than the OHF and refining was ten times faster. The idea of using oxygen was already mentioned by Bessemer in 1856. Two factors impeded earlier implementation. First, industrial methods for producing large quantities of oxygen became available only around 1950. Second, experiments were initially directed at blowing oxygen from the bottom into the converter. This configuration generated so much heat that the tubes through which the oxygen was blown (tuyeres) could withstand only one single heat [Kudrin, 1985]. In the 1970s several processes were developed that used the concept of bottom-blowing. Currently, combined blowing processes, i.e. processes that combine the advantages of top- and bottom-blowing, are in operation at some sites (e.g. OBM and Q-BOP). The state-of-the-art process is a basic oxygen furnace that uses top-gas-recovery and additional scrap melting. Not all impurities are removed in the BO. Further refining takes place in 'ladle furnaces'. Modern BOFs are net energy producers.

The oldest melting process is the crucible process. A closed pot with an average capacity of 25-35 kg - the crucible - was filled with solid wrought iron and heated in a shaft furnace [Kudrin, 1985]. The process required a charge with a composition close to that of the product [Kudrin, 1985] and about 7 tonnes of coke per tonne of steel [Rosenberg, 1982].

A completely different route to steel is the melting of iron in a bath at a high temperature achieved with the help of electric arcs: the Electric Arc Furnace (EAF). First introduced in the late nineteenth century, its application was limited to special steels [Rosenberg, 1982]. At present EAFs are used to produce a whole range of products. EAF technology is very flexible with respect to inputs. All types of iron can be handled as can 100% scrap. Furthermore, it can be built separately from blast furnaces and coke ovens. Performance of EAFs has improved tremendously. In the period 1965-1990 electricity demand declined from 630 to 350 kWh/tonne steel (2.3% a year on average) and electrode consumption declined from 6.5 to 2.2 kg/tonne (4.2% a year on average). Nowadays, refining also takes place in the EAF with the help of oxygen being blown into the furnace.

2.2 THE CURRENT SITUATION

2.2.1 Physical output and specific energy consumption

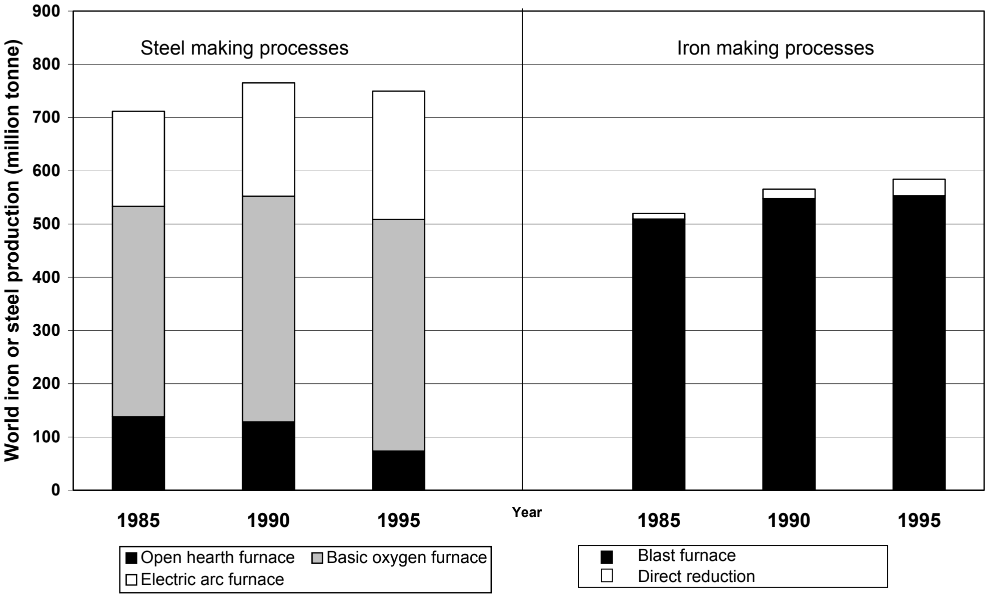

Figure 2.3: Production volumes of the main iron and steel production processes in 1985, 1990 and 1995 [IISI, 1993, 1997].

Figure 2.3 shows the proportion of different iron and steel production processes in the world production of iron and steel. The blast furnace is the most widely used production process for iron. The Basic Oxygen Furnace is still the main steel production technology, but the proportion of the Electric Arc Furnace is increasing steadily. Three steel production routes are illustrated schematically in Figure 2.4. This figure gives also specific energy consumption (SEC), expressed in GJ primary energy per tonne of crude steel (GJ/tcs), for the different production routes [Worrell, 1995]. The SECs represent best-practice values, i.e. the lowest values actually achieved in one plant. As can be seen from the Figure, the SEC differs considerably depending on the process route. Even large differences in SEC occur with the same production method. The

SEC for an integrated primary steel mill varies from 19 to 40 GJ/tcs [WEC, 1995]. The direct reduction-electric arc furnace (DR-EAF) production route shows less variation in SEC, because the technology is newer and there are far fewer plants in operation. EAF steel making itself has become far more efficient over the past 25 years, as we have shown.

Old EAF plants have a SEC that is considerably higher than that given in Figure 2.4. World-wide average SEC for steel making in 1990 is estimated to be on the order of 24 GJ/tcs[3] [WEC, 1995].

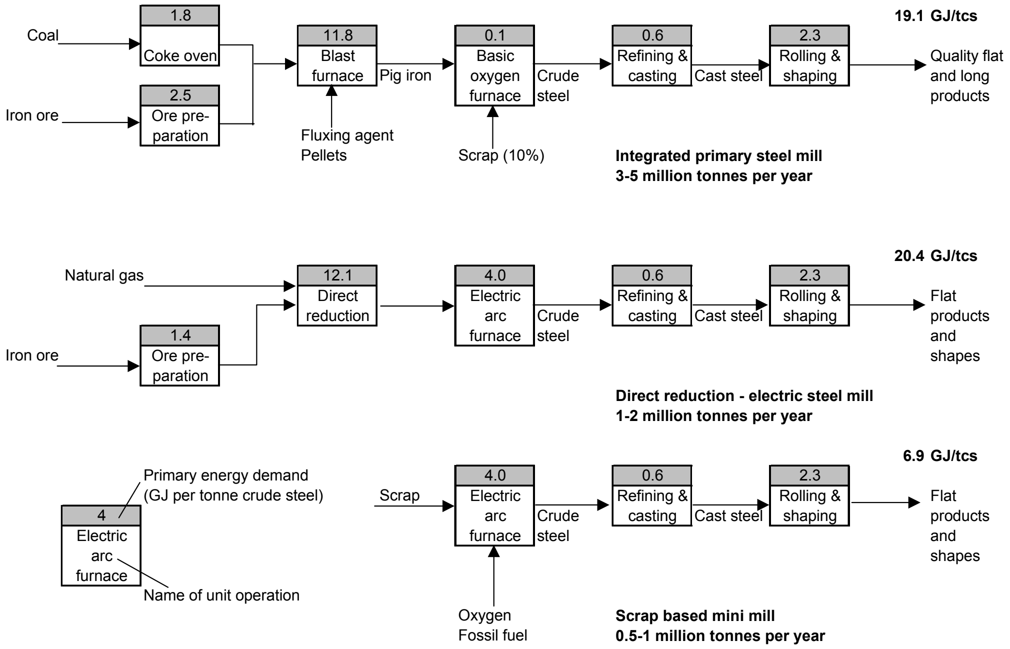

Figure 2.4: Flow sheets of contemporary iron and steel making processes. The specific energy consumption (SEC) per unit operation is also shown, expressed in GJ of primary energy per tonne of crude steel. The SEC of the total processes represents the most efficient plants at the moment. Data for the primary steel mill are taken from [Worrell et al., 1993]. It is assumed that the input of the basic oxygen furnace consists of 10% scrap. All other data are taken from Worrell [Worrell, 1995]. The data for direct reduction are based on the Midrex process. The input of the EAF in the second production process consists solely of direct reduced iron. All processes end with a hot rolling mill. A cold rolling mill and other finishing operations are not taken into consideration, because of the large variation per product. The typical annual capacity is also given.

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[3] World crude steel production for 1990 is estimated at 771 million tonne and the primary energy demand at 18.6 EJ [WEC, 1995]

2.2.2 Geographical distribution

Changes of the production of pig iron and raw steel between 1985 and 1995 are depicted in Figure 2.5 and Figure 2.6. The countries are grouped into regions according to penetration and efficiency of processes so that the production per region is more or less comparable. These regions will be used for the emission estimates in Chapter 5.

Figure 2.1 showed that the rapid expansion of the world crude steel production stopped after 1970. Whereas the annual growth rate was still 5.5% between 1960 and 1970, it was only 1.9% between 1970 and 1980. This decline continued in the 1980s with an annual growth rate of 0.7%. Between 1990 and 1997 the growth rate further declined to 0.4% a year. The global driver for the decline in growth rate was a reduction in demand and overcapacity. However, there are some regional differences.

The production in the *Nafta countries* and the *15 European Union member states* remained fairly stable during the past decade. Hardly any new integrated steel mills have been constructed here. Many existing mills were modernised however, increasing the capacity. The capacity of minimills has expanded and some direct reduction plants have been installed.

The *countries of the Eastern Europe and the former Soviet Union* experienced a collapse of much of their domestic demand that is mirrored in their production numbers of iron and steel. The steel production in these countries is still in the decline (on average –10% in 1998 compared to 1997). It can be expected though that steel production will pick up as soon as the economies are reorganised.

China is the strong grower. In 1998 it was the largest steel producing country with 114 million tonnes of crude steel, a nearly 5% increase compared to 1997 [IISI, 1999a]. China has put much effort in modernisation of its production capacity, closing much of its obsolete open hearth furnaces and investing in new integrated mills [Lu and Wang, 1999].

South America and Africa is the smallest region as far as steel production is concerned. The largest producing country is Brazil, where the steel production is characterised by a large share of charcoal-based iron production.

Of the other countries (*ROW = rest of the world)*, Japan is the biggest steel producer, ranking third on the list of largest producing countries in 1998 with 93.5 million tonnes. This was a reduction by more than 10% compared to 1997, which was due to a depressed domestic market. Also in another Asian country, the Republic of South Korea, the production declined in 1998 compared to 1997. Only Taiwan reported a production increase. Overall the Asian production (except China) showed a decline of 3% in 1998 compared to 1997.

Long-term projections on the future development of the steel industry are not known. Most projections have a time frame of one or two years. IISI reported a 5 year forecast of the apparent steel consumption per region, based on discussion with experts from the Committee on Economic Studies [Christmas, 1999]. The results are summarised in Table 2.2.

Table 2.2: Medium term forecast of apparent steel consumption (million of metric tonnes of steel products [Christmas, 1999]

Country/Region	1995	2000	2005	95-05 % p.a.
EU 15	127.1	139.1	142	1.1
Other Europe	31.6	37.5	40	2.4
CIS	36.3	31.3	33	-1.0
NAFTA	116.9	135.8	140	1.8
South America	23.4	29	33	3.5
China	87.4	130	140	4.8
Japan	80	67.2	70	-1.3
Other Asia	117.2	114.2	128	0.9
Total Asia	284.6	311.4	345	1.9
Africa	13.7	14.2	15	0.9
Middle East	12.7	14.2	15	1.7
Oceania	6.6	6.5	7	0.6
World total	652.7	719.0	763	1.6

IISI expects a small growth in EU 15 and NAFTA countries. In other European countries, notably Turkey and Poland, there is a potential for a higher growth rate. IISI expects the production in the former Soviet Union to pick up slightly after 2000.

South America is expected to recover from a setback. This is also the case in Japan, although there is a large difference between the ten-year average of the two regions. China is very difficult to forecast. According to IISI, experts are divided about the China market will further expand or that the market is currently oversupplied.

All in all, an average growth of 1.6% a year between 1995 and 2005 is expected. Compared to the annual growth in production of 0.4% a year between 1990 and 1997 we mentioned earlier, this is a considerable change.

Left alone uncertainties in production and consumption forecasts, it can be concluded that no major shifts in production centres are to be expected in the medium term. China will remain the single largest steel producing country. NAFTA and EU15 will hold their position. There may be some potential for export of technology and expertise to the recovering steel industry in the former Soviet Union, other European Countries and South America.

Merges between companies will result in a small number of large companies that dominate the world marker with a production of more than 25 million tonnes crude steel each. Now only POSCO (ROK) and Nippon Steel (Japan) have such a production. But the new company Corus, a merge between British Steel and Hoogovens, has already an annual production of 22.5 million tonnes and ranks third on the world list of largest producers.

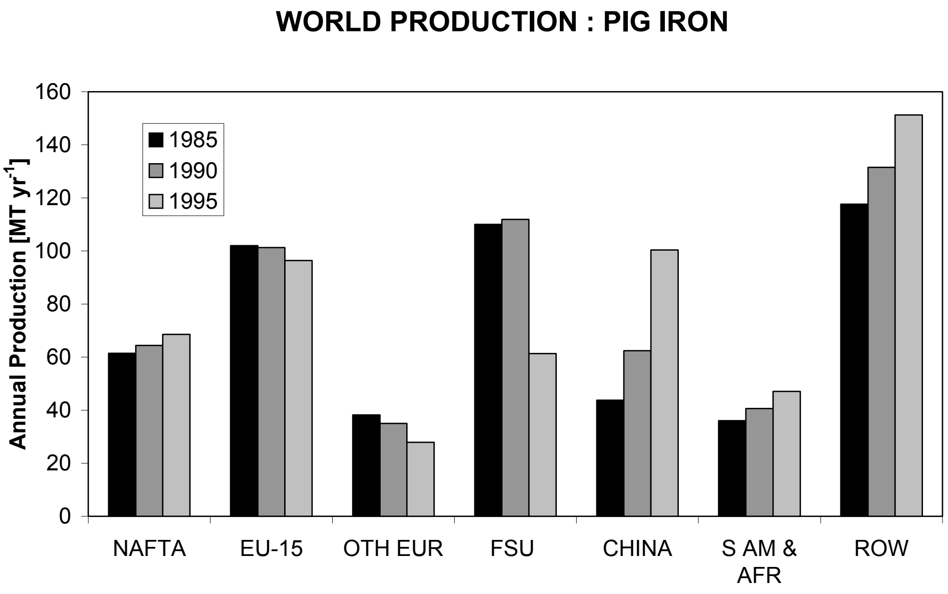

Figure 2.5 Production of pig iron (incl. direct reduced iron) in different regions of the world.

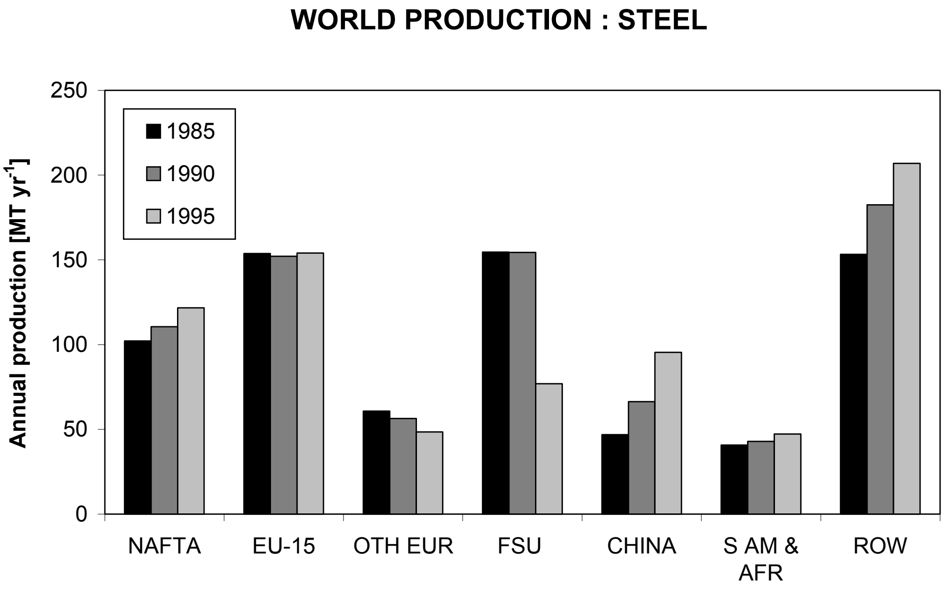

Figure 2.6 Production of steel in different regions of the world.

3. IRON AND STEEL PRODUCTION PROCESSES

3.1 PROCESS DESCRIPTIONS

Figure 3.1 gives a simplified overview of steel making processes. Operations in iron and steel production can be grouped into the following categories:

- Treatment of ores
- Coke making
- Scrap recycling
- Iron making
- Steel making
- Casting
- Milling
- Treatment and finishing

In this chapter descriptions will be given for the main technologies in each category. These descriptions include:

- main processing steps
- basic principles
- chemistry involved
- specific energy consumption
- other emissions than CO2

Techniques to improve the energy efficiency of these processes will be dealt with in Chapter 6.

3.1.1 Treatment of ores

3.1.1.1 Sinter plant

The purpose of the sinter plant is to sinter fine ore particles together into a porous clinker. Sintering of ore is required to improve the permeability of the burden in the blast furnace and to make it easier to reduce. Besides sintering pelletisation is used to prepare iron ore.

The sinter process starts with blending of different ores and revert materials, such as flue dust. Coke breeze is usually used as fuel. It is mixed with the blended ores.

The sinter strand is a large travelling gate upon which the sinter feed is deposited. The coke in the upper layer is ignited by gas burners. While the grate move forwards air is drawn through the sinter feed by fans causing the combustion to proceed through the entire sinter feed layer. Temperatures are 1300-1480°C. At the end of the strand sinter is cooled in the sinter cooler by air.

The energy consumption of a sinter plant is typically 1.7-2.0 GJ/tonne of sinter [IISI, 1998a].

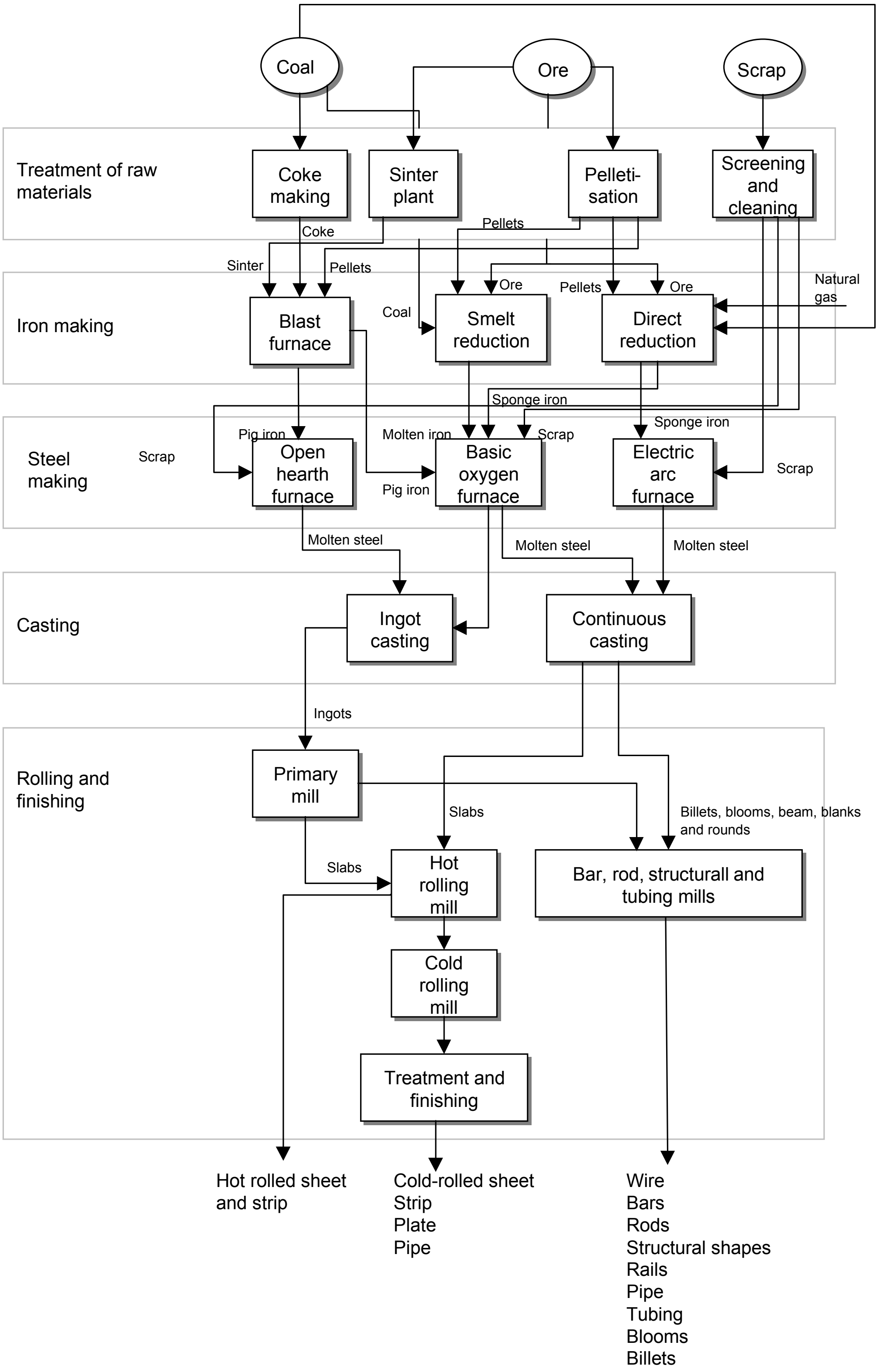

Figure 3.1: Overview of steel making processes.

Gaseous emissions from the sinter plant dominate overall emission from an integrated steel plant. Table 3.1 gives an overview of emissions of sinter plant based on a survey of five European sinter plants [EC,1999]

Table 3.1: Typical emissions from a sinter plant [EC, 1999].

Emission	g/ton of sinter
Carbon dioxide	205000-240000
Dust	170-280
Sulphur oxides	900-1850
Nitrogen oxides	440-710
Carbon monoxide	13000-43000
Hydrogen chloride	17-65
Hydrogen fluoride	1.4-3.5
Volatile organic compounds	150
Heavy metals (Cd, Cr. Cu, Hg, Mn, Ni, Pb, Tl, V, Zn)	0.1-10

3.1.1.2 Pellet plant

In a pellet plant iron ore and additives are agglomerated into small crystallised balls with a size of 10-16mm. Pelletisation normally takes place at the mine. In the EU-15 there is only one integrated steel plant that has a pellet plant (Hoogovens, the Netherlands). In the USA there is at least one integrated steel plant with a pelletising plant (BHP Steel Whyalla)

Pellets are used as charge to the blast furnace. The mixture between pellets, sinter and iron ore fines varies considerably from plant to plant.

The process starts with upgrading of the ore with crushing and grinding as intermediate steps. Then, so-called green balls are formed in the balling drum. Green balls are heated in a grate kiln and the cooled. This process is known as induration. During induration magnetite is partially oxidised to hematite, contributing largely to the heat needed to operate the process.

The energy consumption of the process is about 1.2 GJ per tonne of pellet [IISI, 1998a; EC, 1999]. Table 3.2 gives an overview of emissions of a pellet plant based on a survey of five European sinter plants [EC,1999]. Comparison with Table 3.1 shows that the emissions from a pellet plant are considerably less than from a sinter plant.

Table 3.2: Typical emissions from a pellet plant [EC, 1999].

Emission	g/ton of pellet
Carbon dioxide	15600-31800
Dust	20-130
Sulphur oxides	18-250
Nitrogen oxides	120-510
Carbon monoxide	< 10 – 410
Hydrogen chloride	2-48
Hydrogen fluoride	0.8-39
Volatile organic compounds	<5 - 40
Heavy metals (Cd, Cr. Cu, Hg, Mn, Ni, Pb, Tl, V, Zn)	0.04-0.470

3.1.2 Coke making

Coke is used in the blast furnace for three reasons:

- providing the energy required for the reduction of iron ore;
- being the chemical reducer in the reaction of iron ore to iron;
- providing in a strong and permeable support to allow a free flow of gases through the furnace.

The main advantage of using coke over coal lies in the last reason. Coke is stronger and remains its strength even at high temperatures. Coal tends to soften at elevated temperatures, reducing its permeability.

Nowadays total coke consumption varies between <300-530 kg/thm [IISI, 1998a]. Over the past decade there has been a significant reduction of the coke consumption due to increased injection of fossil fuel – pulverised coal, oil and gas - into the blast furnace. Injection of fossil fuel can only be a substitute for coke as a heat source and partially as reducer. Fossil fuel cannot serve as a strong and permeable support. Therefore, the maximum fuel injection rate is limited and lies currently at about 120 kg/thm of oil and 220 kg/thm of coal but is subject to research [IISI, 1998a]. Nevertheless, as long as blast furnace technology is used coke will remain necessary.

Bituminous, or coking coal, generally delivered by ship of train, is blended and crushed before being charged to the coal tower. Per tonne of coal about 1250-1350 kg of dry coal is required [EC, 1999]. From the coal tower the coke ovens are charged. Coke ovens are assembled in batteries. Each battery may contain up to 60 ovens of 12-18 m long and 5-7.5 m high. The width is limited to 0.3-0.6 m because of heat transfer considerations. Typical capacity of a coke oven is 30 tonne of coal. The coke ovens are separated by heating flues. In a coke oven coal is heated to 1000-1100°C for 14-24 hours in the absence of air (to prevent combustion) to remove the volatile matter. In general, cleaned coke oven gas is used as a fuel. Often the heat of the flue gases is recuperated to heat combustion air or gas [EC, 1999].

The volatile matter and moisture that are driven off during coking are collected, dried and cleaned from e.g. sulphur compounds and tar. The resulting coke

oven gas is used as a fuel or sold. Per tonne of coal approximately 325 m^3 coke oven gas is formed [EC, 1999] with a calorific value of about 19-20 MJ/m^3 [Spakman *et al,* 1997]. The CO_2-emission factor is 870 g of CO_2 per m^3 or 44 kg/GJ [Spakman *et al*, 1997].
The hot coke is pushed out the coke ovens and directly transferred to the quenching zone. Here the coke is quenched by large volumes of water. The heat of the hot coke is lost. An alternative system, known as coke dry quenching, uses an inert gas to cool the coke. The heat is recovered as steam, resulting in an energy saving of at maximum 1700 MJ/tonne of dry coke [IISI, 1998a].

Net energy consumption of coke making with wet quenching is about 3.8-4.2 GJ/ton of dry coke [IISI, 1998a]. One case of a coke oven plant with dry quenching is described that has a net energy consumption of 3.5 GJ/ton of dry coke [IISI, 1998a].

Emission of carbon dioxide stems from the combustion of fuel, generally coke oven gas, and combustion of some of the coke when it leaves the ovens. Numerous other emissions occur during coke making. Table 3.3 gives an overview of emissions of a typical coke oven plant based on a survey at 11 coke oven plants in EU-member states [EC, 1999].

Table 3.3: Typical emissions from a coke oven plant [EC, 1999].

Emission	**g/ton of coke**
Carbon dioxide	58900-67300
Dust	6-25
Sulphur oxides	9-320
Nitrogen oxides	75-200
Ammonia	0.3-1.1
Sulphuric acid	0.2
Cyanic acid	0.01-0.13
Hydrogen sulphide	1-7
Carbon monoxide	45-505
Methane	9
Volatile organic compounds (without methane)	1-3
Benzene	0.1-5
Polyaromatic hydrocarbons	0.06-0.17

Stringent environmental regulations have pressured the steel industry to improve coke making or to find alternatives for coke. A number of older coke oven plants were even shut down.

3.1.3 Iron making

In iron making iron ore is reduced to iron, that is the oxygen that is bound to iron in the ore is removed by a chemical reducer. Currently there are three basic methods of making iron in use:

- the blast furnace method
- the direct reduction method
- the smelt reduction method

Nearly all iron is still produced in the blast furnace, see Figure 2.3. Direct reduction had a share of 4-5 % of the 1997 iron production, totalling 37.1 million tonnes of direct reduced iron [Midrex, 1999]. Only one smelt reduction technology is currently in operation – the Corex process. With two production locations (one in South Africa since 1989 and one in the Republic of Korea since 1995) the total production capacity is about 1 million tonnes of pig iron a year. Another 3.7 million tonnes per year of capacity is under construction [EC, 1999]. Several other smelting reduction processes were under development [De Beer *et al*, 1998]; however, most developments have been stalled.
It is expected that there will be a shift from the blast furnace to new iron making technologies the coming decades [AISI, 1998]. Nevertheless, the blast furnace will continue to be the predominant production route for iron production.

3.1.3.1 Blast furnace

In a blast furnace iron ore is reduced and the resulting iron is melted. The product, called pig iron, is molten iron containing 3-4% of carbon and some other impurities.

The blast furnace basically consists of three operations: the blast furnace itself, hot stoves and blowers.

Blast furnace
The blast furnace is a shaft-like furnace. It is charged from the top with a mixture of ores (agglomerated as sinter or pellets), coke and lime (to remove impurities). Hot air compressed air – blast - is injected through tuyeres at the lower part of the furnace. Auxiliary fuels are injected from the bottom. Figure 3.2 gives a schematic representation of the reactions in a blast furnace.

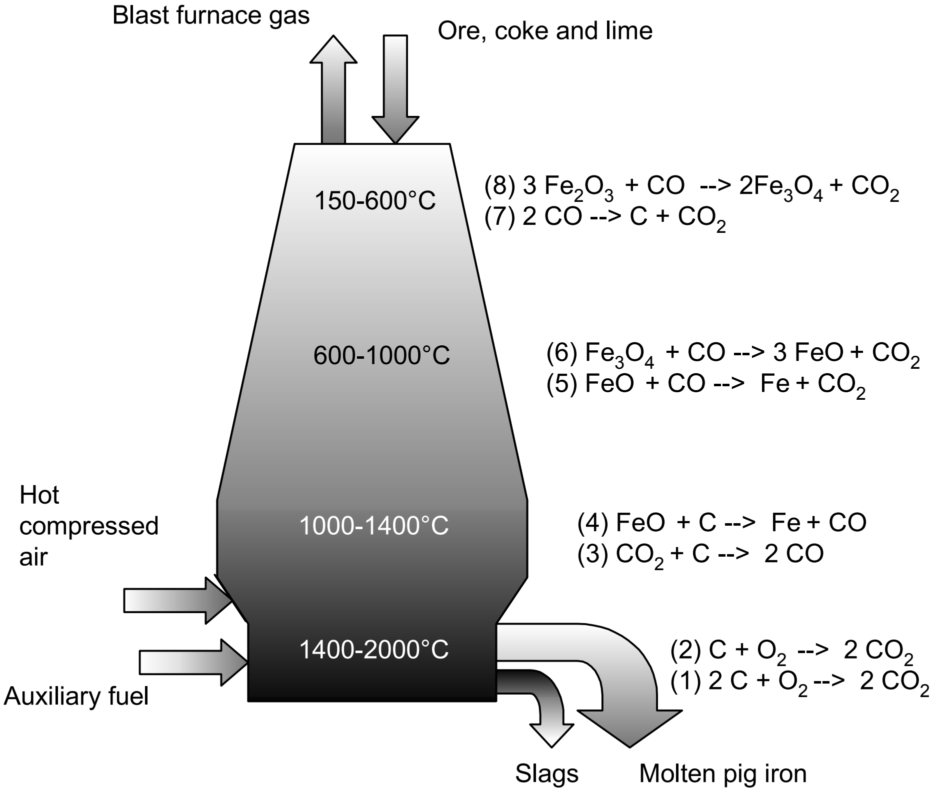

Figure 3.2: Schematic representation of a blast furnace. The main chemical reactions occurring at the different temperature zones are shown.

The temperature zones indicate the zones that can be found in a blast furnace, the hottest zone is at the bottom. Coke is gasified at the bottom (e.g. reactions 1 and 2), providing the heat and the high temperature required for some reactions. Hot gases ascend, and carbon dioxide can react with coke according to the Boudouard reaction (3) to form more carbon monoxide. The temperature of the gas decreases rapidly because heat is exchanged with the coke bed and with molten materials coming down, and because of the endothermic Boudouard reaction and the direct reduction of molten iron oxide. Direct reduction of FeO with carbon (4) occurs only when FeO is in the liquid phase. The melting point of FeO is 1370 °C. Carbon monoxide rises in the furnace, reacting with wustite (5), magnetite (6) and hematite (8). At lower temperatures the Boudouard reaction proceeds in the opposite direction (7).

Molten iron trickles down and collects in a well at the base of the furnace. Although the melting point of iron is 1530 °C, a pasty, porous mass is already formed at 1200 °C; this is related to the fact that carbon is dissolved.

Impurities are removed by reaction with calcium oxide, and a slag is formed. The molten slag floats on the molten iron. Silica that does not react with calcium oxide is reduced by carbon, increasing the energy consumption.

The blast furnace produces also a low calorific gas, blast furnace gas, with a rate of about 1200 to 2000 m^3/tpi [EC, 1999]. After cleaning blast furnace gas is generally used as a fuel in the process. Usually it is enriched with coke oven gas or natural gas. The calorific value of blast furnace gas is 2.7 – 4.0 GJ/m^3 [EC, 1999] and the CO_2-emission factor is 200-272 kg CO2/GJ.

The smallest blast furnaces have a capacity of 500 ktonne pig iron per year [EC, 1999]. However, most modern blast furnaces have a pig iron production of 2-4 Mtonne per year.

Blowers

The blast furnace owes its name to the pressurised volume of hot air - the blast - that is blown through the furnace from bottom to top. The pressure is required to overcome the resistance of the burden and is generally on the order of 3-5 bar. The pressure drop over the furnace is 1-2 bar, so the top gas has still a pressure of 2-3 bar. Blowers are used to compress cold air. The blower can be driven by a steam turbine or an electric motor. The most common form is a steam turbine fed by steam from a steam boiler [IISI, 1998a].

Hot stoves

After compression the blast has a temperature of 100-200°C. A temperature of about 1100°C is required to ensure a temperature in the blast furnace that is sufficiently high to melt iron. Hot stoves are dome-topped cylinders made of brick. Each blast furnace requires three or four stoves that operate on a cyclical basis. The stoves are heated by internal or external combustion of gases. After heating the blast is forced through the stove until the stove is no longer able to heat the blast to the required temperature. Subsequently, the blast is led to the next stove, while the first stove is heated again.

The blast furnace is a mature technology and no major technological breakthroughs are to be expected. Development is aimed at reducing the reliance on coke and to extend the campaign life to reduce capital costs of repairs [AISI, 1998].

The specific energy consumption of iron making in a blast furnace can vary strongly, depending on factors like age, way of operation, use of energy saving technologies and type of raw materials used. The most efficient blast furnaces have a specific energy consumption of about 12.5 GJ/tpi, whereas values of as high as 25-30 GJ/tpi have been reported for less efficient furnaces [WEC, 1995]

Table 3.4 gives an overview of emissions of a blast furnace based on a survey at four EU-member states [EC, 1999].

Table 3.4: Typical emissions from a blast furnace [EC, 1999].

Emission	**g/ton of pig iron**
Carbon dioxide	280000-500000
Dust	10-50
Sulphur oxides	20-230
Nitrogen oxides	30-120
Hydrogen sulphide	0.2-20
Carbon monoxide	770-1750
Heavy metals (Mn, Ni, Pb)	<0.01-0.25
Residues/by-products	**kg/tonne of pig iron**
Slags	200-290
Top gas dust	6-16
Top gas sludge	3-5
Dust from cast house de-dusting	0.5-1.5
Rubble	14-25
Wastewater	0.1-3.3

3.1.3.2 Direct reduction

Direct reduction involves the conversion of iron ore to a solid iron product by natural gas or a coal-derived reducer at temperatures below the melting point of iron (900-1000°C, compared with 2000°C at maximum in a blast furnace). Direct reduce iron (DRI) is physically similar to the ore and contains the minerals that were originally present in the ore. DRI has a low carbon content and can therefore not be used as the sole raw material in a basic oxygen furnace[4]. DRI has to be melted in an electric arc furnace (see section 3.1.4.2) or can be charged as a scrap substitute with pig iron to a basic oxygen furnace. Iron carbide (Fe_3C) is different for DRI that is has a carbon content of 6 wt.%. It will probably predominantly be used as a scrap substitute in electric arc furnaces, that can then be operated at a lower electricity consumption. The major driver for the development of direct reduction process is the need for a low-cost and high-quality substitute for scrap (see also section 3.2).

Direct reduction process can be divided into four categories according to the reducer type and reactor type. An overview is given in Table 3.5.

Since the metal is not melted in a direct reduction process, the energy consumption is lower than that for reduction in a blast furnace. The bulk of the energy consumption of a blast furnace is for reduction (about 65%, equivalent to 10.5 GJ/thm [IISI, 1998a]). The energy consumption of direct reduction process is

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[4] In a basic oxygen furnace the conversion of carbon present in pig iron supplies in the energy need to attain a higher temperature (see section 3.1.4.1)

higher due to a lower thermal efficiency and the occurrence of alternative reactions.

Table 3.5: Characteristics of major direct reduction processes.

Process	Global production – 1998 (million tonne per year)[1]	Iron source[2]	Typical module capacity (million tonne per year)[2,4]	Energy input (GJ/t product)[5]	Stage of development (status end 1998)[1,2]
Reducer: Natural gas			Reactor: shaft furnace		
Midrex	24.82	Pellet/lump ore	1.0	11.9	Industrial
Hyl III	8.72[3]	Pellet/lump ore	1.0	10.9	Industrial[3]
Reducer: Natural gas			Reactor: Fluid bed		
Fior	0.39				Proven technology
FINMET	0.00	Fines: 0.1-12 mm	0.5	14.0	Improved FIOR; plants soon to be operational
Iron Carbide	0.00	Fines: 0.1-1 mm	0.3	16.1	Industrial
Circored	0.00	Fines: 0.1-1 mm	0.5	12.5	First plant operational
Reducer: Coal			Reactor: Rotary hearth or kiln furnace		
FASTMET	0.00	Fines/concentrates	0.5	15.9	Pilot facility in Japan
INMETCO	0.00	Fines/concentrates	0.5	14.3	Waste oxide plant operating: ore-based plants planned
SL/RN	1.30			14.8	
Reducer: Coal			Reactor: Fluid bed		
Cicofer	0.00			11.7	Development

[1] source: [Midrex, 1999]; [2] source: [EC, 1999]; [3] Earlier versions of HyL are still in operation, but it is expected that these processes will be replaced by HyL III in due time [AISI, 1998] Production figure includes HyL I. [4] Plants can consist of several modules, increasing the plants capacity. The highest number of modules used so far at one site is 5 (a Midrex-plant in Iran) [Midrex, 1999]. [5] source: [IISI, 1998a].

In the gas based processes the gas is first reformed to a mixture of mainly hydrogen and carbon monoxide. Reduction than takes place according to the following overall reactions [IISI, 1998a]:

$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$ (overall reaction)
$Fe_2O_3 + 3CO = 2Fe + 3CO_2$ (overall reaction)
$3Fe_2O_3 + 2CH_4 + 5H_2 = 2Fe_3C + 9H_2O$ (iron carbide reaction)

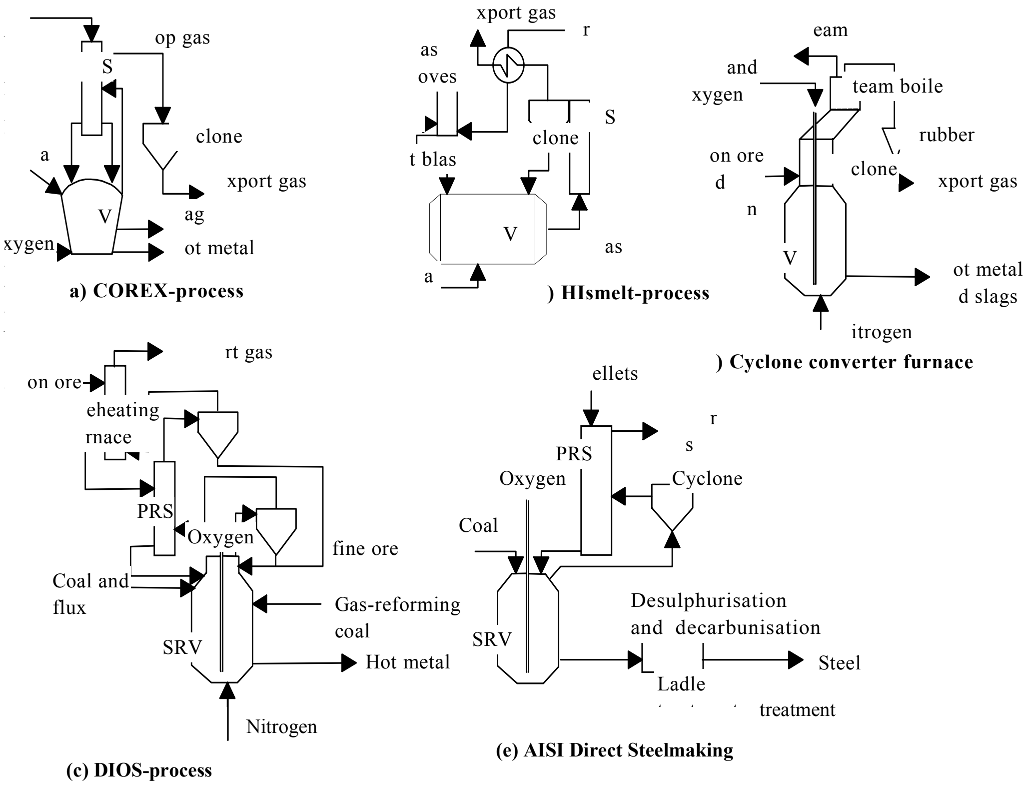
The reducing gas in coal-based processes mainly consists of carbon monoxide, which is formed by combustion and gasification of coal.

The two processes that have 85% of the production world-wide, Midrex and HyL, require ore input in the form of pellets. Ore agglomeration is therefore required, with its associated capital costs and energy consumption. Fluid bed processes can make use of fine ores. However, the productivity of these processes is not high enough and needs improvement [AISI, 1998].
The environmental impact of direct reduction processes is low. There is little dust emission [EC, 1999] and emissions of PAH's, NO_X and dioxins are in general lower than produced in the blast furnace route. No detailed information is available.

3.1.3.3 Smelt reduction

Smelting reduction (SR) processes involve reduction of iron ore without the need for coke and - in most cases - agglomerated ore. The driving forces behind the development of SR processes are the reduction of capital and operation costs and the smaller environmental impact, both of which can be achieved by eliminating coke ovens and ore agglomeration.

In principle, an SR process can consist of a single reactor in which unprepared iron ore and coal react to form a product similar to steel; that is decarburization of the iron takes place in the same reactor. In practice, SR processes consist of at least two reactors and the product resembles pig iron, which has to be refined in a separate reactor for steel to be obtained. **Error! Reference source not**



a) COREX-process

) HIsmelt-process

) Cyclone converter furnace

(c) DIOS-process

(e) AISI Direct Steelmaking

Figure 3.3: Schematic representation of the major smelting reduction processes (not on the same scale). PRS = Prereduction shaft; SRV = Smelting reduction vessel.

SR processes can be divided into two groups that differ considerably in the way the production parameters are controlled. Because the development of these processes also differs, they are also referred to as first- and second- generation processes [Innes, 1995].

First-generation processes are processes in which iron ore is prereduced to a high degree (up to 90%) before being fed to a shaftlike SR furnace. Prereduced ore and coal are present as solids in the reactor, in either a fluidised or a permeable bed. No postcombustion takes place in this furnace. The only commercial SR process, COREX, has a shaft-type furnace. Kawasaki (Japan) developed a smelting reduction process with a shaft-type furnace before it became a partner in the joint Japanese effort to develop the Direct Iron Ore Reduction-process. Hoogovens (in the Netherlands) initially studied a shaft-type process (Converted Blast Furnace), before it focused on the Cyclone Converter Furnace.

In *second-generation processes* the SR reactor is derived from the converter process for steel making. The final reduction takes place in a bath of molten iron and prereduced ore, with a molten slag floating on it. These processes are characterised by rapid reduction of iron ore in the molten slag layer, high heat transfer efficiency, and postcombustion of the process gases above the molten slag layer. No commercial second generation SR process is available, although many processes have been studied or are under development. The most important of these processes are: Direct Iron-ore Smelting (Japan), High Intensity smelting (Australia), American Iron and Steel Institute Direct Steel Making (USA), Converter Cyclone Furnace (The Netherlands), Jupiter (France, Germany), and Romelt (former-USSR, USA).

A group of smelting reduction processes, which can be both first and second generation, uses coal for reduction and electricity for melting, e.g. by electric arcs, plasma, or flash smelting. Examples are INRED, ELRED, and Plasmamelt. For the INRED process it is claimed that all electricity required can be generated by using the heat of the off gas [Chatterjee, 1996]. However, 620 kg of coal per tonne of hot metal is required, which is about 30% more than for modern blast furnaces. The Plasmamelt process requires 275 kg of coal and coke and 1120 kWh electricity per of tonne hot metal [Chatterjee, 1996]. From an energy point of view, this is competitive with modern blast furnaces only when the electricity is generated with an efficiency of almost 100%. We do not consider these processes further.

An overview of the characteristics of the main smelting reduction processes is given in Table 3.6.

Table 3.6: Characteristics of smelting reduction processes.

Process	Developer	Stage of development	Net energy consumption (GJ/thm)[1]	Indication of costs of commercial plant

				(US$/thm)[2]
COREX	Voest-Alpine	Industrial: several plants in operation or under construction or planned	19.1	250
HIsmelt	CRA, Klöckner Werke and MIDREX	100 kta pilot plant operating in Australia since 1994	18.3	200
Dios	Japanese research centres and steel manufacturers	180 kta pilot plant in period 1993-1995; no recent data available	15.5	230-250
CCF	Hoogovens	Cyclone furnace tested; development stalled	14.5	150-180
AISI	AISI/DOE	Smelter tests completed; now directed at processing waste oxides	15-17	160
Romelt	former USSR; rights bought by ICF Kaiser and Nippon Steel	unclear; process to be used for processing waste oxides	22.4	180
Clean Smelt	Italy (Ilva?)	Cyclone and smelter tested in combination	?	?

[1] source [IISI, 1998a]; [2] source [De Beer *et al,* 1999]; [3] source [AISI, 1998].

Smelting reduction has two opposite effects on the energy requirement for a steel plant. On the one hand, the energy requirement will reduce because smelting reduction obviate the necessity for coke making and often also ore agglomeration. This can save about 3 GJ per tonne of crude steel. On the other hand, smelting reduction processes require about 500 m^3 of pure oxygen per tonne of hot metal, requiring about 250 kWh/thm. Smelting reduction itself is usually less efficient in its energy use than a blast furnace. The overall effect is that most smelting reduction process will not be more efficient than the blast furnace including coke ovens and ore agglomeration. The one exception, judging from the developers estimates, seems to be CCF. However, the development of this technology is stalled.

Although it was scheduled in development plans of the mid 1990s to have the first second-generation smelting reduction process in operation around 2000 this will not be achieved. Nearly all development activity is minimised as a result of the crises in the world-wide steel industry and the high investments involved with scaling up the technology. Nevertheless, some processes are on the verge of commercialisation and it can be expected that the turning down of the development activity is a delay and not a slow death of smelting reduction technology.

3.1.4 Steel making

3.1.4.1 Basic oxygen furnace

The objective of the basic furnace is to adjust the composition of the hot metal so that:

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

This is achieved by blowing pure oxygen through a water-cooled lance or submerged tuyères in a peer-shaped refractory-lined vessel filled with hot, liquid iron. The oxidation of carbon (and some impurities, notably silicon) is a highly exothermic reaction. To prevent uncontrollable temperature rise scrap, or scrap substitutes, e.g. DRI, are added. The hot metal ratio, the ratio of liquid pig iron input and steel output, ranges from 65 to 90%, the balance being scrap (substitutes). The temperature in the basic oxygen furnace is normally 1600-1650°C, but depends on the scrap input. The process is discontinuous. Each cycle from charging to tapping requires about 30-40 minutes.

Liquid pig iron is transferred from the blast furnace in torpedo ladles: torpedo shaped vessels with capacities of 100 to 300 tonnes and very well insulated to reduce temperature loss to about 100-150°C. Before being charged to the basic oxygen furnace pig iron is desulphurised.

Scrap should meet requirements concerning impurities. Scrap is purchased, but the market for high-quality is tight. Therefore, in-plant originating iron-containing waste is increasingly being used. Scrap can be preheated before charging. Effective scrap preheating methods are being developed.

Limestone is added to dissolve impurities and form a slag. Slag analysis provides a way to control the process, but a reliable method is still lacking [AISI, 1998]. The slag of basic oxygen furnaces is often used in road construction.

Oxygen is produced in a separate plant, usually applying air liquefaction. About 50 m^3 of oxygen is required per tonne of liquid steel. Nitrogen, also a product of air liquefaction, can be used for bottom stirring to increase reaction speed in the vessel. The electricity demand for oxygen production is about 25 kWh/tonne crude steel.

During the process a gas is formed containing large amounts of carbon monoxide. In the past this gas, with a calorific value of about 9 MJ/m^3, was combusted to carbon dioxide during oxygen blow. Nowadays, most modern basic oxygen furnaces are equipped with a suppressed combustion system, avoiding oxidation of the gas. Basic oxygen furnace gas is recovered and it is used as fuel.
After the oxidation cycle is completed the liquid steel is tapped by tilting the vessel. The liquid steel is transported to the continuous caster in ladles or cast into ingots. In the ladles a series of secondary metallurgy operations can be performed. The most common operation is vacuum degassing.

Table 3.7 gives an overview of emissions of a typical basic oxygen furnace based on a survey at four basic oxygen steelmaking plants in EU-member states [EC, 1999].

Table 3.7: Typical emissions from a basic oxygen furnace [EC, 1999].

Emission	**g/ton of pig iron**
Carbon dioxide	11200-140000
Dust	15-80
Nitrogen oxides	5-20
Carbon monoxide	1500-8000
Heavy metals (Cr, Mn, Cu, Pb)	<0.1-2.5
Residues/by-products	**kg/tonne of pig iron**
Desulphurising slags	2.2-19.2
BOF-slag	85-110
Spittings	4-5
Dust	1.5-7
Rubble	0.8-5

3.1.4.2 Electric arc furnace

In an electric arc furnace steel is melted via electric arcs between cathode and one (for DC) or three (for AC) anodes. The anodes can be placed just above the bath or be submerged in the bath. Nowadays it is common to inject oxygen to promote metallurgical reactions, notably the oxidation of carbon present in the charge. Coal powder is often added to promote slag foaming through CO formation and oxy-fuel burners may be directed at cold spots. In modern electric arc furnaces only 65% of the heat input is supplied by electricity, the remainder being supplied by exothermic reactions and oxy-fuel burners.

The traditional and still the main charge for electric arc furnaces is scrap. Although manufactured iron units (DRI, pig iron, iron carbide) are good to excellent scrap substitutes – due to the low level of impurities and the high carbon content[5] - less than one million tonne of the 40 million tonnes of metallics charged to electric arc furnaces in the USA in 1995 were manufactured iron units [AISI, 1998].

The iron units are loaded in a basket together with limestone – for slag formation - and charged into the furnace. Preheating of the scrap is more and more applied. In the single shaft furnace about half of the charge can be preheated. The 'Finger Shaft Furnace' (VAI/FUCHS) makes optimal use of the energy available in the process gases and 100% of the scrap can be preheated. Side wall burners are also used for preheating.

The electrodes are made of carbon and are consumed during operations. The electrode consumption has reduced from 6 kg/tls in 1970 to a current level of 1.8 kg/tls [AISI, 1998].

The electricity consumption has come down from about 550 kWh/tls in 1970 to less than 350 kWh/tls now [AISI, 1998]. This reduction is not only the result of efficiency improvement but also caused by increased use of additional firing. the exothermic oxidation of carbon and post-combustion of off-gas. The energy demand depends, amongst others, on the charge materials. In Table 3.8 the specific energy consumption for two commercial Finger Shaft furnaces are given, one with a 100% scrap charge and one with a 55% DRI and 45% scrap charge. The specific energy consumption of the second furnace is higher due to the facts that (a) DRI is not preheated and (b) DRI has slags, which have to be melted as well.

Table 3.8: Characteristics of two commercial Finger Shaft Furnaces.

	Von Roll/SWG (Switzerland)[1]	**HYLSA (Mexico)[2]**
charge	100% scrap	55% DRI and 45% scrap
power (kWh/tls)	315	432
oxygen (Nm^3/tls)	27.5	31
natural gas (Nm^3/tls)	7	4
electrode (kg/tls)	1.4	1.2
carbon powder (kg/tls)	15	15
SEC (GJ/tls) [3]	2.7-3.7	3.3-4.6

[1] [Hofer, 1997]; [2] [Hofer, 1996; Rong *et al.*, 1996]. [3] Low and High estimate of specific primary energy consumption using the following conversion factors: from electricity to primary energy 0.6/0.4 (low/high); electrode 30.95 GJ/tonne; oxygen 280 kWh/ton; natural gas 31.65 MJ/m^3; coal and carbon powder 29/32 GJ/tonne (low/high).

Electric arc furnaces form the heart of so-called mini-mills, steel plants with a capacity of 0.5 to 1 million tonne steel per year. Mini-mills used to be dedicated to the production of long products only. Hot rolling mills for flat products

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[5] DRI has a high level of slags and a relatively low level of carbon. A higher carbon is level is desirable since carbon oxidation can provide in part of the energy needed for melting.

can be operated competitively only at large capacities and, therefore, were the domain of large integrated mills. The introduction of new techniques, notably new casting techniques and new refining techniques, made the production of high-quality flat products from EAF-steel competitive with primary steel products.

Table 3.7 gives an overview of emissions of a typical electric arc furnace [EC, 1999]. The ranges are due to the fact that data are based on measurements at several furnaces with different systems for fume collection.

Table 3.9: Emissions from electric arc furnaces. Data based on measurements at various furnaces [EC, 1999]

Emission	**g/ton of steel**
Dust	1-780
Sulphur oxides	24-130
Nitrogen oxides	120-240
Hydrogen chloride	0.8-9.6
Carbon monoxide	740-3900
Hydrogen fluoride	<0.7-40
Heavy metals, mainly Zn, but also Hg, Cr, Cd, Cu, Ni and Pb)	<0.3-60
Solid wastes/by-products	**kg/tonne of steel**
Slag from furnace	100-150
Slag from ladle	10-30
Dust	10-20
Refractory bricks	2-8

3.1.5 Casting

Casting results in a series of semi-finished steel products, differing in shape and size. In Box 3.1 definitions are given of these products. Semi-finished steel products are further processes in rolling and finishing operations, which we dealt with in the next section.

Casting of steel is one of major areas within the steel industry where technological developments are taking place. Thin slab casters have found there way into minimills the past decade, making the production of strip in minimills economically attractive. Casting and rolling operations used to be separated processes, requiring intermediate storage and transport, are becoming more and more integrated. Strip casting offers the possibility of casting strip directly and eliminating rolling at all.

The traditional casting process is ingot casting, but continuous casting is rapidly replacing ingot casting. In many OECD countries the share of continuously cast steel is nearly 100%. The drivers for this technology change are increased yield and productivity, reduced energy consumption and lower labour and capital costs. Ingot casting requires expensive mills to roll the ingots into slabs. Whereas ingot casting involves complete cooling and reheating before rolling, continuous casting makes direct casting into blooms, billets or slabs possible.

3.1.5.1 Ingot casting

Ingot casting is a batch process, consisting of the following major operations:

- casting
- cooling
- reheating
- rolling

Liquid steel is teemed (poured) into moulds, where it slowly solidifies. This process may take several days. Ingots weight 25 to 30 tonnes and are further processed into slabs or billets. First, the ingots are reheated in a reheating furnace. Only then the ingots can be rolled to slabs, blooms or billets in a primary mill. These products are then cooled, descaled, and inspected before being moved to rolling mills where they are again reheated.

Ingot casting is an outdated process for bulk steel production. However, it continues to be the preferred method to produce steel for some users, including large bar applications, high-performance bar and tubing applications [AISI, 1998].

In spite of its niche market function, we will not deal with ingot casting any further in this study.

3.1.5.2 Continuous casting

Continuous casting is a method of pouring steel into a billet, bloom, or slab directly from its molten form. Steel from the BOF or electric arc furnace is poured into a tundish (a shallow vessel that looks like a bathtub) atop the continuous caster. As steel carefully flows from the tundish down into the water-cooled copper mold of the caster, it solidifies into a ribbon of red-hot steel. At the bottom of the caster, torches cut the continuously flowing steel to form slabs or blooms.

Continuous casting avoids the need for large, expensive mills for rolling ingots into slabs. Continuous cast slabs also solidify in a few minutes versus several days for an ingot. Because of this, the chemical composition and mechanical properties are more uniform.

3.1.5.3 Thin slab casting

Thin slab casting resembles continuous casting. The casting mold, which gives shape to the steel, is adapted to cast slabs with a thickness of 40-90 mm. Thin slab casting combines casting and rolling in one plant by tight control and the use of a reheating furnace that brings the steel to a uniform temperature of about 1100°-1200°C in a hearth furnace or an induction furnace. After the rolling mill, a thickness of less than 2 mm can be achieved.

Compact strip production of SMS Schloemann-Siemag, Inline Strip Production of Mannesmann Demag, and continuous thin slab casting and rolling technology (Conroll) of VAI are the major techniques, but other are available or being developed [Stelco, 1993; Parodi, 1993]. In 1995 about 15 thin slab casters had already been installed world-wide or had been ordered, and several pilot plants were in operation [De Beer *et al*, 1998]. Most of these installations are combined with an EAF. With a combination of an EAF and thin slab caster, flat products can be produced at costs that are competitive with the costs of flats products made in an integrated steel plant. However, several integrated steel manufacturers announced that they will install thin slab casters.

An innovation to thin slab casting is liquid core reduction. Slabs with a thickness of less than 25 mm can be cast by compressing the cast steel shortly after it leaves the mold, i.e. while the edges are already solid and the core is still liquid. To roll strips of 1-10 mm, a reheating furnace and rolling mill are still required. Several techniques are under development.

3.1.6 Rolling and finishing

The semi-finished steel products from the casting operations are further processed to produce finished steel products in a series of rolling and finishing operations. It is beyond the scope of this study to outline all operations and products in detail. Instead we focus on the operations that have the largest impact on the energy consumption of the process. An overview of the operations is given in Figure 3.4.

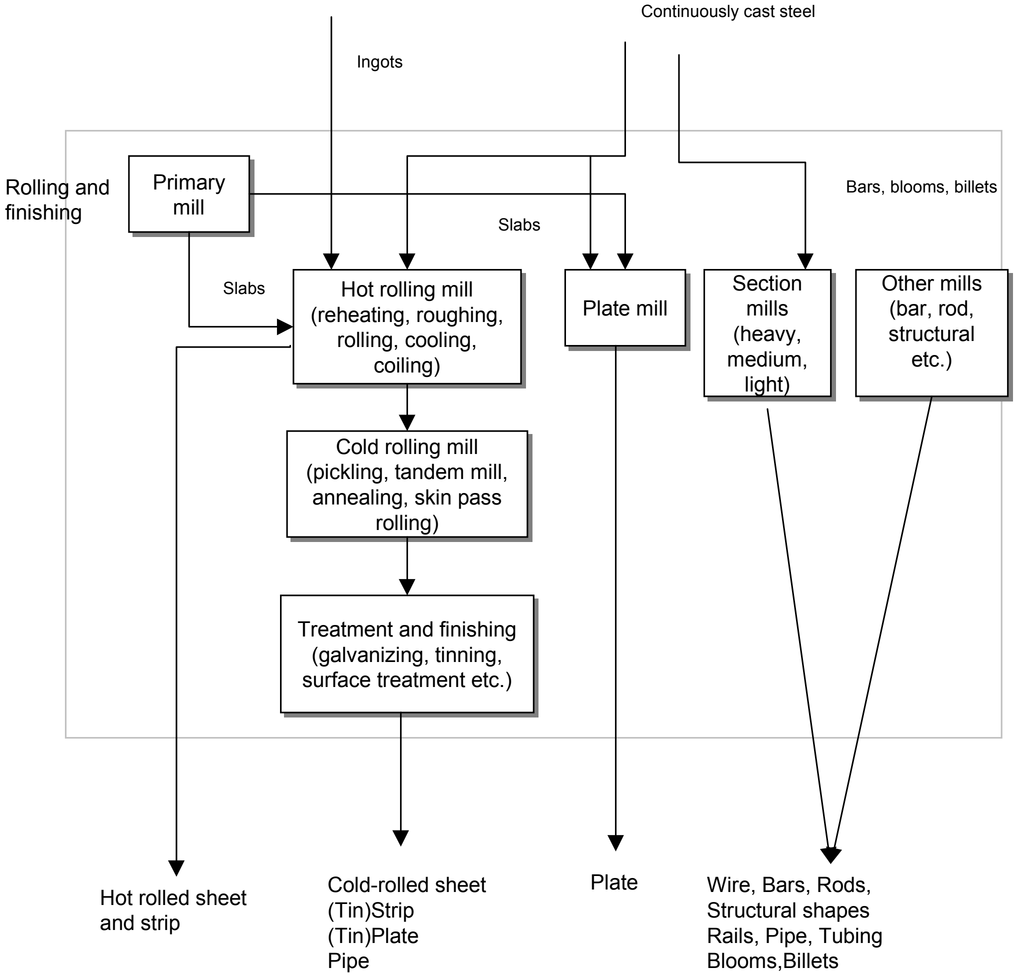

Figure 3.4: Overview of major operations in rolling and finishing of steel.

Strip and sheet

Slabs are reduced in thickness in a hot strip mill. A hot strip mill consists of a reheating furnace to bring the slabs to the correct temperature for rolling, and rolling mills. Slabs can be charged hot directly, after temperature normalisation, from the continuous caster. However, a considerable share of the slabs are first cooled and stored before being milled. Rolling normally takes place in two steps. First, slab thickness is reduced from 150-270 mm to 20-80 mm in the roughing mill. Then, in the finishing mill a further reduction to 1-30 mm is achieved [IISI, 1998a]. The product is coiled and sold or sent to the cold mill for further processing.

In the cold mill hot rolled coil is reduced in thickness to about 0.15 mm to produce a sheet suitable for a variety of uses, e.g. for car bodies to tin cans [IISI, 1998a]. The process begins with the removal of a thin film of iron oxide by a warm acid bath. The strip is then immediately cold rolled in the tandem mill before further oxidation can take place. To make to the cold rolled steel soft and malleable it is annealed, which involves heating to about 700°C followed by slow cooling. The batch annealing process can take as long as 2 days, whereas the continuous annealing takes only about 10 minutes [IISI, 1998a]. After annealing a number of operations can be carried out to improve metallurgical properties or obtain the correct steel specifications for downstream processing.

Cold mills produce cold rolled sheet (1.8-0.35 mm) or tinplate (0.3-0.15 mm).

Plate mill

Steel plate is used in a wide variety of highly demanding applications. Therefore, Plate mills are configured in such a way that precise control over the steel properties is ensured. Plate mills include a reheat furnace, a rolling mill (roughing and finishing), a heat treatment furnace, a cooling bed, a shear and a finishing line.

3.2 CURRENT LEVELS OF AND FUTURE TRENDS IN RECYCLING

Significant amounts of scrap are consumed for steel production in all steel production processes. The electric arc furnace is usually largely fed on scrap with minor varying amounts of direct reduced iron or pig iron. The now somewhat obsolete open hearth furnace is very flexible (15-100 %) in respect to the amounts of pig iron and scrap consumed per ton of steel. The basic oxygen furnace has a rather narrow range (15-25 %) of scrap consumption per ton of metal. Scrap is here required to consume the excess heat from the oxidation reaction. Due to these strong couplings of scrap consumption to steel production it is not surprising that over the last few decades global scrap consumption just as pig iron production has followed steel production quite closely (Figure 3.5).

The supply of scrap is fed from different sources: so-called circulating scrap, prompt scrap and obsolete and capital scrap. According to the definitions in UN/ECE [1997] circulating scrap originates directly from steel production, prompt scrap is produced in the manufacturing industry. Both types usually have a well known composition and a low content of contaminants. Obsolete scrap comes from the dismantling of products (e.g. vehicles) at the end of their life while capital scrap originates from the dismantling of industrial structures or from scraped machines. Table 3.10 lists values for the significance of these sources of scrap. It is interesting to note that the return of metal from applications after their use-phase (“Obsolete and capital scrap”) is below 50 % of total scrap consumption. The different sources of scrap exhibit rather different characteristics in respect to temporal availability and their response to scrap prices.

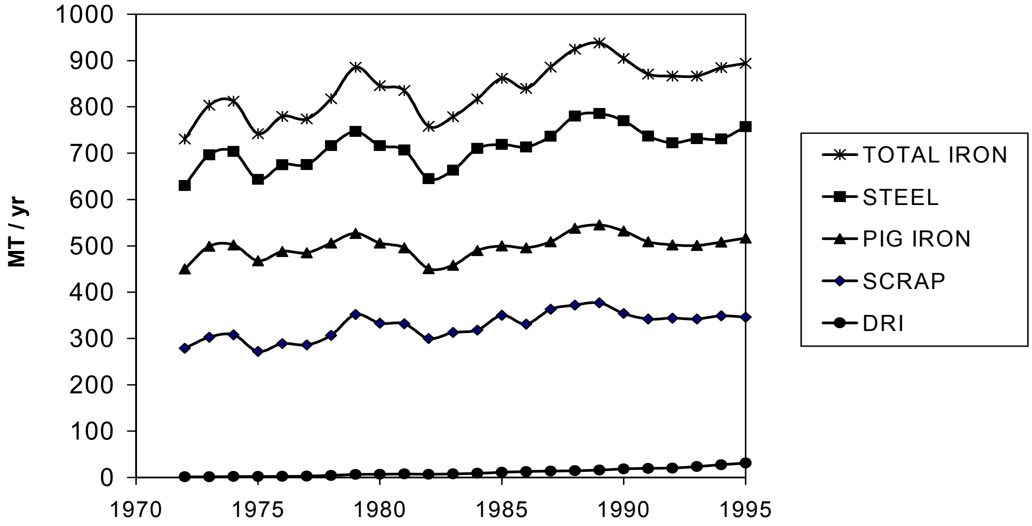

Figure 3.5 Global crude steel production, production of pig iron (PI), scrap consumption (SC), production of direct reduced iron (DRI) and total supply of iron between 1972 and 1995 after IISI [1983, 1993, 1997] and UN/ECE [1997]. The total supply of iron is calculated as the sum of PI, SC and DRI. The surplus of the total supply of iron relative to crude steel is due to the consumption for foundry iron and because of double counting of circulating scrap. In 1995 the consumption of foundry iron was about 60 million tons and circulating scrap amounted to about 100 million tons [UN/ECE, 1997].

Table 3.10 Different sources of scrap in 1996 [UN/ECE, 1997]

Source of scrap	Amount of scrap [MT , %]
Circulating scrap	100 (28 %)
Prompt scrap	100 (28 %)
Obsolete and capital scrap	160 (44 %)
TOTAL	360 (100 %)

The current situation of scrap collection is not fully captured by common statistics UN/ECE [1997]. This is mainly due to inconsistencies in the classifications between countries. The future development of global scrap supply and demand is thus extremely uncertain. Scrap is certainly competing with direct reduced iron in electric arc furnaces. The supply of high grade (circulating and prompt scrap) is likely to decrease as production technologies in steel plants and factories are optimised to avoid material losses. The reservoir of low grade (capital and obsolete) scrap is certainly large. The extent to which it will be tapped in the future certainly depends on whether collection quality can be increased. There may also be considerable potential for innovative metallurgic solutions to increase usage of lower grade scrap qualities.

4. CO_2-EMISSION OF STEEL MAKING ROUTES

In this chapter four main steel making routes are described:
A. Primary integrated steel mill
B. Scrap-based minimill
C. Direct reduction – electric melting mill
D. Blast furnace –open hearth plant.

The first two routes dominate global steel production. In 1998 about 60% of the world steel was produced in a primary integrated steel plant and 30% in a scrap-based minimill [IISI, 1999b].
Plants that only use direct reduced iron as input are unusual; direct reduced iron is more often used as scrap substitute in a minimill. It has also been suggested to use direct reduced iron to dilute the impurities in the scrap. We do not consider this route separately since it is a combination of route B and C. Furthermore, the situation that one has to dilute trace contaminants by for instance a factor 2 just through mixing with 50% direct reduced iron will not occur that frequently. In most cases other scrap cleaning operations will be necessary since low grade scraps are inherently highly contaminated with other elements and have varying (not specified) compositions.
The open hearth furnace is being faced out at a high rate. Whereas in 1975 its share in global steel production was still about 30%, in 1998 this share was reduced to less than 5% [IISI, 1999b]. The former Soviet Union has still the largest open hearth furnace capacity. In China a restructuring of the steel industry reduced the open hearth furnace capacity from 33% in 1978 to 5% in 1998. The intention is to have all remaining open hearth furnaces shut down in 2000 [Li and Wang, 1999].

In the remaining of this chapter we will give a short description of each production route. An estimate of total investment costs will be given. No data are available to specify these costs for different locations.

In the remainder of this report we will focus on the first two routes. For completeness, we also mention the other two routes here.

In Table 4.1 estimates are given of the specific energy consumption of these four routes. Table 4.2 estimates the associated emission of carbon dioxide.

4.1 PRIMARY INTEGRATED STEEL MILL

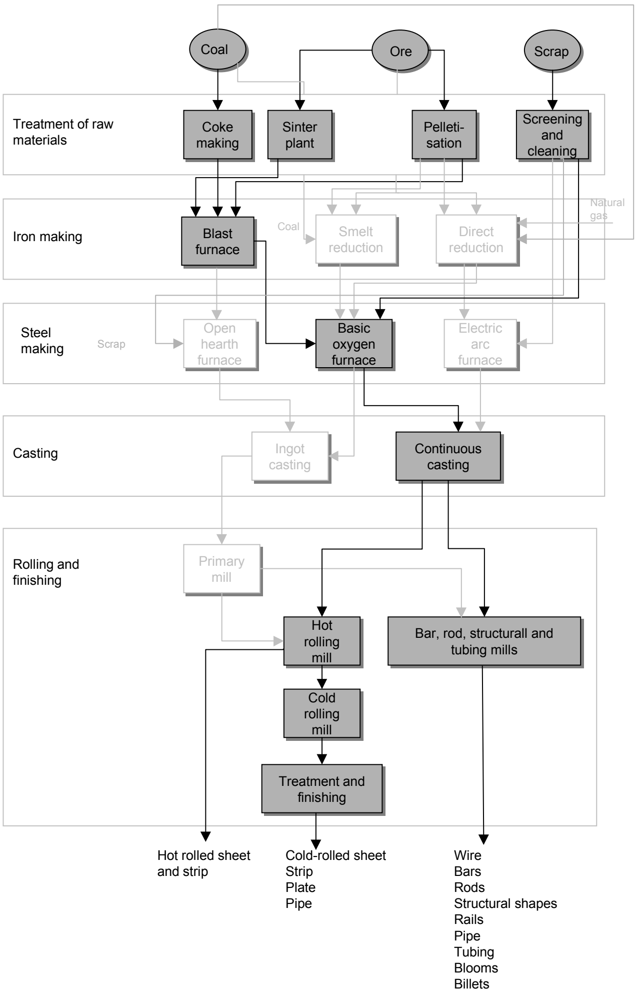

Figure 4.1: primary integrated steel mill

About 60% of the global steel production is made by this route. It consists of a coke making facility, ore agglomeration plants, blast furnace(s), basic oxygen furnace plants, continuous casting and rolling and finishing operations. All operations are located at one site, although pellets are also produced in separate facilities. Ingot casting is also still in use, but the penetration of continuous casting is as high as 83% in 1998 [IISI, 1999b].

Typical capacity is 3-5 million tonne per year. Investment costs of a complete integrated mill with a capacity of 5 million tonnes are estimated at 2.5-5 billion US$. However, it is more common that specific operations are replaced instead of building a complete new plan.

World-wide the specific primary energy consumption for this process route ranges from 19 to 40 GJ/tcs.

4.2 SCRAP-BASED MINIMILL

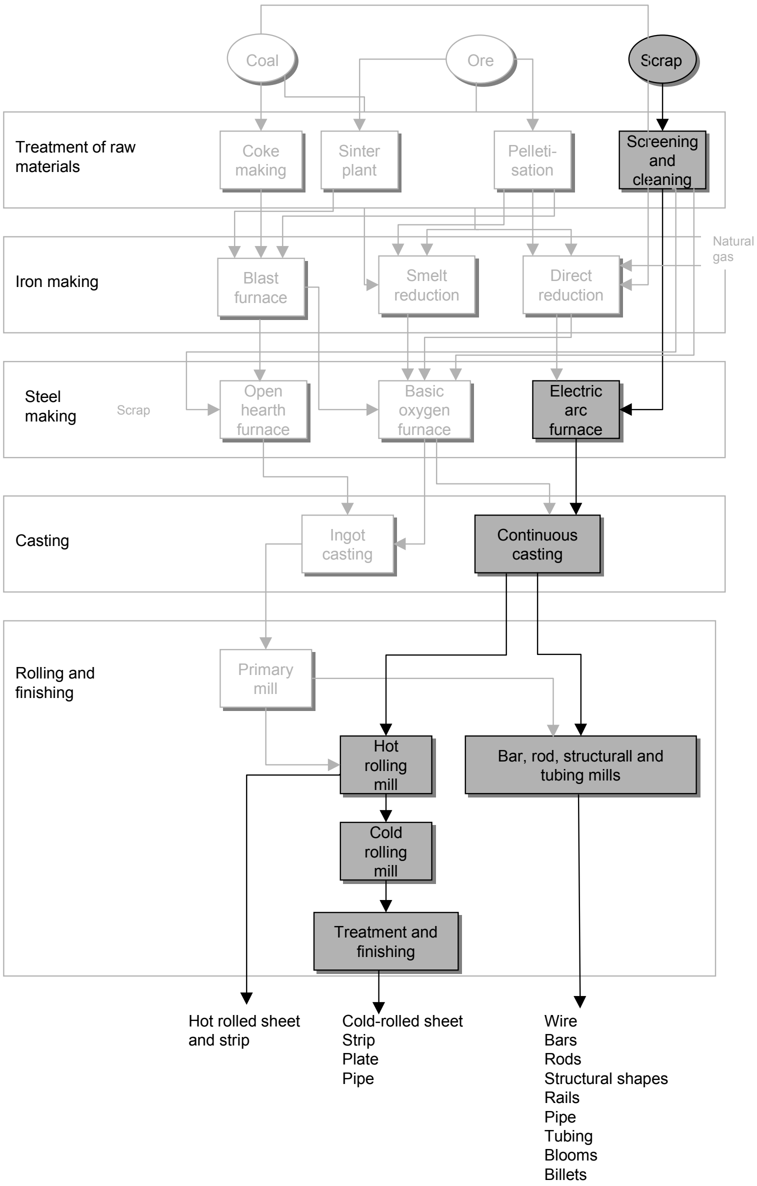

Figure 4.2: Scrap-based minimill

The share of this process in world steel production is 30-35%. Especially in the United States the minimill made strong upsurge, mainly due to its relatively low capital requirements and flexibility of location. Integrated steel mills are locked to main transportation routes for iron ore and coal, such as waterways.

This type of steel production processes consists of one or more electric arc furnaces and casting, rolling and finishing operations. Scrap is the traditional input, but with the recent shortage of high-quality low-price scrap, scrap substitutes, e.g. direct reduced iron, are increasingly being used.

The typical capacity is 0.5-1.0 million tonne crude steel per year. Investment costs for a 1.0 million tonnes plant are estimated at 50-250 million US$.

The power consumption of state of the art furnaces is 300-350 kWh/tcs. Other energy inputs are for oxygen production, carbon powder, electrode consumption and natural gas. Many minimills work on nuclear or hydro energy.

4.3 DIRECT REDUCTION – ELECTRIC MELTING MILL

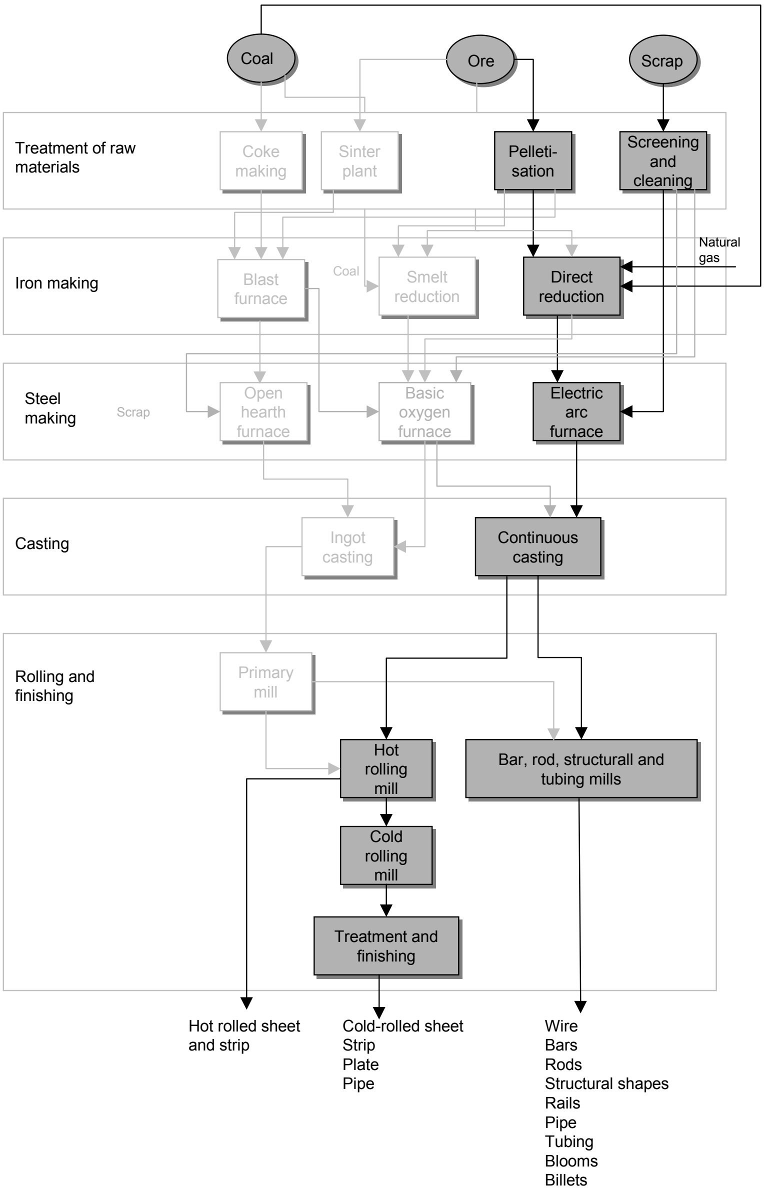

Figure 4.3: Direct reduction - electric melting mill

World-wide about 37 Mt of direct reduced iron was produced in 1998 [Midrex, 1999]; this is about 6% of the world iron production. MIDREX and HyL are the most applied direct reduction processes. Coking and sintering is not required, but currently industrial direct reduction plants do require pellets or lump ore. New process can be charged with fine ores.
The typical capacity is 1-2 million tonne per year. Investment costs are estimated at 200-400 million US$ for the direct reduction plant only.
The specific primary energy consumption is about 20 GJ/tcs.

4.4 BLAST FURNACE – OPEN HEARTH ROUTE

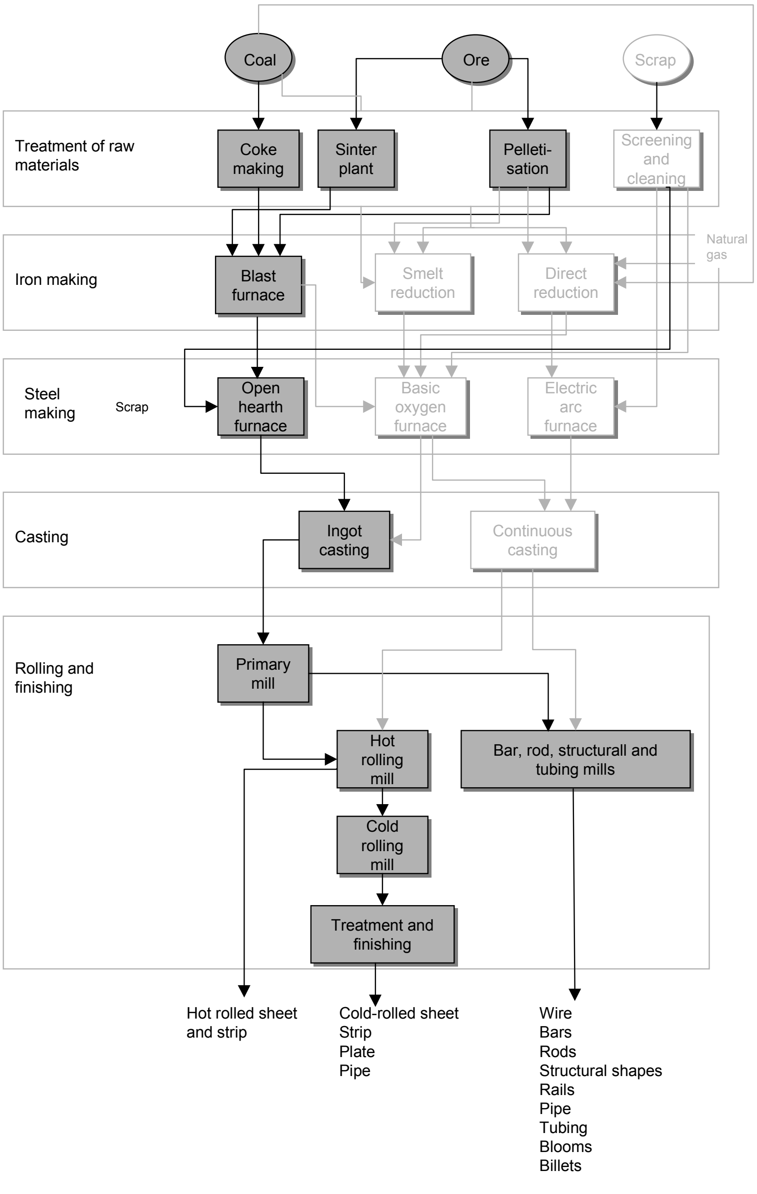

Figure 4.4: Blast furnace - open hearth route

The open hearth furnace was the main steel production process until the introduction of the basic oxygen furnace in the 1950s. In most countries open hearth furnaces have been shut down. It is still being operated in for instance China and former USSR.
No recent estimate of the investment costs is available, since no new open hearth furnaces are being built. The specific primary energy consumption is estimated at 30-40 GJ/tcs.

Table 4.1: Specific energy consumption for four steel making routes. For every route one column gives low and one column gives high values. The data are based on practical, average values. Both lower and higher SECs may occur in specific cases.

Energy consumption of steel making routes		**Practical values** **Net energy input**		**Route A** **Integrated steel plant**			**Route B** **Scrap-based minimill**			**Route C** **DR -EAF**			**Route D** **BF- OHF**		
	stage product	GJ/tonne stage product		stage product/tls	GJ/tonne steel product		stage product/tls	GJ/tonne steel product		stage product/tls	GJ/tonne steel product		stage product/tls	GJ/tonne steel product	
Treatment of ore and raw materials					3.0	3.8		0.2	0.3		1.3	1.3		3.2	4.1
Coke making	dry coke	3.5	5.1	0.37	1.3	1.9							0.44	1.5	2.2
Pelletising	pellet	1.3	1.3	0.33	0.4	0.4				0.96	1.2	1.2	0.33	0.4	0.4
Sintering	dry graded sinter	1.7	1.9	0.72	1.2	1.4							0.72	1.2	1.4
Ore handling	lump ore	0.2	0.3	0.33	0.1	0.1				0.64	0.1	0.1			
Screening scrap	clean scrap	0.2	0.3	0.15	0.0	0.0	1.10	0.2	0.3	0.00	0.0	0.0	0.15	0.0	0.0
Iron making					11.4	14.0		0.0	0.0		13.1	17.5		16.3	20.0
Blast furnace	pig iron	13.0	16.0	0.88	11.4	14.0							1.25	16.3	20.0
Direct reduction	direct reduced iron	11.9	15.9		0.0	0.0				1.10	13.1	17.5		0.0	0.0
Steel making					-0.5	0.5		3.7	6.0		3.7	6.0		2.4	2.4
Open hearth furnace	liquid steel	2.4	2.4		0.0	0.0		0.0	0.0		0.0	0.0	1.00	2.4	2.4
Basic oxygen furnace	liquid steel	-0.5	0.5	1.00	-0.5	0.5		0.0	0.0		0.0	0.0		0.0	0.0
Electric arc furnace	liquid steel	3.7	6.0		0.0	0.0	1.00	3.7	6.0	1.00	3.7	6.0		0.0	0.0
Casting					0.1	0.2		0.1	0.2		0.1	0.2		1.7	1.7
Ingot casting	ingot	1.7	1.7		0.0	0.0		0.0	0.0		0.0	0.0	1.00	1.7	1.7
Continous casting	semi-finished steel product	0.12	0.18	0.98	0.1	0.2	0.98	0.1	0.2	0.98	0.1	0.2			
Rolling and finishing					2.6	3.8		2.6	3.8		2.6	3.8		4.5	6.2
Hot strip mill	hot rolled coil	1.7	2.7	0.45	0.8	1.2	0.45	0.8	1.2	0.45	0.8	1.2	0.45	0.8	1.2
Cold mill	cold rolled sheet/tinplate	2.1	3.2	0.25	0.5	0.8	0.25	0.5	0.8	0.25	0.5	0.8	0.25	0.5	0.8
Primary mill	semi-finished steel product	2.0	2.5		0.0	0.0		0.0	0.0		0.0	0.0	0.98	2.0	2.5
Plate mill	steel plate	2.2	3.9	0.13	0.3	0.5	0.13	0.3	0.5	0.13	0.3	0.5	0.13	0.3	0.5
Section mill	section	2.4	2.9	0.34	0.8	1.0	0.34	0.8	1.0	0.34	0.8	1.0	0.34	0.8	1.0
Finishing operations	tinplate/galvanised steel	1.4	2.1	0.12	0.2	0.3	0.12	0.2	0.3	0.12	0.2	0.3	0.12	0.2	0.3
Overall		MJ/Nm3 O2		Nm3/tls	1.6	2.8	Nm3/tls	1.2	2.2	Nm3/tls	1.2	2.2	Nm3/tls	1.0	2.0
Oxygen production	oxygen	5.1	7.4	110	0.6	0.8	30	0.2	0.2	30	0.2	0.2	0.00	0.0	0.0
Power plant	electricity/steam	1.0	2.0	1.00	1.0	2.0	1.00	1.0	2.0	1.00	1.0	2.0	1.00	1.0	2.0
Total specific energy consumption					18.2	25.1		7.7	12.5		21.9	31.0		29.1	36.4

Table 4.2: CO_2-emissions associated with the specific energy consumption specified in Table 4.1 for four steel making routes. Also in this table for each route a high and a low value are given.

CO2-emission of steel making routes		**Practical values**		**Route A**			**Route B**			**Route C**			**Route D**		
				Integrated steel plant			**Scrap-based minimill**			**DR -EAF**			**BF- OHF**		
	stage product	tonne CO2/tonne stage product		stage product/tls	tonne CO2/tonne steel product		stage product/tls	tonne CO2/tonne steel product		stage product/tls	tonne CO2/tonne steel product		stage product/tls	tonne CO2/tonne steel product	
Treatment of ore and raw materials					0.20	0.24		0.02	0.03		0.10	0.11		0.20	0.25
Coke making	dry coke	0.15	0.22	0.37	0.06	0.08							0.44	0.07	0.10
Pelletising	pellet	0.10	0.10	0.33	0.03	0.03				0.96	0.10	0.10	0.33	0.03	0.03
Sintering	dry graded sinter	0.14	0.15	0.72	0.10	0.11							0.72	0.10	0.11
Ore handling	lump ore	0.02	0.02	0.33	0.01	0.01				0.64	0.01	0.01			
Screening scrap	clean scrap	0.02	0.02	0.15	0.00	0.00	1.10	0.02	0.03	0.00	0.00	0.00	0.15	0.00	0.00
Iron making					1.14	1.40		0.00	0.00		0.73	0.98		1.63	2.00
Blast furnace	pig iron	1.30	1.60	0.88	1.14	1.40							1.25	1.63	2.00
Direct reduction	direct reduced iron	0.67	0.89							1.10	0.73	0.98			
Steel making					-0.04	0.04		0.25	0.40		0.25	0.40		0.19	0.19
Open hearth furnace	liquid steel	0.19	0.19										1.00	0.19	0.19
Basic oxygen furnace	liquid steel	-0.04	0.04	1.00	-0.04	0.04									
Electric arc furnace	liquid steel	0.25	0.40				1.00	0.25	0.40	1.00	0.25	0.40			
Casting					0.01	0.01		0.01	0.01		0.01	0.01		0.00	0.00
Ingot casting	ingot	0.14	0.14												
Continous casting	semi-finished steel product	0.01	0.01	0.98	0.01	0.01	0.98	0.01	0.01	0.98	0.01	0.01			
Rolling and finishing					0.20	0.29		0.20	0.29		0.20	0.29		0.35	0.48
Hot strip mill	hot rolled coil	0.13	0.21	0.45	0.06	0.09	0.45	0.06	0.09	0.45	0.06	0.09	0.45	0.06	0.09
Cold mill	cold rolled sheet/tinplate	0.16	0.25	0.25	0.04	0.06	0.25	0.04	0.06	0.25	0.04	0.06	0.25	0.04	0.06
Primary mill	semi-finished steel product	0.15	0.19										0.98	0.15	0.19
Plate mill	steel plate	0.17	0.30	0.13	0.02	0.04	0.13	0.02	0.04	0.13	0.02	0.04	0.13	0.02	0.04
Section mill	section	0.19	0.22	0.34	0.06	0.08	0.34	0.06	0.08	0.34	0.06	0.08	0.34	0.06	0.08
Finishing operations	tinplate/galvanised steel	0.11	0.16	0.12	0.01	0.02	0.12	0.01	0.02	0.12	0.01	0.02	0.12	0.01	0.02
Overall		tonne CO2/Nm3 O2			0.12	0.21		0.09	0.17		0.09	0.17		0.08	0.16
Oxygen production	oxygen	0.34	0.50	110.00	0.04	0.05	30.00	0.01	0.01	30.00	0.01	0.01	0.00	0.00	0.00
Power plant	electricity/steam	0.08	0.16	1.00	0.08	0.16	1.00	0.08	0.16	1.00	0.08	0.16	1.00	0.08	0.16
Total specific CO2 emission (tonne CO2/tls)					1.62	2.20		0.56	0.91		1.38	1.97		2.45	3.08

5. MODELLING EMISSIONS FROM IRON AND STEEL MAKING

This part of the study describes the methods and reports results of the greenhouse gas emission estimates for the global iron- and steel industry in 1990 which is the base year of the Kyoto-Protocol. To characterise the ongoing technological developments around 1990, additional emission estimates were made for 1985 and 1995.

5.1 METHODOLOGY

To estimate greenhouse gas emissions from the iron and steel industry a bottom-up analysis was carried out based on available national data rather than on a site-by-site approach. The guiding principle for this analysis was to use a uniform and consistent methodology that would treat all countries uniformly and thus avoid discrimination because of unavailability or availability of country specific studies on this topic.

5.2 SYSTEM BOUNDARIES

The boundaries of the system for which emissions are to be estimated need to be clearly defined. Ten basic process steps were included to obtain a “gate-to-gate” view of the iron and steel production. These ten processes cover those production steps that would typically be part of an integrated iron- and steel plant. In addition, emissions from electricity generation for power consumed are taken into account on a country specific level.

Included processes

- Ore preparation
- Coking
- Blast Furnace Reduction
- Direct Iron Reduction
- Basic Oxygen Furnace
- Electric Arc Furnace
- Open Hearth Process
- Continuous Casting Route
- Ingot Casting Route
- Rolling and Finishing

Excluded processes

- Mining (energy use and methane emissions)
- Auxiliary substances e.g. fluxes (energy use and chemical CO_2 emissions)
- Transportation of raw materials and products
- Real mix of finished products
- Embodied energy of construction of plants and machinery

The additional contribution of these processes to total emissions is briefly discussed in section 5.9.

5.3 STATISTICAL MATERIAL

This study makes extended use of the statistical data which are periodically published as statistical yearbooks and supplements by the International Iron Steel Institute (IISI) [e.g. IISI, 1993; IISI, 1996a]. In its surveys IISI attempts to cover the whole world production of iron and steel through collection of information from various national and international sources [IISI, 1996a]. Among other industry specific data sets the IISI reports also contain data on scrap trade and consumption and the production of raw materials such as ore and coke. The IISI reports typically list national production numbers of e.g. crude steel along with specific shares of technologies, e.g. basic oxygen, electric arc furnace or open hearth.

The differences between the sum of national production numbers extracted from the IISI statistics for this study and the reported IISI aggregated world production was smaller than ±0.3% for coke, ±0.5% for pig iron, ±1% for sinter, pellets and raw steel and ±5% for direct reduced iron for 1985, 1990 and 1985. These errors are thus not insignificant but much smaller than estimated changes of emission levels between 1985 and 1995.
Our emission estimate covers the period 1985 to 1995 in steps of five years. None of the years 1985, 1990 and 1995 marks an extreme of the economic cycle relative to prior or subsequent years. More recent data than 1995 are not yet fully available for all countries while data sets reaching further back into time than 1985 suffer from reporting inconsistencies and again are not available for all major producing countries.
The statistical database of this analysis relied on the reporting format of IISI, which has changed its aggregation system between 1985 and 1995. Some countries like Iraq have temporarily disappeared from the IISI reporting. It is not entirely clear whether the iron and steel production in these countries has ceased because of war, civil war or revolutionary disruptions or whether information has simply become unavailable.

5.4 TREATMENT OF ELECTRICITY USE

CO_2-emissions from many processes within the iron and steel industry such as pig iron production are clearly dominated by the use of coal or coke which can be assigned a uniform CO_2-emission factor per energy unit. This is not the case where electricity is the dominant source of energy such as in the electric arc furnace. Depending on the way how grid electricity is generated in individual countries (e.g. thermal, nuclear or hydro) specific emissions per kilowatt hour of electricity can vary substantially as shown in Table 5.1. Furthermore, most integrated steel plants generate part of the electricity use in-house in top gas turbines or by burning process gas. Since detailed information is required per plant, it was not possible to correct for this effect. The values in Table 5.1 are to be considered as preliminary proxies because of accounting problems associated with combined heat power, electricity imports / exports and data availability.

Table 5.1 Proxy fossil CO_2 emission factors associated with electricity generation in 1990 [Kg CO_2 $(KWh)^{-1}$]. Calculated using data from the World Energy Council (International Energy Data Report 1998) by dividing the national fossil fuel CO_2 emissions from power plants by the national electricity supply after correction for imports / exports. These values from 1990 were also applied to calculate emission factors for 1985 and 1995.

Austria	0.27	United States	0.61
Belgium	0.35	Argentina	0.36
Finland	0.16	Brazil	0.02
France	0.19	Chile	0.45
Germany	0.73	Venezuela	0.38
Italy	0.57	Trinidad & Tobago	0.67
Luxembourg	1.07	Egypt	0.23
Netherlands	0.62	South Africa	0.87
Portugal	0.52	Iran	0.59
Spain	0.42	PR China	0.94
Sweden	0.02	India	0.82
United Kingdom	0.66	Japan	0.36
Bulgaria	0.83	Republic of Korea	0.68
Czech Republic	0.82	Taiwan	0.43
Hungary	0.50	Indonesia	0.57
Poland	1.25	Saudi Arabia	0.41
Romania	0.88	Australia	0.81
Slovak Republic	0.36	New Zealand	0.11
Russia	0.78		
Ukraine	1.12		
former USSR	0.85	**Weighted Mean**	**0.62**

5.5 ENERGY CONSUMPTION AND EMISSION FACTORS

For the emission estimates a semi-dynamic approach was chosen. This means that for the sake of simplicity (and because of a lack of reliable data) it is assumed that energy consumption per process and specific technology remained constant between 1985 and 1995 while a replacement between different technologies as documented in the IISI time series is taken into account. This method is likely to underestimate emission reductions, as it does not take into account energy savings that can be accomplished within one technology. Table 5.2 lists the used energy consumption values which were largely derived from publications by IISI.

It needs to be emphasised that the assignment of energy consumption values to individual process steps is not unambiguous. In the literature the BOF process is considered to be basically energy neutral: the energy required to produce the oxygen and argon and blow them on and through the liquid metal is recovered in the form of BOF-gas which contains combustible carbon monoxide which is formed when the oxygen reacts with the carbon dissolved in the liquid iron. The BOF process thus energetically feeds on the preceding BF step where the dissolved carbon is assigned as consumed energy.

Table 5.2 Applied fixed energy consumption values for individual processes. Values are physical energy inputs into the system - not primary energy consumption.

Process	Specific process energy consumption	Share of electricity in energy consumption
Ore preparation	1.0 GJ / T pellets [IISI, 1998a] 1.8 GJ / T sinter [IISI, 1998a]	15 % - pell [IISI, 1998a] 12 % - sint [IISI, 1998a]
Coking	5.0 GJ / T coke [IISI, 1998a]	5% [IISI, 1996b]
Blast Furnace Reduction	13.5-25 GJ / T lqd iron [own estimates - see below]	1 % [IISI, 1998a]
Direct Iron Reduction	11.9 GJ / T DRI	4 % [IISI, 1998a]
Basic Oxygen Furnace	~ 0 GJ / T lqd steel: sum of 0.3 GJ / T lqd steel from electricity & net -0.3 GJ / T lqd steel from gas [IISI, 1998a]	not applicable
Electric Arc Furnace	2.1 GJ / T lqd steel [IISI, 1998a]	90 % [IISI, 1998a]
Open Hearth Process	2.4 GJ / T lqd steel [Thyssen-Krupp, 1999]	5 % [own estimate]
Continuous Casting	0.1 GJ / T cc steel [IISI, 1998a]	50 % [IISI, 1998a]
Ingot Casting	1.7 GJ / T ic steel [IISI, 1998a]	5 % [IISI, 1998a]
Rolling and Finishing	3.0 GJ / T rf steel	20 % [IISI, 1996b]

Losses of the metal in different steps are an important factor that needs to be considered as well. These losses, e.g. oxidation losses of liquid iron in the EAF and BOF processes, may lead to considerable additional energy requirements per ton of crude steel that cannot be included into the data in Table 5.2. Energy consumption and emission estimates will nevertheless be correct if the energy data are combined with reliable data that differentiate correctly between ore, pig iron, raw steel, cast steel and finished products.

The treatment of electricity in needs to be addressed: in publications on the energy consumption within the iron and steel industry values on electricity consumption in MWh are commonly converted into primary energy consumption by multiplying with a factor 9.208 to arrive at GJ. This assumes a mean conversion efficiency of 39 % of the primary energy input. This study is not so much focussed on primary energy consumption but more on emissions and thus also takes into account differing conversion efficiencies and CO_2 emissions associated with different sources of electricity. Thus, energy consumption values in Table 5.2 are expressed as physical energy inputs into the process. Electricity consumption values are converted from MWh to GJ of electricity by multiplying with the physical factor of 3.6. Values will be significantly lower than comparable estimates from the literature if electricity is a large share of the total.

A few major producers of iron and steel like China, India, the group of Eastern European Countries (in this study basically “Other Europe”) are known to have comparatively a high specific energy consumption in the iron and steel industry. Unfortunately, only few publications are available that present reliable and well documented data on the mean energy consumption of this industry in these countries. Instead of using this incoherent information, in this study respective country specific values were derived from available data on coke production [IISI, 1993 and IISI, 1996c]. The default energy consumption of 13.5 GJ per ton of liquid metal was scaled according to their specific coke production per ton of pig iron in 1985 relative to the 1985 value of EU-15. The 1985 value was used because at that time fuel injection was of minor relevance in Europe. The calculated values for the Former USSR, the group of “Other Europe”, India and China are 16 GJ / T, 22 GJ / T, 25 GJ / T and 23 GJ / T, respectively. For all other countries the default value of 13.5 GJ / T was used for the BF step. There is evidence e.g. from China that this procedure underestimates energy consumption [e.g. Lu et al., 1997]. It needs to be emphasised that coke production can only be used as a first proxy for the energy consumption of the pig iron production in a certain country. This is due to trade in coke, other uses of coke, the use of other fuels for fuel injection for the BF step and different combustion values of a mass unit of coke in different countries.

For the conversion of energy consumption into CO_2 emissions the emission factors given in Tabel 5.3 were used. For those processes that exhibit an electricity input of more than 10 % of its total energy use country specific emission factors for electricity generation were used. Fuel specific emission factors were extracted from RWI [1998].

Table 5.3 Emission factors used for emission estimates

Process	**CO_2 - emission factor**
Ore preparation	a uniform 0.08 T CO_2 / GJ for a mix of fossil fuels
Coking	a uniform 0.044 T CO_2 / GJ for coke oven gas
Blast Furnace Reduction	a value of 0.1 T CO_2 / GJ for coke is used except for Brazil (0.07 T CO_2 / GJ) where 30 % charcoal are used for iron making.
Direct Iron Reduction	a value of 0.056 T CO_2 / GJ is used for all countries except for India (0.093 T CO_2 / GJ) and South Africa (0.085 T CO_2 / GJ) because of the widespread use of coal instead of natural gas.
Basic Oxygen Furnace	national emission factors corresponding to a combination of emission from electricity 0.3 GJ / T lqd steel and recovery of 0.3 GJ / T BOF gas
Electric Arc Furnace	national emission factors corresponding 100 % electricity use
Open Hearth Process	a uniform value of 0.08 T CO_2 / GJ for a mix of fossil fuels is applied
Continuous Casting	national emissions factors are used assuming 50 % electrical energy and 50 % from a mix of fossil fuels (0.08 CO_2 / GJ)
Ingot Casting	a uniform 0.08 T CO_2 / GJ for a mix of fossil fuels
Rolling and Finishing	national emissions factors are used assuming $_2$0 % electrical energy and 80 % from a mix of fossil fuels (0.08 CO_2 / GJ)

5.6 EMISSION ESTIMATES

The exact functions used to calculate emissions in this study are listed in Table 5.4. It is important to note that from process to process a similar method was used. Depending on data availability and spatial and temporal variance of the parameter.

5.7 EMISSION ESTIMATE (1985-1995)

This study estimates that emissions from the iron and steel industry have increased from 1310 MT CO_2 in 1985, to 1427 MT CO_2 in 1990 and 1444 MT CO_2 in 1995. The lion's share of emissions is attributable to the production of pig iron in the blast furnace. Smaller, but still significant contributions originate from the rolling and finishing of products, ore-preparation, coking and the electric arc furnace.

Figure 5.1 highlights the dynamics of recent relative changes of global emissions on a process-by-process level. Apparently DRI, continuous casting, elec-

tric arc furnaces exhibited the largest growth rates between 1985 and 1995 while only ingot casting had a significant negative trend in associated emissions due to its general global decline. In terms of absolute changes the picture in Figure 5.2. The strongest absolute increase is found from BF and EAF while IngCast and OH contribute small absolute decreases. Interestingly, Ore-Prep and Coking remained at constant levels despite growing production of pig iron production.
A regional analysis of the calculated emission database also reveals interesting information. The seven regions exhibit somewhat similar weights in emissions (Figure 5.6) but strongly different dynamics between 1985 and 1990 (Figure 5.7). Large increases from China and ROW partly offset with a strong decrease from FSU and a smaller decrease in other Europe.

Table 5.4 Method to calculate emissions. NP means National Production, EC means Energy Consumption, EF means Emission Factor and SHARE means Share of a specific technology of the total (0 ≤ SHARE ≤ 1). The attributes (in parenthesis) i and t mark values for specific countries i and specific years t. If only one or no attribute is given the value is global or constant or both.

Process	CO_2 - emission factor
Ore preparation	**NP**sinter(i,t) × **EC**sinter × **EF**sinter + **NP**pellets(i,t) × **EC**pellets × **EF**pellets
Coking	**NP**coke(i,t) × **EC**coke ×**EF**coke
Blast Furnace Reduction	**NP**pig_iron(i,t) × **EC**pig_iron(i) × **EF**pig_iron
Direct Iron Reduction	**NP**dri(i,t) × **EC**dri × **EF**dri(i)
Basic Oxygen Furnace	**NP**steel(i,t) × **SHARE**bof(i,t) × **EC**bof × **EF**bof(i)
Electric Arc Furnace	**NP**steel(i,t) × **SHARE**eaf(i,t) × **EC**eaf × **EF**eaf(i)
Open Hearth Process	**NP**steel(i,t) × **SHARE**oh(i,t) × **EC**oh × **EF**oh
Continuous Casting	**NP**steel(i,t) × **SHARE**cc(i,t) × **EC**cc × **EF**cc(i)
Ingot Casting	**NP**steel(i,t) × **SHARE**ic(i,t) × **EC**ic × **EF**ic
Rolling and Finishing	**NP**steel(i,t) × **EC**rf × **EF**rf(i)

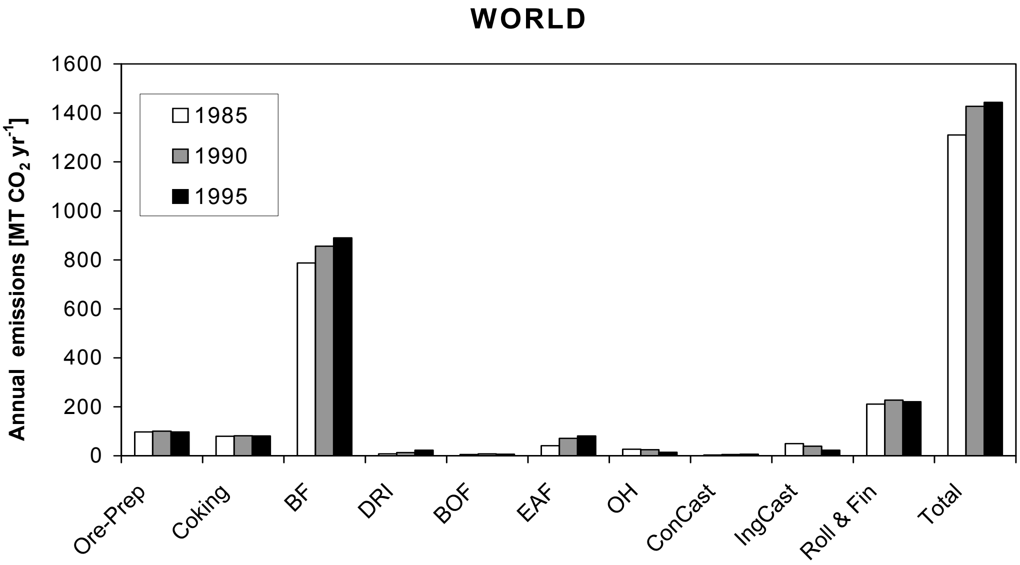

Figure 5.1 Absolute emissions from different processes of iron and steel making

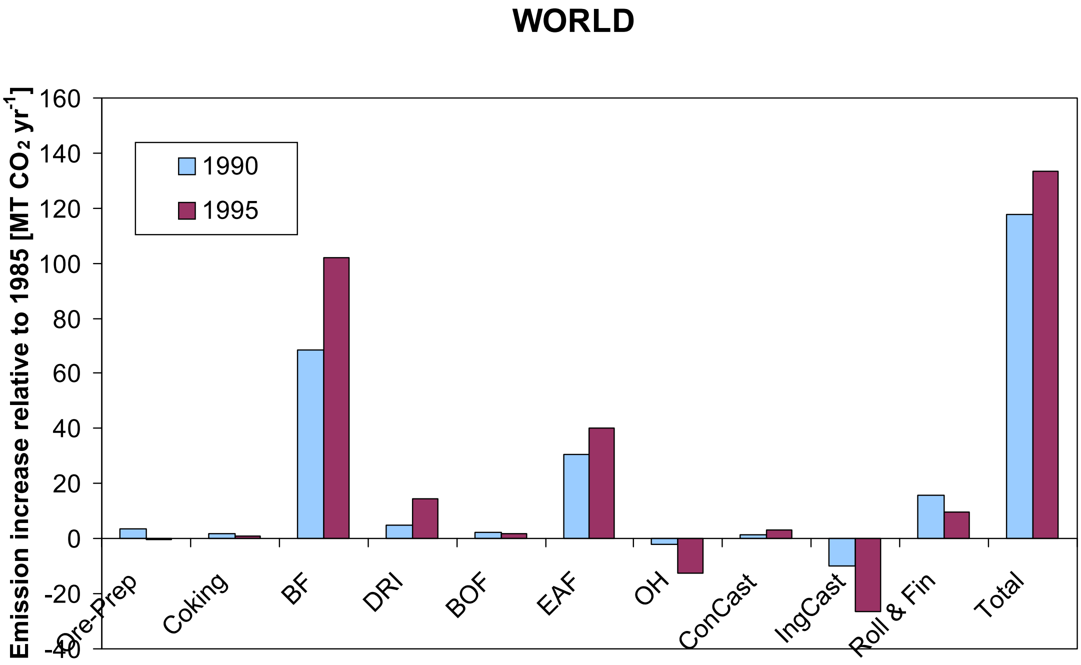

Figure 5.2 Absolute changes of CO$_2$ emissions relative to 1985 levels for different processes of iron and steel making.

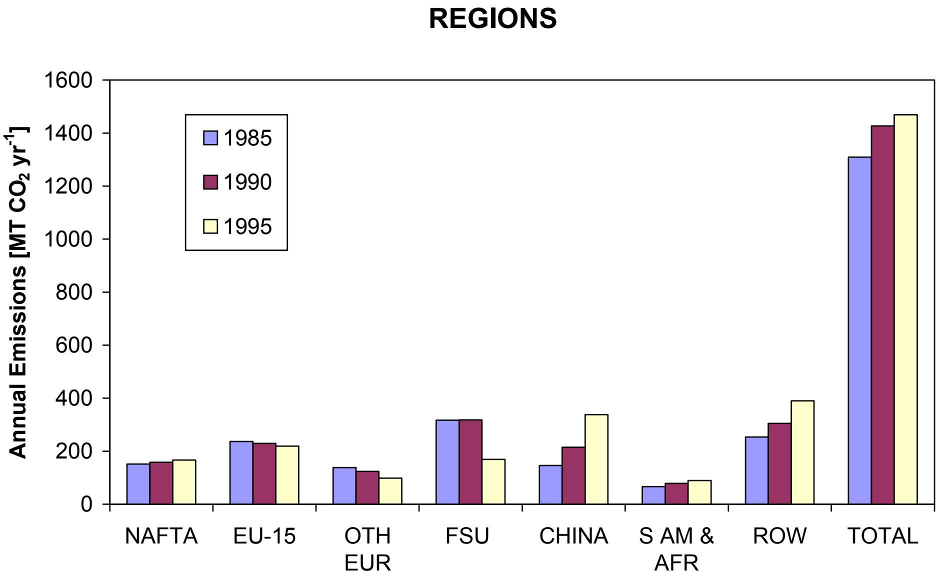

Figure 5.3 Emissions from iron and steel production in different regions.

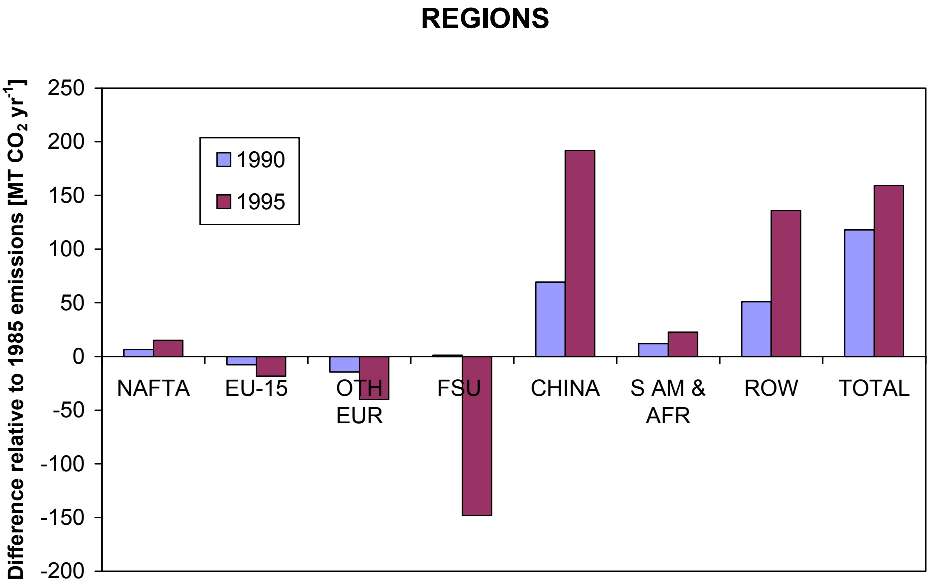

Figure 5.4 Increase of emissions from iron and steel production in different countries and regions since 1985.

5.8 LIFE CYCLE ANALYSIS

The environmental performance associated with process and product systems is increasingly important in materials selection together with the considerations of functionality, performance and cost. Among the tools available Life Cycle Assessment (or Life Cycle Analyses (LCA)) provides a comprehensive approach to evaluating environmental performance of products and materials from mining of raw materials through to end-of-life stages [IISI, 1998]. An LCA study should look at the whole chain, from cradle to grave, also taking into account transportation and energy use during use of the product. A set of ISO-standards have been set up that define how an LCA should be performed (ISO 14000).

Most LCA studies focus on comparing different products made out of steel or products that contain metal parts, for example consumer electronics or furniture. The goal of these LCA studies is to find the best product or material from an environmental perspective. The data used in these studies are not always reliable and most of the studies were conducted for a manufacturing company and are not available outside that company. From a (world-wide) greenhouse gas emission point of view these studies are of little interest.

Also some studies have been done to compare different iron and steel producing technologies. These studies focus on options to reduce energy use and material loss. These LCA-studies do not look at the whole chain, but just at the different steel-producing technologies.

The most important study regarding to green house gas emissions from the iron and steel industry is an LCA study done by the IISI "World-wide LCI database for iron and steel" [IISI, 1998]. A brief summary and some results of this study are given below.

The LCA inventory study has been carried out to quantify resource use, energy use and environmental emissions associated with the processing of twelve steel industry products from the extraction of raw materials through the steel factory gate. The use of the manufactured products, end of life and scrap recovery and recycling have not been included, making this a 'cradle-to-gate' study. Also the impact of downweighting on energy use and emission of greenhouse gasses has not been included in this study.

The main goal of the study was to develop a unified and rigorous LCA methodology for steel products world-wide in accordance with the IISI policy statement on LCA to provide reliable data to meet requests from customers and external studies. The study was carried out by an independent consultant ECOBILAN, under supervision of IISI.
The selected products are of importance to the automotive, construction and packaging industry, for environmental aspects of material choice in these sectors.

The products are: hot rolled coil, cold rolled coil, galvanised sheet, painted sheet, tinplate sheet, tin-free sheet, sections, plate and a collection of products under the heading rebar-wire rod/engineering steels. In total, 55 sites operated by 37 companies including all kinds of operations, participated in the study. Most areas of the world were included and a range of operating configurations was presented.

The LCA's were performed according to relevant ISO standards. A Critical Review Panel (CRP) monitored and commented on the methodology and the integrity of the study. The conclusions of the CRP are very positive. The main conclusion is that the database, that is the result of the LCA's, is the largest and most representative one and that it will provide a basis for decision making in the context of sustainable development.

As this study focuses on greenhouse gas emissions, some results concerning air-emissions will be given. Waste water, use of recourses and effects of by-products were also taken into account, but these results will not be discussed here.
The main greenhouse gas emission form the iron and steel industry is CO_2.In this LCA-study also non-greenhouse gases (CO, NO_x, SO_x) and particulates were measured for some exhaust gasses. Some other gas-emissions were also inventoried by means of a questionnaire, but in this way there were insufficient samples taken to draw conclusions. Greenhouse gas emissions are presented in figure 5.5. and 5.6.

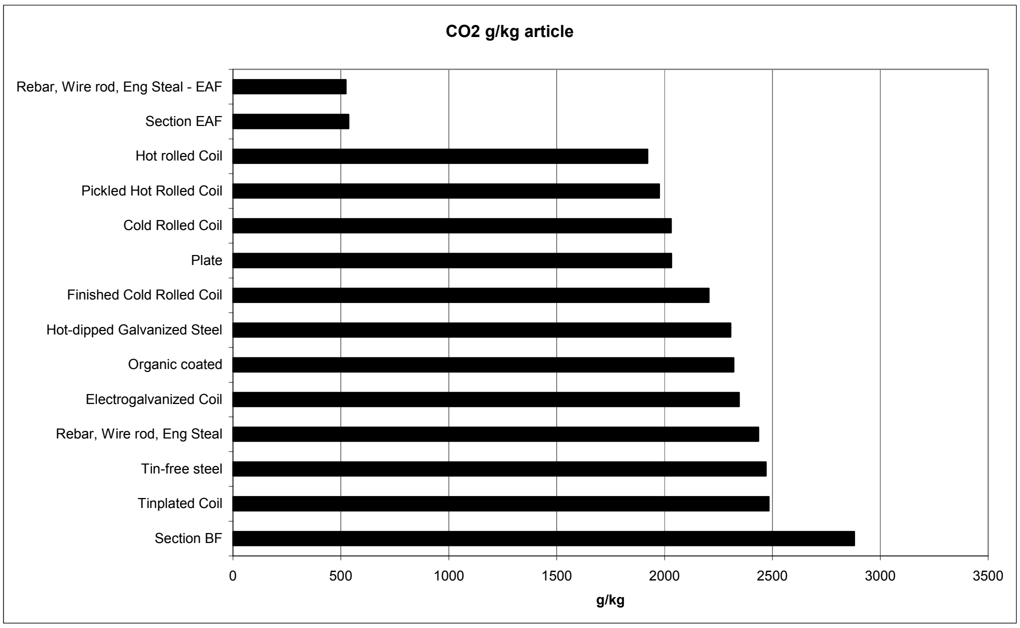

Figure 5.5 CO_2-emission per product (g/kg) [IISI 1998]

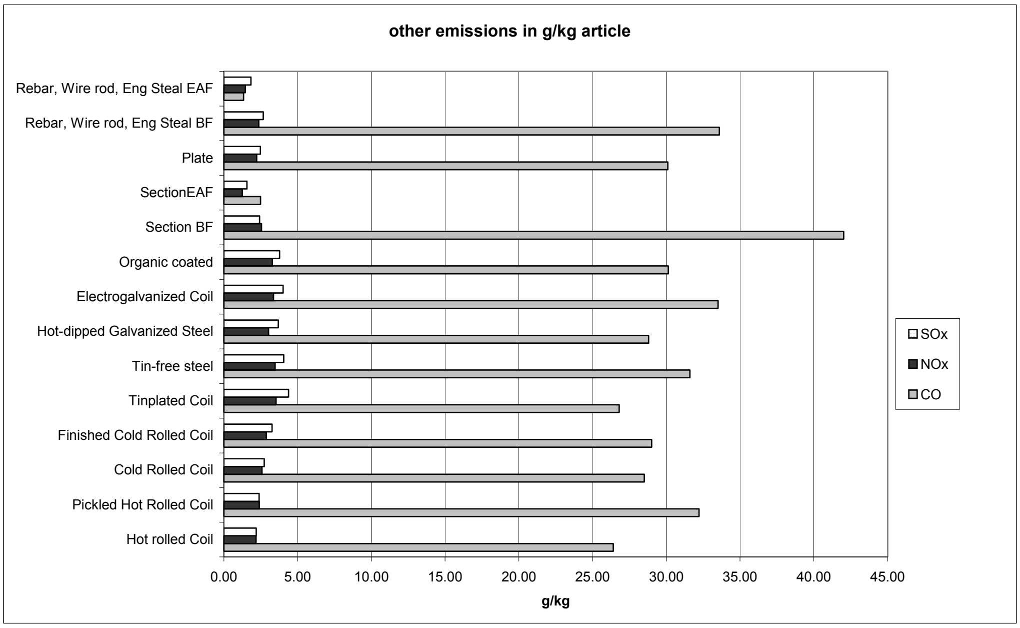

Figure 5.6: Global average emissions (g/kg article) [IISI, 1998]

5.9 RELEVANT EMISSIONS OUTSIDE OF THE SYSTEM BOUNDARIES

As pointed out above several processes were not included in this analysis. Their greenhouse gas emissions will be put in relation to what was defined as iron and steel industry in this study.

Omitted processes:
A) Mining (energy use and methane emissions)
B) Auxiliary substances e.g. fluxes (energy use and chemical CO_2 emissions)
C) Transportation of raw materials and products
D) Real mix of finished products
E) Embodied energy for construction of plants and machinery

If lifecycle data are required, this study uses the data from BUWAL [1991], which may not be the most recent in some cases, but has the big advantage of being publicly available.

A) Mining of coal and iron ore: The mining of coal and iron ore should also be considered. From BUWAL [1991] typical energy consumption values of 900 MJ (thermal) and 450 MJ (electrical) for one ton of coal from an underground mine can be derived. The energy consumption for coal from open pit mines is significantly lower at 4 MJ (thermal) and 32 MJ (electrical) per ton of coal. For comparison: the thermal combustion value of 1 ton of coal is about

29,000 MJ. For the mining of 1 ton of iron ore BUWAL reports a typical energy consumption of 0.5 GJ (thermal).
Methane emissions from coal mining should also be considered in the greenhouse gas emission inventory if mining were included. Methane is regulated under the Kyoto protocol and is to be considered using a global warming potential of 21 relative to CO_2. The IPCC-Inventory guideline [IPCC/OECD/IEA, 1996] reports typical emission of about 10 Kg and 1 Kg of methane per ton from underground mines and open pit mines, respectively. These emissions correspond to 0.2 tons and 0.02 tons of CO_2-equivalents per ton of coal. These values can be compared to the 2 to 3.7 tons[6] of CO_2 released through the combustion of coal.

B) Auxiliaries: The use of auxiliary compounds like limestone is quite significant but also quite variable in terms of composition and quantities. In average about 0.03 tons of dolomite or limestone are used [IISI, 1998b] per ton of primary steel. The actual range varies between 0 and 0.2 tons per ton of steel. Generally roughly 50 % of the mass of dolomite and limestone will be emitted as CO_2 leaving CaO or MgO in the slag phase. BUWAL [1991] estimates that the mining of 1 ton of limestone requires 50 MJ (thermal) and 10 MJ (electrical).

C) Transportation: BUWAL [1991] reports the energy requirements per kilometre-ton (kmT) of transportation as 0.2 MJ /kmT for bulk transport on the open sea, 0.5 MJ /kmT for barge transport on rivers, 0.9 MJ/kmT for truck transport and 0.1 MJ /kmT (electrical) for train transport.

D) Real mix of products: For this study an indicative value of 3 GJ / T of steel was used to account for the energy requirements and associated emissions for rolling and finishing. The IISI-Lifecycle Inventory Project [IISI, 1998b] reports mean energy consumption values for different steel products. These values are not directly comparable to those derived in this study because of different system boundaries and accounting methods. Nevertheless, they spread per ton of different products from the BF route like hot rolled coil, pickled hot rolled coil, cold rolled coil, finished cold rolled coil, tinplated coil, tin-free steel and hot-dip galvanised coil: 25.0 GJ, 26.6 GJ, 27.9 GJ, 30.2 GJ, 34.5 GJ, 34.7 GJ and 31.5 GJ, respectively. This indicates that comparisons of energy efficiencies and emission estimates should ideally include the real product mix in a country or in a certain steel plant.

E) "Embodied energy": No quantitative information was available on the required energy for the construction of plants and machinery. An indicative number can be derived from UN/ECE [1997] where a number of 5 million tons of capital scrap generated from demolition in steel works and foundries is reported for the year 1996. Compared to the crude steel production of 750 million tons

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[6] The CO_2-emission from coal depends on the carbon content. Pure carbon would give a CO_2-emission of 3.7 tonne per tonne of coal. Most coal are much lower in carbon content.

in 1996 it can be concluded that "embodied energy" requirements for plants and machinery may be in the order of 1% of the total energy requirement of the industry.

Table 5.5 summarises the potential effect on energy consumption and emissions from the sources. It is evident that under certain circumstances the mining of coal and the production of real finished products can contribute significant additional emissions to those explicitly quantified in this study.

Table 5.5 Contribution to energy use and emissions from processes that are not included into the emission estimate of this study. Values are indicative values for the Western World. Individual sites or processes could depart from these ranges.

	Energy consumption per T steel	**CO_2 emissions per T steel**
Mining of iron ore	500 MJ	0.05 T CO_2
Mining of coal	20 to 1,400 MJ	0.03 – 0.3 T CO_2
Methane fr. coal mining	-	0.01 – 0.1 T CO_2 eq.
Mining of auxiliaries	5-20 MJ	<0.01 T CO_2
Carbon dioxide fr. lime	-	0 - 0.1 T CO_2
Transportation	< 1,500 MJ	< 0.1 T CO_2
Real products	(-1,000) - 8,000 MJ	(-0.1) - 0.8 T CO_2
"Embodied energy"	200 MJ	0.01 T CO_2
FOR COMPARISON: TYPICAL VALUE FOR PRIMARY STEEL	***23,000 MJ***	***1.8 T CO_2***

5.10 SUMMARY

According to this study it is estimated that the global iron and steel industry emitted 1310, 1427 and 1442 million tons of CO_2 in 1985, 1990 and 1995. Total anthropogenic emissions of CO_2 from fossil fuel consumption and cement production in 1990 were around 21,700 million tons yr^{-1} [Olivier, *et al*, 1996]. Even within the narrow system boundaries commonly used for this industry it was thus responsible for roughly 7 % of global CO_2 emissions. If mining activities, the transportation of raw materials and at least half-finished products were included, this share would increase to near 10 % of total CO_2 emissions.

Recent changes of emissions in the regions have been larger than visible on the global aggregation level. This is due to a decline of production and emissions in the countries of the former Soviet Union and the Eastern Europe on the one hand and due to a rapid increase of production and emissions in China and other dynamic developing countries on the other hand.

It should be kept in mind that the energy consumption per process step is the key parameter influencing emission levels. The global coverage of these parameters is incomplete. Data on their temporal evolution in different regions are virtually absent. A reliable short term emission monitoring of the iron- and steel industry still needs to be established.

6. OPTIONS TO REDUCE EMISSIONS

6.1 TECHNIQUES TO IMPROVE THE ENERGY EFFICIENCY

Techniques to improve the energy efficiency of steel making routes can be divided into available technologies and new or emerging technologies. There are many references that deal with energy efficiency improvement in the iron and steel industry. Here only some recent and dependable overview studies are given.
For an elaborate overview of available technologies is referred to Worrell *et al.* [1999]. IISI also gives detailed descriptions of available technologies [IISI, 1998a]. Another useful source is the 'Best Available Techniques Reference Document on the Production of Iron and Steel' [EC, 1999]. This document also describes some new techniques. New and emerging technologies are also described by AISI [1998] and De Beer *et al.* [1998].

We will describe techniques to improve the energy efficiency of the two predominant steel making routes: integrated primary steel making and electric arc minimills. For each route the main energy efficiency improvement options are described, both available and emerging techniques. Some techniques that have a smaller improvement potential are also mentioned.

One of the objectives is to construct carbon dioxide abatement curves of energy efficiency improvement per region. To do so we do not only need data on savings potential but also on costs. Furthermore, we need data on the current and the maximum penetration of an option. Since such data are scarcely available per region, estimates have to be used. It has to be emphasised that because of this data problem, the abatement curves represent tentative results only. How the abatement curves are constructed is described in paragraph 6.1.

6.1.1 Available techniques for integrated primary steel plants

In this section available techniques to improve the energy efficiency of integrated steel mills are described. Potential saving on fuel and electricity and costs of all available measures for integrated steel plants are summarised in Table 6.2. To determine the potential reduction of CO_2-emissions and associated costs per region assumptions on existing and maximum penetration are required. These are given in Table 6.3. For some techniques, e.g. continuous casting and replacement of open hearth furnaces, the existing penetration is available through statistics from IISI. For most techniques assumptions had to be made. These assumptions are given at the descriptions of the techniques.

Ore preparation (sintering). The technique with the largest saving potential is recovery of the heat of the sinter cooler air. The recovered heat can be used to preheat raw material or combustion air or to produce steam. Sinter plant heat recovery has been applied in several integrated mills world wide [AISI, 1998; Worrell *et al.*, 1999]. Energy savings are estimated at 0.55 GJ/tonne sinter; the electricity demand increases by 1.5 kWh/tonne sinter. These data are based on a retrofitted system at Hoogovens, the Netherlands [Worrell *et al*, 1999]. Capital costs are estimated at 3 US$/tonne sinter.

Sinter plant heat recovery is not common in the USA [Worrell *et al*, 1999], but is installed at numerous mills in Europe. We assume a 30% penetration in EU15 and Nafta and in Remaining countries (mainly in Japan, Korea and Taiwan). In the other regions we assume a zero penetration in 1995. Technically, the technique can be applied at all mills, so the maximum penetration is 100%.

Other measures that can be taken at the sinter plant are material segregation charging, sinter bed depth increase and reducing leaks in the offgas system. Total savings are estimated at 0.1-0.15 GJ/tonne sinter [IISI, 1998a] and is included in the option miscellaneous.

Coke making. The sensible heat of the hot cokes contain half of the energy input to the process [IISI, 1998a]. In conventional wet quenching this energy is lost to the atmosphere. Coke dry quenching cannot only recover part of this energy, but also reduce dust emissions from coke plants. Dry coke quenching is typically installed as an environmental control technique [Worrell *et al.*, 199]. The coke is quenched by an inert gas and the heat is used to produce steam. This steam can be used to, for instance, generate electricity. Coke dry quenching has been implemented at several plants in Japan, Germany, Brazil, Finland and Taiwan [Worrell *et al.*, 1999]. The steam production equals 0.8-1.4 GJ/tonne of coke [Worrell *et al.*, 1999; IISI, 1998a]. Since it is not expected that many new coke plants will be built, retrofit capital costs should be taken: 70 US$/tonne coke. Operation and maintenance costs are estimated to increase by 0.5 US$/tonne coke.

The existing penetration of coke dry quenching is small: 2% in EU15-Nafta and 5% in remaining countries (estimate on the basis of number of installations). Maximum technical penetration is 100%.

Other measures that can be taken at the coke ovens are:
- recovery of the sensible heat of coke oven by-product gas
- recovery of the sensible heat of waste gas
- coal moisture control
- coke oven aspiration
- fuel gas preheating
- Programmed heating.

Total savings of these measures is estimated at 0.4-0.8 GJ/tonne coke [Worrell *et al.*, 1999; IISI, 1998a] and is included in the option miscellaneous.

Blast furnace.

Pulverised coal injection - Injection of fuel, particularly pulverised coal, into the blast furnace to replace part of the coke is already a common measure in many countries. Since the processes in the blast furnace are to a large extent still a black box, the maximum injection rate is still not clear but is estimated at 280-300 kg of pulverised coal per tonne of pig iron. Experiments with such a high injection rate at Hoogovens turned out to be a failure [De Jong, 1999]. The highest injection rate achieved so far is 225 kg/tonne pig, amongst others at Hoogovens.

The maximum injection rate depends amongst others on the shape and size of the blast furnace. We assume that at small furnaces an injection rate of 130 kg/tonne pig iron can be reached, whereas at larger blast furnaces 225 kg/tonne pig iron is attainable. The divisions between large and small furnaces differ per region, but this not exactly known, nor is the current injection rate per furnace. Estimates are given in Table 6.3.

Coal injection results in savings at coke making. Per tonne of coke that is replaced about 1.08 tonne of coal is required [Worrell *et al.*, 1999]. The energy saved is on average 5 GJ/tonne coke replaced, that is the energy requirement for coke making.

Capital costs are related to the need for coal grinding equipment and are 50-55 US$/tonne of coal injected [Worrell *et al.*, 1999]. Additional operation costs are related to extra oxygen injection and operation of the grinding line. This is offset by the reduced costs for operation the coke ovens. A saving on fuel costs is achieved as injectant coal is about 10% cheaper than coking coal, equalling 5 US$/tonne.

Top gas recovery turbines – Blast furnace that are operated at a pressure of 2-4 bar can be equipped with turbines that recover part of the energy of the top gas in the form of electricity. The gas has to be cleaned before entering the turbine. In the common wet cleaning system the temperature of the gas reduces from 150° to 40°C [IISI, 1998a]. Using a dry cleaning system up to 30% more energy can be recovered. However, such a system has not been implemented and is far more expensive than the wet cleaning system.

Wet top gas recovery turbines can only be operated at furnaces with a high pressure and the economics are more favourable at larger furnaces. The electricity production is in the range of 20-40 kWh/tonne pig iron [IISI, 1998a; Worrell et al., 1999]. Capital costs are US$20/tonne pig iron [Worrell et al., 1999]. Operation and maintenance costs are estimated at US$0.2/tonne pig iron.

This technology is very common in Europe and Japan, but not in the USA and other countries. The maximum penetration is limited to about 80% (estimate, no distinction to world regions possible). The remainder of the furnaces has a pressure that is too low for economic exploitation of this technology.

Hot blast stove automation – Stove efficiency is affected by many factors: the hot blast temperature, the calorific value of the gas, excess combustion air, enrichment of combustion air with oxygen, cycle times, operation practice, stove design and condition of the stoves [IISI, 1998a]. Some of these factors can be

optimised by use of computer control. Savings are estimated at 0.37 GJ/tonne pig iron and capital costs are 0.3 US$/tonne pig iron [Worrell et al., 1999]. Since this technology is common to modern large furnaces, the existing penetration is estimated at 50% in EU15-Nafta and remaining countries. For the FSU, where developments came to a hold a decade ago, the existing penetration is estimated at 5%. For China the penetration is estimated at 10%.
Improved blast furnace control systems – Computer aided control systems are successfully used at blast furnaces in Europe, Japan, Canada and USA [Worrell et al., 1999]. Savings are estimated to be 0.4 GJ/tonne pig iron and capital costs are estimated at 0.5 US$/tonne pig iron [Worrell et al., 1999]. The same penetration assumptions are made as for hot blast stove automation.

Other measures that can be applied to blast furnaces:
- heat recovery from hot stove waste gas
- oxygen enrichment of combustion air for stoves
- cold blast main insulation
- improving blower efficiency (coupled with cogeneration)
- heat recovery from slag.

The total saving of these measures is estimated at 0.2 GJ/tonne pig iron and is included in the measure miscellaneous.

Basic oxygen furnace. By avoiding combustion of BOF-gas each time the converter is opened for charging or discharging, BOF-gas can be recovered and used as fuel. This system is known as suppressed combustion and is already very common in Europe and Japan. The existing penetration is EU15-Nafta is estimated at 60% and in remaining countries at 50%. For FSU the penetration is estimated at 5% and for China at 10%. Maximum technical penetration is 100%.
The sensible heat can be recovered in a waste heat boiler. An additional environmental benefit is the reduced dust emission. The dust, with a high metal content, can be recycled in the sinter plant. BOF gas recovery can be optimised by using an expert system and pressure control [IISI, 1998a]. Total energy savings are 0.6-1.0 GJ/tonne of liquid steel [Worrell et al., 1999; IISI, 1998a]. Suppressed combustion can make a basic oxygen furnace a net energy producer. Capital costs are 22 US$/tonne of liquid steel [Worrell et al., 1999].

Other measures that van be taken at the basic oxygen furnace are:
- vessel bottom stirring
- programmed ladle heating
- dry gas cleaning
- variable speed drives on fans

The total savings of these measures are estimated at 0.05-0.1 GJ/tonne liquid steel and are included in the measure miscellaneous.

Open hearth furnace. The open hearth furnace is an outdated process to make steel. The specific energy consumption is 2-3 GJ/tonne liquid steel higher than of the basic oxygen furnace. Table 6.1 gives an overview that still had open hearth capacity in 1998 [IISI, 1998a]. The total production is about 5% of the global steel production. Especially in the former USSR countries the share of open hearth furnaces is still high. In China the share decreased from 33% in 1978 to 5% in 1998; the intention is to have all open hearth furnace shut down in the year 2000 [Li and Wang, 1999].

Table 6.1: 1998 production of steel in open hearth furnaces [IISI, 1999b]

Country	Production (million tonnes	Share total steel production
Russia	12.2	28%
Ukraine	11.8	48%
PR China	5.6	5%
India	3.4	14%
Other former USSR	0.8	14%
Poland	0.7	7%
Romania	0.7	11%
Other Asia	0.2	2%
Czech Republic	0.1	1%
World	**35.5**	**5%**

We assume that all open hearth furnaces will be shut down and replaced by basic oxygen furnaces. No capital costs are ascribed to this energy saving since the replacement is seen as an autonomous technological development.

Casting

Adopt continuous casting - In 1998 the penetration of continuous casting was 83.3% world wide; penetrations per world region are given in Table 6.3 [IISI, 1999b]. The remainder was cast as ingots. Ingot casting uses about 1.5-3.0 GJ/tonne cast steel more than continuous casting. It is assumed that continuous casting will fully penetrate. Investment costs are 69 US$/tonne cast steel [Worrell et al., 1999]. Operation cost can be reduced significantly: -31 US$/tonne cast steel [Worrell et al., 1999].

Thin slab casting – Thin slab casting allows casting of thinner slabs (40-125 mm) than with continuous casting (150-300 mm) (See also section 3.1.5). Less energy is required to reheat the slabs before rolling. Thin slab casters were originally designed for minimills, but are now being constructed or planned by some integrated steel manufacturers. IISI [1998a] reports for the energy consumption of an actual thin slab caster (CSP-technology) the following data: 250 GJ of electricity/tonne and 350 MJ fuel/tonne. Continuous casting, reheating and hot rolling use about 810 MJ of fuel and 600 MJ of electricity per tonne of slabs. Thus savings amount to 350 GJ of electricity and 460 MJ of fuel per tonne of slabs.

Investment costs for construction of new thin slab casters at Hoogovens and Thyssen are US$200/tonne rolled steel and US$300/tonne rolled steel, respectively [De Beer *et al.*, 1998]. We assume that the lower costs can be realised also at future projects. Operation and maintenance costs are 80% to 110% of that for continuous casting. We estimate the average reduction in O&M-costs at 0.5 US$/tonne rolled steel.

Thin slab casters can only be applied to the production of slabs. Furthermore, it competes with continuous casting, which is a mature technology. Since thin slab casting is not yet a proven technology for integrated steel mills, we do not assume full penetration before 2010. Thin slab casting will initially mainly be used to extent the capacity of existing mills. The assumed maximum penetration varies per region and is reported in Table 6.3.

Other measures that can be applied to casting are:

- efficient ladle preheating

Savings are estimated at 0.02 GJ/tcs and are included in the measure miscellaneous.

Rolling and finishing

Hot charging and direct rolling – Often the distance between caster and rolling mill is large, resulting in a temperature decrease of the slabs that are transported directly to the rolling mill. In most mills the largest share of the slabs is first stocked for a period that varies from days to weeks before being rolled. These slabs are cooled completely.

The sensible heat of the hot slabs can be retained by direct rolling or storing the slabs in a conversion box. Direct rolling techniques require that the distance between caster and roller is small and that the slabs are of high-quality so that intermediate inspection is not required. Furthermore, it the production schedule has to be altered.

Energy savings are estimated to be 0.6 GJ of fuel/tonne of hot rolled steel on average [Worrell et al., 1999; IISI, 1998a]. The techniques can only be applied to slabs that are continuously cast (in thin slab casters the rolling mill is already linked to the caster).

Investment costs can vary strongly per plant but are averaged at US$15/tonne. Reduced slab stocking and handling results in a saving on operation costs of US$-1.15/tonne [Worrell et al., 1999].

Existing penetration is estimated on the basis of known plants at 5% in EU15-Nafta and remaining countries. In other regions this technique is not in operation. Maximum penetration is limited by the share of slabs and by lay-out of steel mills and is set at 25%.

Recuperative burners – Recuperative burners can be installed at the reheating furnace. Separate heat recovery from combustion air is already common in modern steel plants. Additional savings that can be attained by using recuperative burners are small. Therefore, this measure can only be applied economically to furnaces that have no heat recovery at all (20% in the western world [Worrell et al., 1999]; 80% in the rest of the world). The fuel savings is 0.7 GJ/tonne product on average and investment costs are estimated at US$ 2.5/tonne [Worrell et al., 1999]. The same penetration is assumed as for hot charging.

Other measures that can be applied to rolling and finishing:

- process control in hot strip mill
- insulation of furnaces
- controlling oxygen levels and variable speed drives on combustion air fans
- energy efficient drives in hot rolling mill
- waste heat recovery from cooling water
- reduce the unfired preheat zone
- computer/combustion control modes
- scheduled free rolling
- coil box
- thermo-mechanical control process at the plate mill
- longer furnace at section mill to decrease waste gas temperature
- reducing discharge temperature at section reheating furnace
- various measures at cold mill and finishing operation

The total fuel savings of these measures are estimated at 0.5 GJ/tonne product and the total electricity savings at 0.1 GJ/tonne product and are included in the measure various.

Overall measures

Cogeneration – Integrated steel mills often have a power plant that consists of a steam boiler and back-pressure and condensing steam boilers. The primary goal is to raise steam to drive the blowers for blast compression. The remainder of the steam is converted to electricity. The capacity and the efficiency of the power plant are highly plant specific. The steam demand for the process is estimated at 1 GJ/thm. Assuming that 3.5 GJ/thm of process off-gas is burned to raise steam with an efficiency of 90% and electricity with an efficiency of 30%, 0.65 GJ of electricity can be produced when the steam demand is met.

A combined cycle cogeneration plant consists of a gas turbine, a waste heat boiler and a steam turbine. Existing power plants can be repowered to a cogeneration plant. Since process gas has a lower calorific value than natural gas the design of the gas turbine has to be altered. In Japan and the Netherlands combined cycles are in operation that make use of low calorific gas (about 4 GJ/m^3) [De Beer *et al.*, 1998]. The efficiency at maximum power generation is 46%; when steam is extracted the efficiency is lower. An overall efficiency of 85% is attainable. We assume a thermal efficiency of 45% and an electric efficiency of 40%.

To produce the same amount of steam 2.2 GJ of gas is required and 0.88 GJ of electricity can be produced. Thus a saving of 1.3 GJ of fuel is achieved; this fuel can be converted to electricity or used for another purpose. The electricity production increases by 0.23 GJ/tonne of product.

For an integrated mill with a capacity of 7 million tonnes a 250 MW combined cycle plant will be required. Investment costs are about US$1000/kW. Per tonne of steel product this equals US$36. Operation and maintenance costs are assumed to remain equal.

The existing penetration of CHP in integrated steel plants is not known. We assume a penetration of 10% in EU15-Nafta and Remaining countries, of 5% in

China (at some new mills) and 1% in Remaining countries. We assume that this measure can technically be implemented at all steel mills.

It should be noted that these figures are tentative only; large variations in the potential saving will occur from mill to mill.

Good housekeeping and preventative maintenance – This involves training personnel to be attentive to energy consumption and efficiency. Examples are reduction of material losses in shaping and finishing steps. At Hoogovens a saving of 0.3 GJ/tonne of products could be achieved in this way [De Jong, 1999]. Other measures are related to a reduction of heat leakage's, e.g. by closing the doors [Worrell et al., 1999]. The total saving of this measure is estimated at 0.5 GJ/tonne. Investment costs are minimal and set at US$0.01/tonne. Operation costs related to training of personnel are estimated at US$0.02/tonne. We assume a higher degree of implementation in EU15-Nafta and remaining countries (10%) than in China (5%) and FSU (1%).

Miscellaneous – Measures covered under miscellaneous are mentioned at the separate operations. Fuel and electricity savings total to 1 GJ and 0.2 GJ/tonne of product, respectively. Investment costs are averaged at US$5/tonne and operation and maintenance costs at 10% of the investment costs. We assume a higher degree of implementation in EU15-Nafta and remaining countries (25%) than in China (5%) and FSU (1%).

6.1.2 New and emerging techniques for integrated steel plants

In this section new and emerging techniques to improve the energy efficiency of integrated steel plants are described. The saving potential is estimated and where known the investment costs are given. Barriers to implementation are also addressed.

Coke making

Coke making does not only use 15-20% of the energy consumed in a steel mill, it is also the operation with a large environmental burden. Developments are primarily directed at reducing emissions to the atmosphere.

Jumbo coke reactor – This involves a reconfiguration of traditional coke ovens with larger individual batch process ovens. Special features increase oven productivity, reduce the number of ovens, increase raw material flexibility, improve coke quality, reduce the specific energy consumption, and improve environmental control. The technology was tested in a pilot plant consisting of a single chamber [IISII, 1998a]. Pilot plant tests did not show an energy saving compared to conventional coke ovens but this may be due to incomparable operating practices [IISI, 1998a].

Continuous coking and syngas production – This development involves continuous production of coke from metallurgical coal and cleaning and cracking of the gases under completely sealed conditions. The cleaned gases can be used as syngas [AISI, 1998]. Energy savings are not known.

A major barrier to the implementation of new coking technologies is the associated high development and investment cost. Replacement of existing coke plants will only take place at the end of their technical lifetime. Competition is to be expected from new iron making technologies that avoid the use of coke.

Closing of coke batteries – A general tendency in developed countries is to look for options to avoid the construction of new coke ovens to replace old ovens that will be taken out of operation in the near future. One way to deal with this is to increase the amount of pulverised coal injected into the blast furnace. Another way is to use alternative iron reduction technologies. Direct reduction is already a commercial technology. Smelting reduction is still under development, except for the COREX-process. These technologies have the ability to reduce iron ore without coke but by using coal or natural gas.

Iron making

Smelt reduction – See section 3.1.3.3. A barrier to the development is the high development cost. Steel companies are not willing to carry these costs alone. For example, Hoogovens had been looking for an industrial partner for the development of their smelt reduction process for some years without success before they decided to postpone the development. Despite support of the Dutch government the risk was too high. The merging with British Steel can also be a reason for the postponement. The new company (Corus) has to decide on a common strategy first before making a risky decision whether or not to continue with the development of smelt reduction. On the one hand, the tendency of companies to merge can be seen as a barrier to the development and implementation of new technologies. On the other hand, the capacity to invest may increase.

The energy saving of smelt reduction over a conventional integrated steel plant is 1.5 GJ/thm at maximum. This can be achieved with the CCF-technology. Development of this technology is stalled for the moment. According to previous development plans, a commercial plant could be realised in less than 10 year.

We assume that smelt reduction technologies can still be commercially available by 2010. The rate of penetration is limited by the rate at which existing blast furnaces are placed out of operation and the growth in steel demand. Furthermore, smelt reduction processes have to compete with minimills.

Casting

Near net shape casting –Figure 6.1 provides an overview of current and potential future casting strategies as seen by the American Iron and Steel Institute [AISI, 1998]. This figure shows that for all technologies new casting techniques are being developed or conceived. As the future casting techniques all produce steel products that are close to the final shape, these techniques are generally referred to as near net shape casting techniques.

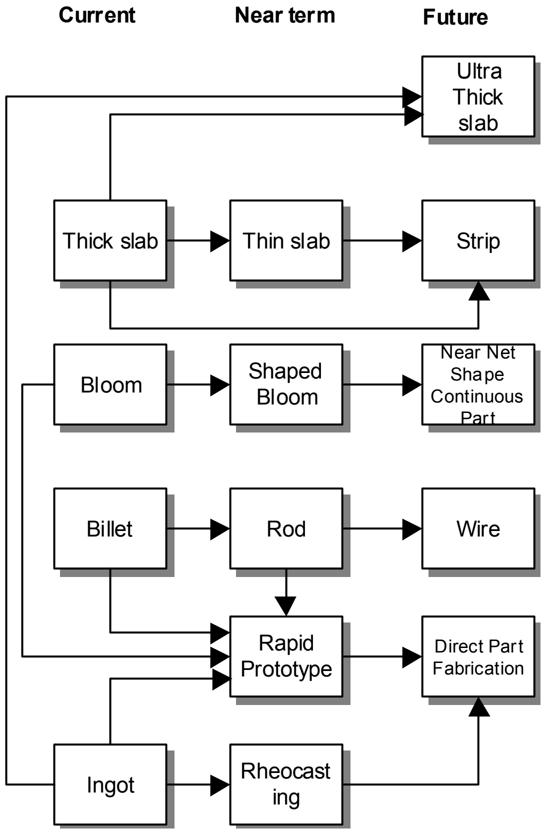

Figure 6.1: Current and potential future casting strategies according to AISI [1998].

The development of near net shape casting techniques is driven by low capital and operating costs, flexibility, niche markets and the potential for new product development [AISI, 1998]. Near net shape casting allows a significant reduction of the size of a steel plant: continuous casting, rolling, finishing and storage can be avoided to a large extent.

Near net shape casting techniques are being developed by steel machinery manufacturers in conjunction with steel makers. The main barrier is the initial investment costs.

Table 6.2: Overview of the main available techniques to improve the energy efficiency of integrated steel mills that can be taken up to 2010.

	Process	**Option**	**Fuel savings** *(GJ/t stage-product)*	**Electricity savings** *(GJe/t stage product)*	**Operation and maintenance costs** *(US$/t stage product)*	**Capital costs** *(US$/tonne stage product)*	**Life-time** *(year)*
1	Sintering	Sinter plant heat recovery	0.55	-0.01	0.00	3.00	25
2	Coke making	Dry coke quenching	1.00	0.00	0.50	70.00	25
3	Blast furnace	Pulverised coal injection from 0 to 130 kg/thm	0.65	0.00	-1.95	7.15	25
4	Blast furnace	Pulverised coal injection from 130 to 225 kg/thm	0.44	0.00	-1.43	5.23	25
5	Blast furnace	Top pressure recovery turbines	0.00	0.11	0.00	20.00	15
6	Blast furnace	Hot blast stove automation	0.37	0.00	0.00	0.30	15
7	Blast furnace	Improved Blast furnace control systems	0.40	0.00	0.00	0.36	15
8	Basic oxygen furnace	BOF-gas and sensible heat recovery	0.92	0.00	0.00	22.00	15
9	Open hearth furnace	Adopt basic oxygen furnace	2.50	0.00	0.00	45.00	25
10	Casting	Adopt continuous casting	2.86	0.00	-31.00	69.00	25
11	Casting	Thin slab casting	0.45	-0.02	-10.00	250.00	25
12	Rolling and finishing	Hot charging	0.60	0.00	-1.15	15.00	25
13	Rolling and finishing	Recuperative burners	0.60	0.00	0.00	2.50	10
14	Overall	Cogeneration	1.30	0.23	0.39	39.00	15
15	Overall	Preventative maintenance	0.45	0.04	0.02	0.01	15
16	Overall	Miscellaneous	1.00	0.20	0.05	5.00	15

Table 6.3: Estimated penetration in 1995 and maximum technical penetration in 2010 of techniques to improve the energy efficiency of integrated steel plants per world region.

		UE15 & Nafta		**FSU & EET**		**China**		**Remaining countries**	
Process	Option	Existing penetration	Maximum technical penetration	Existing penetration	Maximum technical penetration	Existing penetration	Maximum technical penetration	Existing penetration	Maximum technical penetration
		(% in 1995)	*(% in 2010)*	*(% in 1995)*	*(% in 2010)*	*(% in 1995)*	*(% in 2010)*	*(% in 1995)*	*(% in 2010)*
Sintering	Sinter plant heat recovery	29%	100%	0%	100%	0%	100%	30%	100%
Coke making	Dry coke quenching	2%	100%	0%	100%	0%	100%	5%	100%
Blast furnace	Pulverized coal injection from 0 to 130 kg/thm	75%	80%	25%	80%	60%	80%	50%	80%
Blast furnace	Pulverized coal injection from 130 to 225 kg/thm	5%	40%	0%	40%	5%	40%	5%	40%
Blast furnace	Top pressure recovery turbines	47%	80%	5%	80%	10%	80%	48%	80%
Blast furnace	Hot blast stove automation	50%	100%	5%	100%	10%	100%	50%	100%
Blast furnace	Improved Blast furnace control systems	50%	100%	5%	100%	10%	100%	50%	100%
Basic oxygen furnace	BOF-gas and sensible heat recovery	59%	100%	5%	100%	10%	100%	50%	100%
Open hearth furnace	Adopt basic oxygen furnace	100%	100%	72%	100%	72%	100%	41%	100%
Casting	Adopt continuous casting	95%	100%	54%	100%	40%	100%	90%	100%
Casting	Thin slab casting	0%	20%	0%	20%	0%	20%	0%	20%
Rolling and finishing	Hot charging	5%	24%	0%	24%	0%	24%	5%	24%
Rolling and finishing	Recuperative burners	5%	25%	0%	25%	0%	25%	5%	25%
Overall	Cogeneration	10%	100%	1%	100%	5%	100%	10%	100%
Overall	Preventance maintenance	10%	100%	1%	100%	5%	100%	10%	100%
Overall	Miscelleneous	25%	100%	1%	100%	5%	100%	25%	100%

6.1.3 Available techniques for minimills

In this chapter we describe techniques that can be applied to electric arc furnaces, the heart of the minimills. Energy efficient techniques that can be applied to other operations in the minimill, mainly casting, rolling and finishing, are equal to that for an integrated steel mill. Potential and costs of the techniques are summarised in Table 6.4. In Table 6.5 is indicated which measures can be applied and what is the existing and maximum penetration. Since data on degree of penetration are very rare these data are based mainly on own estimates. Results should therefore be seen as tentative.

Automated control. Artificial intelligence techniques, e.g. fuzzy logics or neural networks, can be applied to optimise the energy input. Especially with the complex heating schemes that are used in modern UHP-furnaces this type of control systems is necessary [AISI, 1999]. The savings depend on the raw material input, the type of furnace and the furnace operation. In line with [Worrell et al., 1999] we assume that a saving of 30 kWh/tonne is possible on average. Other advantages of automated controls are an increased productivity and a lower electrode consumption. Worrell et al. [1999] estimate the capital costs at US$0.95/tonne steel. The penetration in the USA was 9% in 1994. We assume that in 1995 in the EU15 and Nafta the penetration was 10%, in FSU&EET and China the penetration was 0% and in the remaining countries 5%. Maximum penetration is in all regions 90%.

Post-combustion. During the melting and refining of steel carbon monoxide is released. By injecting oxygen this carbon monoxide can be post-combusted and the heat released can be returned to the molten steel bath. Post-combustion is also used in oxy-steel making and is studied closely in relation to smelt-reduction. The technique can result in an increased productivity of the electric arc furnace.

The savings on electricity demand are in the range of 20-40 kWh/tls [IISI, 1998a]. However, an oxygen consumption of about 9 Nm^3/tls is required [IISI, 1998a]. To make this oxygen 5 kWh/tls is needed. We assume net savings of 25 kWh/tls. Investment costs are estimated at US$1/tls.

No data for the penetration of post-combustion system are available. We assume that post-combustion is applied to 20% of the furnaces in EU15 & Nafta, to 5% in FSU & EET and China and to 10% in the remaining countries. Post-combustion can technically be applied to nearly all furnaces (90%).

Ultra High Power furnaces. By using UHP-furnaces (700 kVA/t heat size) instead of normal power furnaces (on average 480 kVA/t heat size in the USA [Worrell et al., 1999]), transformer losses can be reduced by 3% on average. The associated saving on electricity is input is 15 kWh/tls. The use of UHP might lead to increased refractory wear, making cooling necessary. Based on a retrofit at one minimill in the USA the capital costs can be estimated at

US$8.3/tls. Operation and maintenance costs are estimated at 1% of the capital costs.
Modern electric arc furnaces usually are already UHP-furnaces. Older furnaces can be retrofitted, except for the smaller furnaces. In 1994 about 40% of the electric arc furnaces in the USA were UHP-furnaces [Worrell et al., 1999]. We assume a penetration in 1995 of 40% in EU15-Nafta, 10% in FSU&EET, 20% in China and 30% in the remaining countries. Maximum penetration is assumed to be 70% in all regions.

Bottom stirring. Injection of an inert gas in the bottom of the furnace increases the heat transfer between slag and melt. This measure can only be applied to furnaces without oxygen injection, because these furnaces are sufficiently turbulent. Savings on the electricity demand are averaged at 20 kWh/tls. Capital costs are US$0.6/tls [Worrell et al., 1999]. Existing penetration is estimated at 5% in EU15-Nafta, 0% in FSU&EET and China, and 2% in remaining countries. Penetration is limited to the smaller furnaces. Therefore, the maximum penetration is set at 15%.

Foamy slag practice. A foamy slag, obtained by carbon or oxygen injection, reduces the heat losses from the melt. Savings are estimated at 5-7 kWh/tls [Worrell et al., 1999]. Capital costs for installing oxygen lances are estimated at US$10/tonne capacity. On the one hand, there are additional costs for operation of the lances and for oxygen. On the other hand, increased productivity results in annual costs savings, which are estimated to be US$1.8/tls [Worrell et al., 1999]. We assume overall annual costs savings of US$1/tls.
Applying foamy slag practice is a quite common technology [Worrell et al., 1999]. A 60% penetration is assumed in EU15-Nafta, 30% in FSU&EET and China, and 50% in remaining countries. Maximum penetration is assumed to be 90% in all regions.

Scrap preheating. Preheating of the scrap before being charged into the furnace by use of the hot off-gases of the furnace is a way to save on the power demand for melting. Two technologies are in use: the Finger Shaft Furnace and Conroll. Scrap preheating in the Finger Shaft Furnace is achieved by holding the scrap in a bucket above the furnace. Cooled fingers in the form of a grab at the bottom of the bucket hold the scrap in place. When the preheating stage is finished the grab is released and the scrap is loaded into the melt. In the Consteel process scrap is preheated in a long tunnel with countercurrent off-gases and auxiliary burners. The scrap is fed continuously into the furnace.
With both systems a saving of about 80 kWh/tls can be achieved [IISI, 1998a]. Both systems have already been applied to numerous furnaces in USA, Europe and Japan. An existing furnace is easier to retrofit to a Finger Shaft Furnace than to a Conroll-process. Retrofit costs to a Finger Shaft Furnace are US$6/tls for a 100 tonnes furnace [Worrell et al., 1999]. Production costs savings are estimated at US$4.5/tls. An additional fuel consumption of 0.2 GJ/tls is required [De Beer *et al.*, 1998].

It is estimated that 10% of the minimills in EU15-Nafta have installed scrap preheating. It is assumed that scrap preheating is not used in FSU&EET and China. In the remaining countries we estimate a penetration of 5%. Maximum penetration in all regions is estimated at 75%.

Oxy-fuel burners. Burning oil or natural gas can replace part of the electricity demand of an electric arc furnace. Oxy-fuel burners can be positioned at the side wall to impinge on cold spots. Another arrangement is a single burner through the work door. The savings depend on burner power and burner operation. Burner power is determined by the size of the furnace and burner operation depends on melting practice and configuration of the furnace.
Per Nm^3 of natural gas about 6.8 kWh/tls can be replaced [IISI, 1998a]. Typical savings are on the order of 30-70 kWh/tls [IISI, 1998a]. In this study we assume an average of 50 kWh/tls. To replace this electricity demand about 6 Nm^3 of gas is required, equalling 0.24 GJ[7].
Capital costs are estimated at US$4.80/tls [Worrell et al., 1999]. Application of oxy-fuel burners can lead to reduced tap-to-tap times [IISI, 1998a] and reduce the nitrogen content in steel [Worrell *et al.*, 1999]. These advantages lead to an improvement of the operation costs of US$0.4/tls.
Oxy-fuel burners are a quite common technology in developed countries. We assume a 75% penetration in EU15-Nafta, a 25% penetration in FSU&EET and China and a 50% penetration in the remaining countries. In all regions a maximum penetration of 90% is assumed.

Direct Current (DC)-arc furnaces. About 90 DC-arc furnaces are operating around the world. The advantages of DC-furnaces over AC-furnaces relate to improved heat distribution in the furnace, reduced electrode consumption, reduced tap-to-tap time and reduce flicker on the grid. It is expected that EC-technology is limited to larger furnaces [Worrell et al., 1999]. Based on operational data savings on electricity demand of about 10 kWh/tls can be determined [IISI, 1998a; Worrell *et al.*, 1999]. Additional costs compared to an AC-furnace are estimated at US$3.9/tls [Worrell et al., 1999]. Due to the advantages of a DC-furnace operation and maintenance costs are reduced by US$2.5/tls [Worrell et al., 1999].
DC-technology will only be applied to new furnaces. We assume a maximum penetration of 20% in all regions. In EU15-Nafta the current penetration is estimated at 5%, in FSU&EET and China at 0% and in the remaining countries at 3%.

Miscellaneous. Other options to improve the energy efficiency of a minimill, that are not dealt with separately are:

- energy monitoring and management
- energy efficient drives in rolling mill
- variable speed drives on fans
- waste heat recovery on cooling water of casting

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[7] Assuming a lower heating value of 31.65 MJ/Nm^3 natural gas (Dutch Standard).

- hot metal charging
- adjusting raw material quality
- efficient secondary refining
- twin shell concept.

The total electricity savings of these measures are estimated at 0.2 GJ/tls and the fuel savings at 0.05 GJ/tls. Capital costs are estimated at US$5/tls and operation and maintenance costs at 10% of the capital costs.

6.1.4 New and emerging techniques for minimills

Three areas that offer opportunities to improve the efficiency of minimills will be discussed:

- heat recovery of hot steel
- near net shape casting
- flexibility to raw material.

Heat recovery of hot steel. The energy required for heating scrap from 25°C to melting point and subsequent melting is between 1.05 to 1.36 GJ/tonne; the lower limit is for pig iron and the upper limit is for pure iron [De Beer *et al.*, 1999]. Modern electric arc furnaces approach this value. It can be concluded that electric arc furnaces are already efficient smelters. No new or emerging technologies are identified. Developments are directed at improving the DC-technology and post-combustion in combination with scrap-preheating [AISI, 1999].

The largest energy loss in minimills is related to the heat loss of the hot steel when cooling. Although a few techniques have been developed for integrated steel mills to recover heat at high temperatures, none of them seems economically applicable to nor minimills neither integrated steel mills [De Beer *et al.,* 1998]. The technical feasibility has not been proven either.

Near net shape casting techniques. Further improvements in near net shape casting can reduce the energy demand for casting and rolling. Furthermore, these developments can make minimills even more competitive with integrated steel mill for certain products. For details is referred to section 6.1.4.

Flexibility to raw materials. The limited availability of high-quality scrap encouraged the steel sector to look for scrap substitutes. Direct reduced iron is an example. One development topic is to link the direct reduction unit to the electric arc furnace so that the direct reduced iron can be charged while hot. Problems relate to re-oxidation of the iron. A system was developed to transport direct reduced iron in a pipeline under a nitrogen atmosphere [AISI, 1998]. Another new material is iron carbide, that consists of up to 6.7% carbon. Oxidation of carbon in the furnace releases energy and reduces the electricity demand of the furnace. Estimated savings are on the order of 250-275 kWh/tls [AISI, 1998]. The additional energy demand for the production of iron carbide is estimated at 7.5 GJ/tls, so no overall saving is achieved.

Table 6.4: Overview of the main available techniques to improve the energy efficiency of minimills that can be taken up to 2010.

	Process	**Option**	**Fuel savings** *(GJ/t stage-product)*	**Electricity savings** *(GJe/t stage product)*	**Operation and maintenance costs** *(US$/t stage product)*	**Capital costs** *(US$/tonne stage product)*	**Lifetime** *(year)*
1	Electric arc furnace	Automated controls	0.00	0.11	0.00	0.95	15
2	Electric arc furnace	Post combustion	0.00	0.09	0.02	1.00	15
3	Electric arc furnace	UHP-transformers	0.00	0.06	0.08	8.30	15
4	Electric arc furnace	Bottom stirring	0.00	0.07	-2.00	0.60	0.5
5	Electric arc furnace	Foamy slag practice	0.00	0.02	-1.80	10.00	15
6	Electric arc furnace	Scrap preheating	-0.20	0.29	-4.50	6.00	15
7	Electric arc furnace	Oxy-fuel burners	-0.24	0.18	0.40	4.00	10
8	Electric arc furnace	DC-furnaces	0.00	0.18	-2.50	3.90	25
9	Casting	Thin slab casting	0.46	0.35	-0.50	200.00	25
10	Rolling and finishing	Recuperative burners	0.70	0.00	0.00	2.50	10
11	Overall	Preventance maintenance	0.50	0.04	0.02	0.01	15
12	Overall	Miscelleneous	0.05	0.20	0.05	5.00	15

Table 6.5: Estimated penetration in1995 and maximum technical penetration in 2010 of techniques to improve the energy efficiency of minimills per world region.

Process	Option	**UE15 & Nafta** Existing penetration *(% in 1995)*	Maximum technical penetration *(% in 2010)*	**FSU & EET** Existing penetration *(% in 1995)*	Maximum technical penetration *(% in 2010)*	**China** Existing penetration *(% in 1995)*	Maximum technical penetration *(% in 2010)*	**Remaining countries** Existing penetration *(% in 1995)*	Maximum technical penetratio n *(% in 2010)*
Electric arc furnace		10%	90%	0%	90%	0%	90%	5%	90%
Electric arc furnace	Post combustion	20%	90%	5%	90%	5%	90%	10%	90%
Electric arc furnace	UHP-transformers	40%	70%	10%	70%	20%	70%	30%	70%
Electric arc furnace	Bottom stirring	5%	15%	0%	15%	0%	15%	0%	15%
Electric arc furnace	Foamy slag practice	60%	90%	30%	90%	30%	90%	50%	90%
Electric arc furnace	Scrap preheating	5%	75%	0%	75%	0%	75%	2%	75%
Electric arc furnace	Oxy-fuel burners	75%	90%	25%	90%	25%	90%	50%	90%
Electric arc furnace	DC-furnaces	5%	20%	0%	20%	0%	20%	3%	20%
Casting	Thin slab casting	5%	20%	0%	20%	0%	20%	2%	20%
Rolling and finishing	Recuperative burners	5%	25%	0%	25%	0%	25%	2%	25%
Overall	Preventance maintenance	10%	100%	1%	100%	5%	100%	7%	100%
Overall	Miscelleneous	25%	100%	1%	100%	5%	100%	20%	100%

Pig iron can also be used as a raw material for electric arc furnaces. It has the advantages that it has a high density, low melting point and low metallurgical residuals. Over and above, it is a carbon contributor [AISI, 1998]. Minimills that include a smelt reduction process, which can operate economically at a lower capacity than blast furnaces, might appear in the future.
Chemical upgrading of scrap is also an option to improve the quality of the furnace charge. The current trend is that alloys of steel and other metals, e.g. zinc, are used to improve the quality of the steel. New facilities to separate steel from zinc are being constructed (in Chicago) or have just been put into operation (France). The overall energy effect, including transportation and separation, it not clear yet. Alloys of steel and plastics are also under development [De Jong, 1999]. Plastics have the advantage over metals that they can serve as carbon donator in the furnace. The environmental impact of this option has to be researched carefully.

6.1.5 CO_2- Abatement curves for energy efficiency improvement

The techniques to improve the energy efficiency can be plotted in a CO_2 abatement curve. Abatement curves give a ranking of the options on specific costs. Abated CO_2-emissions are cumulated.

<u>Construction of abatement curves</u>
In abatement curves the specific costs of an option are plotted against the cumulative avoided CO_2 emission. Specific costs are calculated according to:

$$\text{Specific costs} = \frac{\text{Annualised capital costs + annual O \& M - annual saved energy costs}}{\text{Annual abated CO}_2\text{emission}} (US\$ / tonne CO_2)$$

The annualised capital costs are calculated according to:

$$\text{Annualised capital costs} = \frac{\mathrm{d}}{(1 - (1+\mathrm{d})^{-\mathrm{n}})} \times \text{Investment}$$

Where d = the discount rate (in this study 5% and 10% is used[8]) and n is the technical lifetime of the measure.

The saved energy costs are calculated with the following energy prices:

coal US$1.5/GJ	(as specified in the Technical and Financial Assessment Criteria of the IEA Greenhouse Gas R&D Programme)

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[8] This is in accordance with other studies of the IEA Greenhouse Gas Programme. The industry uses higher discount rates to reflect the costs of capital. Discount rates of 20% for normal investment and 50% for non-essential cost reduction schemes (e.g. energy saving schemes) have been mentioned by one reviewer.

electricity US\$14/GJ (=US\$0.05/kWh) (being the average price for large consumers in the Netherlands.)

To determine the influence of the energy price the economic potential will also be determined with energy prices that are reduced by 50%.

The energy price is dependent on the world region and due to changes. One can easily evaluate the effect of the energy price by expressing it in US\$/tonne CO_2 and drawing a straight horizontal line in the abatement curve. All options that lie below this line can be considered to be cost-effective with this energy price.

The annual abated CO_2-emission is calculating by multiplying the primary energy saved by an average CO_2-emission factor.

The primary energy saved per tonne of product is determined by first determining the primary energy saved per tonne of product. Savings on electricity are converted to primary energy using a factor of 2.5, representing a 40% efficiency of power generation. Then, the primary saving per tonne of product is calculated by using a factor that represents the amount of stage product per tonne of steel product (see Table 5.3). This value is corrected for the current penetration and the maximum penetration of the measure (see Table 6.3 and Table 6.5). The current penetration differs per region and is a measure for the efficiency.

The CO_2-emission factors differ per region. Unfortunately, these values are not known exactly. However, based on the CO_2-emission inventory in Chapter 5, we were able to deduce a set of CO_2-emission factors. These factors are given in Table 6.6.

Table 6.6: CO_2-emission factors of integrated steel mills and minimills per world region.

Region	Integrated steel mills	Minimills
EU15-Nafta	1.8	0.7
FSU&EET	2.2	1.1
China	4.1	1.3
Remaining countries	2.4	0.9
World	**2.4**	**0.9**

The differences between world regions in CO_2-emission factor reflect differences in efficiency of processes (including electricity generation), operating practice and fuel type.

Drawbacks

Abatement curves give a quick insight into the amount of CO_2 that can be avoided against certain costs. However, the abatement curves should be used with caution. We will discuss the main drawbacks of abatement curves.

- Not all costs are taken into account. For instance, costs for acquiring all the appropriate data to evaluate and choose an investment (so-called transaction costs) are usually not included.

- Costs necessarily represent an average. Especially in this study, where world regions are considered, this may cause uncertainties. Operation costs are quite different in China than in the EU. According to the specification of the study cost factors for the Netherlands are used.
- Saving potentials also represent average values. The potential for energy saving often depends on local conditions and operation practice. These effects cannot be taken into account in a globally study like this.
- The list of options is not exhaustive.
- Since specific costs depend on the avoided CO_2-emission the ranking in an abatement curve may not give the optimal investment-abatement solution. For instance, consider two measures that both have annual costs of US$-50/tonne CO_2. The first measure avoids 2 tonne of CO_2 and the second 5 tonne of CO_2. Specific costs can be calculated to be US$-25/tonne CO_2 and US$-10/tonne CO_2 respectively. It seems that the first measure is more cost-effective. However, the second measure avoids a larger amount of CO_2 against the same costs. One should only be aware of this effect at negative specific costs.

Results

In Table 6.7 the potentials for energy-efficiency improvement in integrated steel mills and minimills for 2010 is given per world region. The CO_2-emission in 2010 is determined on the basis of the 1995 CO_2-emission and an assumed growth scenario. The scenario is described in Chapter 8. The “Frozen Technology” scenario is used here, meaning that the efficiencies of all technologies are frozen at the 1995-level.

The technical potential is the difference between the projected CO_2-emission in 2010 and the CO_2-emission in that year assuming that all aforementioned technically available options have been implemented.

The economic potential is that part of the technical potential that has a net positive economic effect. I.e. the benefits of the options are higher than the costs. This is expressed by negative specific costs. In the table only the results for a discount rate of 5% are presented, because these values do not differ much from the results when a discount rate of 10% is used. When the discount rate is raised to 50%, the global economic potential reduces 6% for integrated mills and to 8% for minimills (low energy prices). In Figure 6.2 to Figure 6.9 abatement curves are presented.

Table 6.7: Potentials for energy-efficiency improvement in integrated steel mills and minimills per world region in 2010.

Region	Unabated CO_2-emission in 2010 according to frozen efficiency scenario	Technical potential for energy-efficiency improvement (in parenthesis the share of the unabated emission)	Economic potential for efficiency improvement, with discount rate of 5%	
		coal = electricity =	US$1.5/GJ US$14/GJ	US$0.75/GJ US$7/GJ
Integrated steel mills				
EU15-Nafta	327	54 (16%)	45 (14%)	29 (9%)
FSU-EET	281	87 (31%)	74 (26%)	58 (20%)
China	435	122 (28%)	104 (24%)	81 (19%)
Remaining countries	450	101 (23%)	88 (20%)	67 (15%)
Total integrated steel mills	*1494*	*365 (24%)*	*311 (21%)*	*235 (16%)*
Minimills				
EU15-Nafta	79	10 (13%)	9 (11%)	8 (11%)
FSU-EET	33	6 (17%)	5 (14%)	4 (13%)
China	31	5 (17%)	4 (14%)	4 (13%)
Remaining countries	102	15 (15%)	13 (12%)	12 (12%)
Total minimills	*245*	*36 (15%)*	*30 (12%)*	*29 (12%)*
Total iron and steel production	**1738**	**401 (23%)**	**341 (20%)**	**241 (14%)**

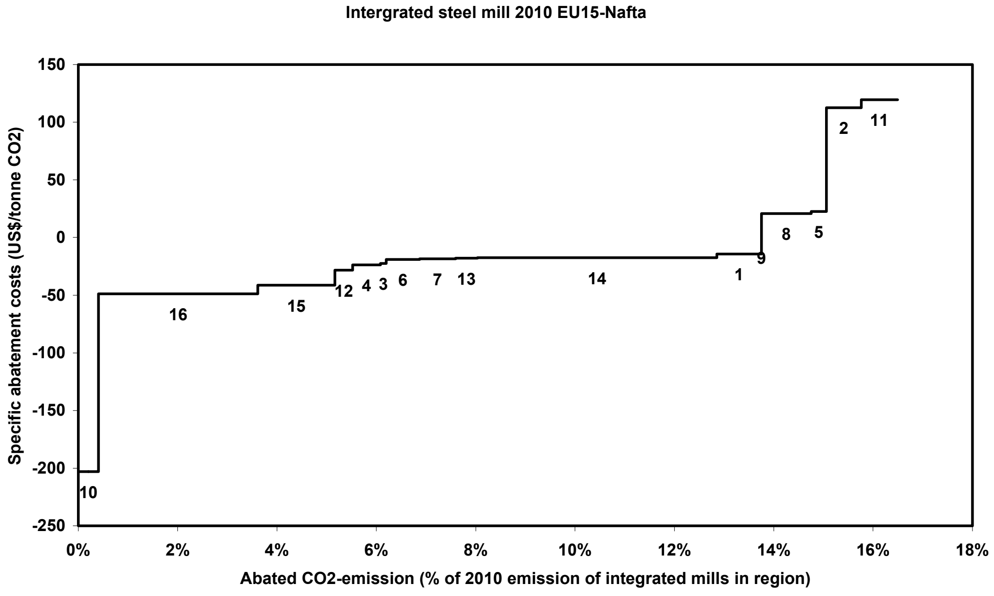

Figure 6.2 CO_2-abatement curve for energy-efficiency improvement in integrated steel mills in EU15 and NAFTA for 2010. Labels refer to the technologies specified in Table 6.2.

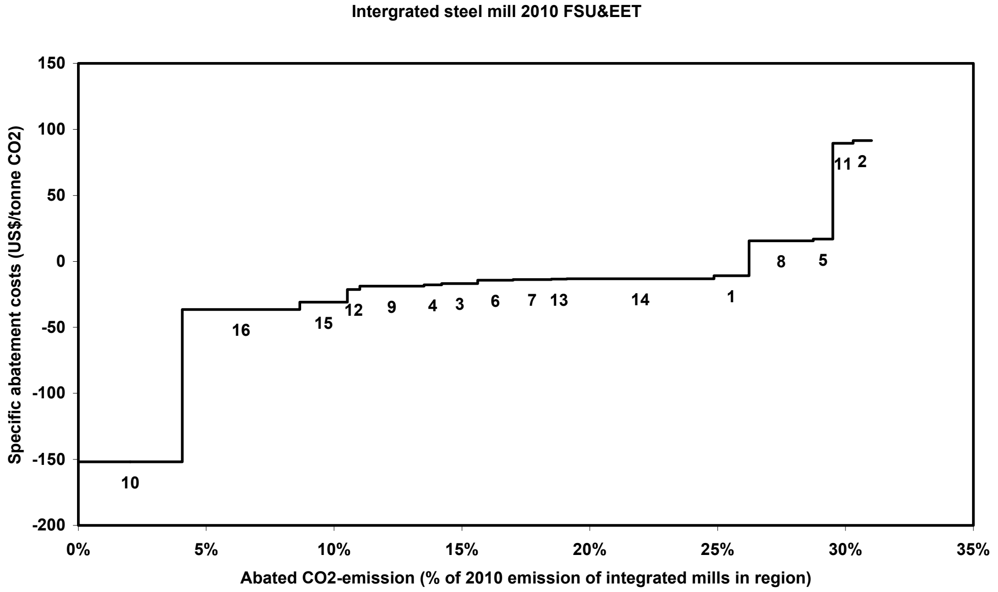

Figure 6.3: CO_2-abatement curve for energy-efficiency improvement in integrated steel mills in FSU and EET for 2010. Labels refer to the technologies specified in Table 6.2.

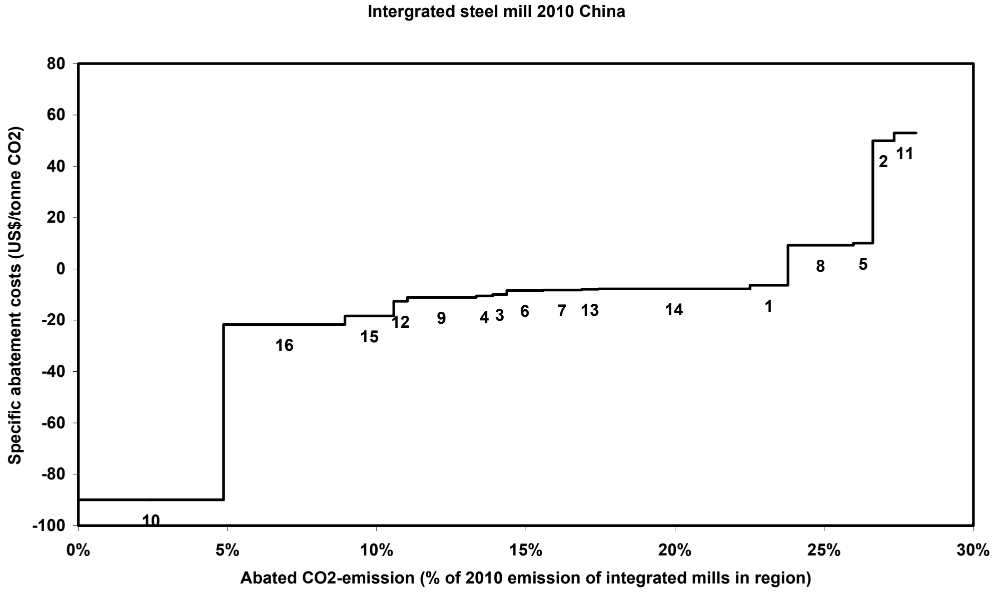

Figure 6.4: CO_2-abatement curve for energy-efficiency improvement in integrated steel mills in China for 2010. Labels refer to the technologies specified in Table 6.2.

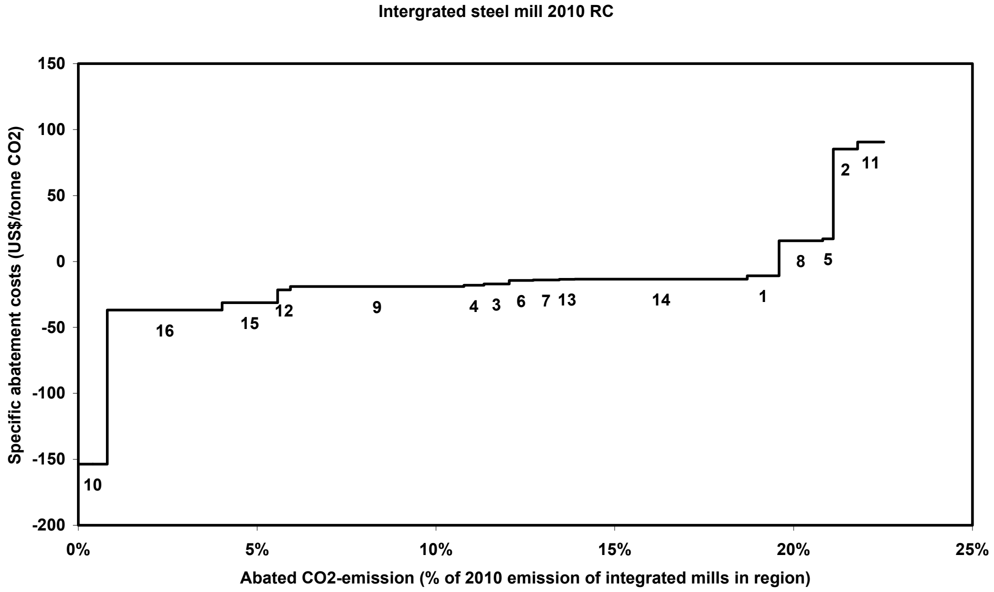

Figure 6.5: CO_2-abatement curve for energy-efficiency improvement in integrated steel mills in the remaining countries for 2010. Labels refer to the technologies specified in Table 6.2.

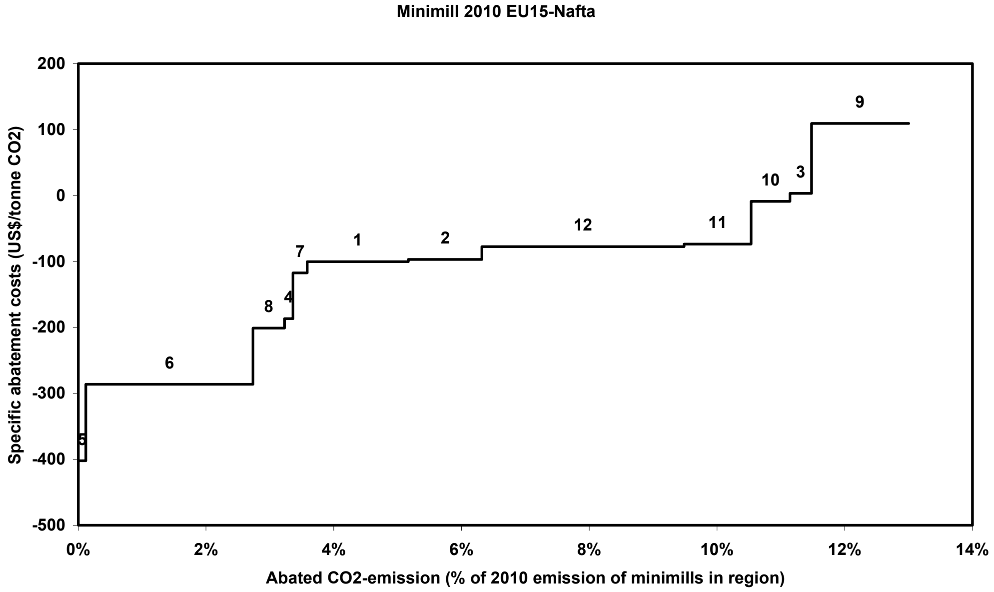

Figure 6.6: CO_2-abatement curve for energy-efficiency improvement in minimills in EU15 and NAFTA for 2010. Labels refer to the technologies specified in Table 6.4.

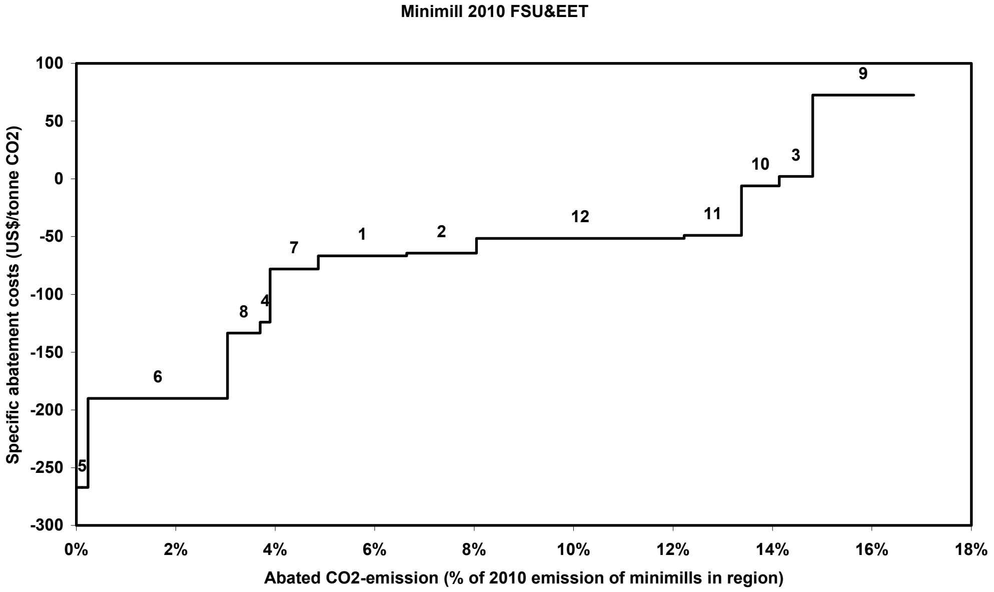

Figure 6.7: CO_2-abatement curve for energy-efficiency improvement in minimills in FSU and EET for 2010. Labels refer to the technologies specified in Table 6.4.

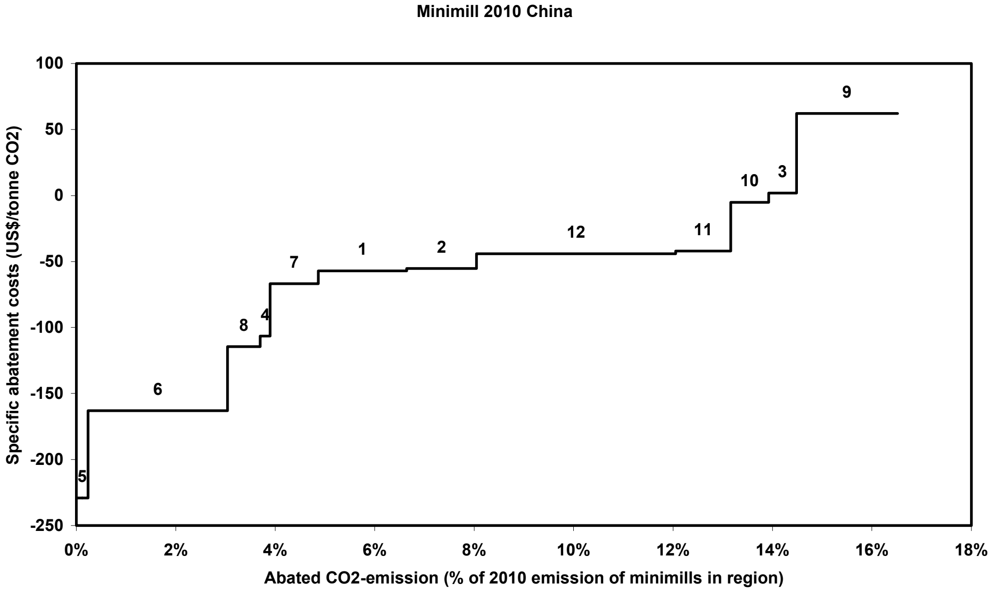

Figure 6.8 CO_2-abatement curve for energy-efficiency improvement in minimills in China for 2010. Labels refer to the technologies specified in Table 6.4.

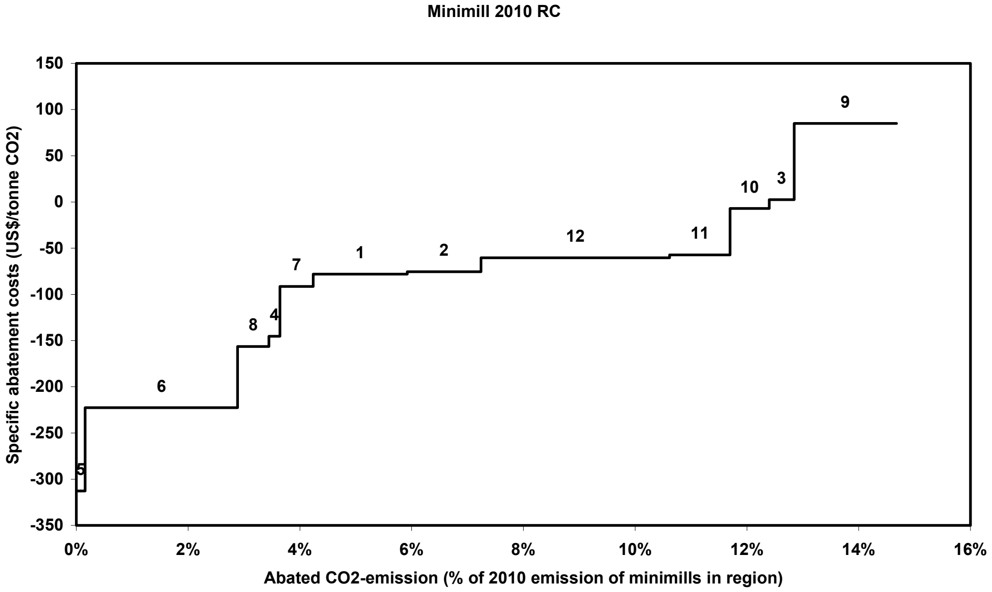

Figure 6.9: CO_2-abatement curve for energy-efficiency improvement in minimills in the remaining countries for 2010. Labels refer to the technologies specified in Table 6.4.

The technical potential for energy-efficiency improvement averaged over the world is 23% of the unabated CO_2-emission in 2010, which equals about 400 Mtonne of CO_2. Of this potential emission reduction, approximately 90% may be achieved in integrated steel mills. The remaining 10% has to be realised in minimills.

The economic potential averaged over the world is 20% using a discount rate of 5% and standard energy prices. Using a discount rate of 10% hardly changes the economic potential. Halving the energy prices does have a noticeable effect: the economic potential reduces to 15%.

6.1.6 Reduction of the CO_2-emission up to 2020

To estimate the potential for 2020 new and emerging techniques have to be taken into account. These techniques offer the possibility to make steel mills much smaller. In integrated steel mills smelt reduction processes can replace ore preparation, coke making and the blast furnace, and near net shape casting techniques can reduce the size of casting and rolling operations. In minimills near net shape casting can be applied. These developments translate not only in a reduction of the energy demand, but also in a cost reduction. It should be noted, however, that the implementation of these new techniques will most probably not be faster than the rate of autonomous replacement and capacity expansion. When existing equipment is replaced before the end of its lifetime by new techniques, considerable costs should be taken into account. An abatement curve would therefore consist of a very cheap part and a very expensive part. The ratio between these parts completely depends on the replacement rate of existing techniques by new and emerging techniques.

We consider it not useful to construct abatement curves for 2020. The assumptions that have to be made concerning replacement rate depend on too many factors: e.g. economic development in the steel industry, technical development of the techniques, ratio between primary and secondary processing. One abatement curve on the basis of these assumptions would be misleading and can easily lead to wrong conclusions.

Instead, we make a conservative and an optimistic estimate of the effect of new and emerging techniques on the total CO_2-emission of the iron and steel industry. First, we estimate how efficient a future steel mill can be. This estimate is illustrated in Figure 6.10. It is assumed that all technologies will be further improved, resulting in an increase in efficiency.

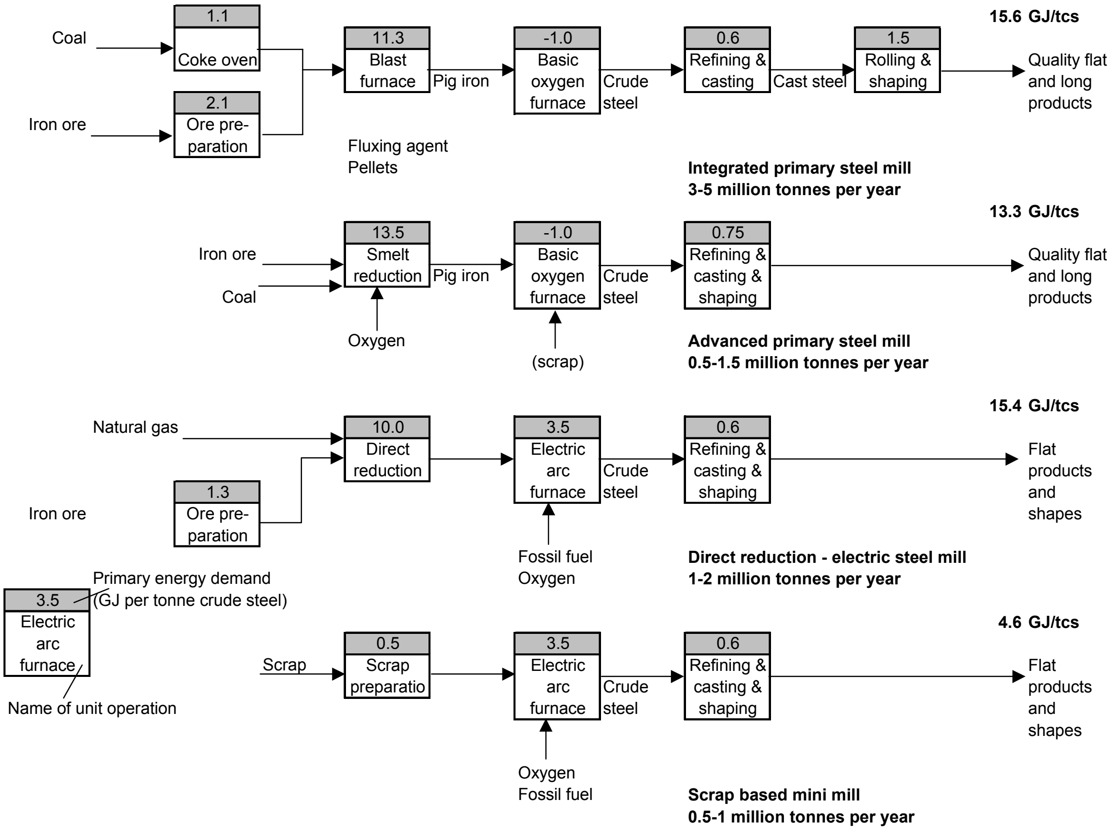

Figure 6.10: Flow sheets of future steel making processes. See Figure 2.4 for a comparison with current steel-making processes. The expected specific energy consumption is also given, expressed in GJ of primary energy per tonne of hot rolled steel [De Beer *et al.*, 1998].

Comparison with Figure 2.4 shows that advanced primary steel making can be about 30% than the current best practice integrated steel mill The efficiency of steel making based on blast furnace technology can be improved by about 15% with reference to the current best practice specific energy consumption. With reference to the world average specific energy consumption of 24 GJ/tcs, the potentials are 45% and 32% respectively. The technical potential in minimills is about 30% compared to the best practice. It should be emphasised that only a small part of these potentials can be attained cost-effectively.

The conservative estimate is that new technologies will be available from 2010 onwards and that 10% of the growth of the steel production will be met by capacity based on these new technologies. The growth in production according to our economic scenario is 90 million tonne of steel between 2010 and 2020. Thus 1%, or about 9 million tonne of steel, will be produced by new technologies. Assuming an average efficiency improvement of 30%, the abated CO_2-emission will be 5 Mtonne. This equals about 0.3% of the global CO_2-emission of the iron and steel industry that is projected according to a frozen efficiency scenario in 2020.

The optimistic estimate is that all new capacity from 2010 onwards will be based on new and emerging technologies. Following the same line of reasoning as above, the emission reduction in 2020 will be 50 Mtonne CO_2, or 3% of the projected emission in 2020.

Capacity based on smelt reduction will only result in a reduction of CO_2-emission when a decision has to be made between smelt reduction and blast furnace. If a choice can be made between smelt reduction and a minimill, the minimill is the best choice from the viewpoint of CO_2-emission. This shows that the implementation of new technologies should be seen in the light of the total steel industry and not of one production route.

6.2 SHIFT FROM PRIMARY TO SECONDARY IRON AND STEEL

A shift from primary iron to secondary iron may reduce the energy consumption per ton of raw steel by about 75 %. To increase the share of secondary iron can thus offer significant emission reduction options. Using mean values for specific CO_2 emissions per production route - taken from Table 4.2 - a simple relation between emissions and respective shares of scrap based minimills and blast furnaces in national production can be derived, as visualised in figure 6.11. These values relate to steel products.

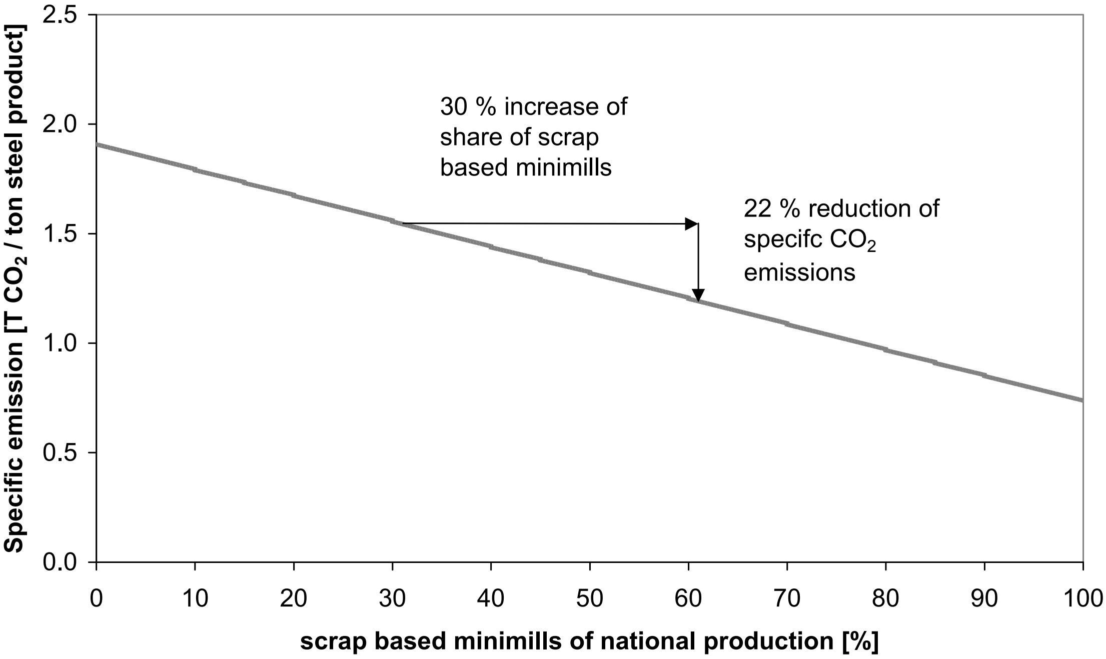

Figure 6.11 Generalised dependence of specific CO_2 emission factors per ton of steel product on the share of scrap based minimills (versus the primary blast furnace route) of national steel production.

The national shares of EAF (not always scrap based) in different nations virtually cover the full range between 0 and 100 % as shown in Figure 6.12 for the year 1990 [IISI, 1996a]. This figure might give the impression that in many

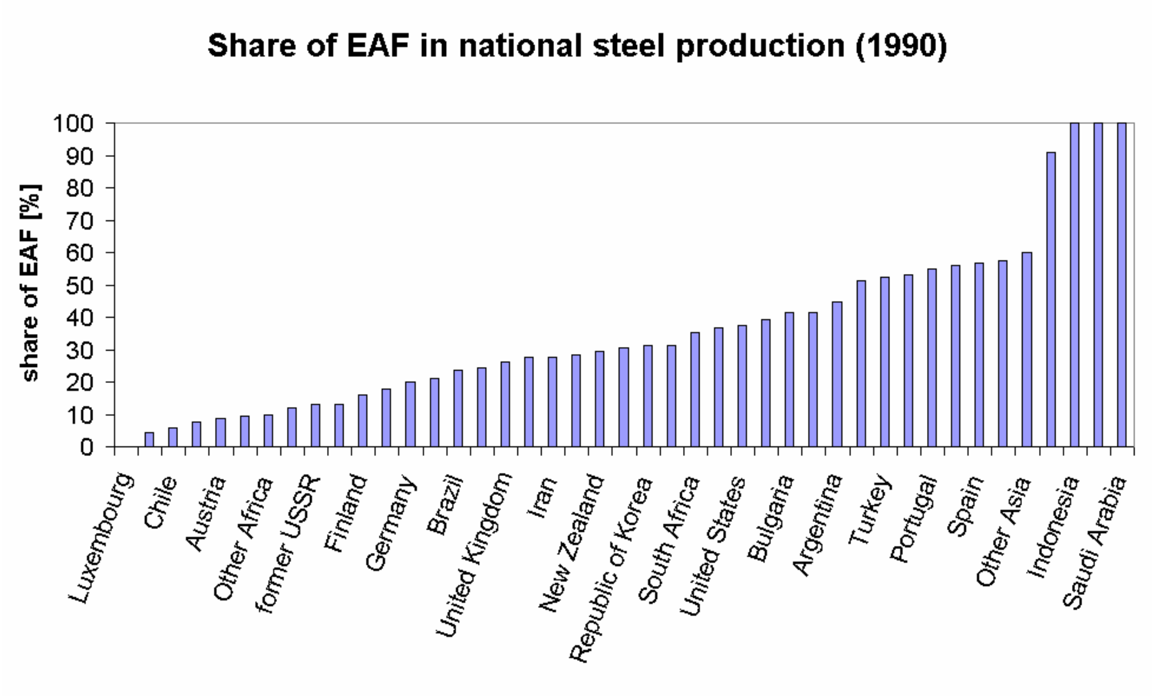

Figure 6.12 Share of electric arc furnaces (EAF) in national steel production in 1990.

countries there exists a considerable potential for CO_2-emission abatement by a shift from primary to secondary steel. However, in practice this is not the case. The mix of products in these countries is anything but uniform. Steel qualities from primary and secondary routes can exhibit significant differences. Some steel qualities cannot be produced through the secondary route. The actual technology mix of national steel production is the result of a complex mix of economic factors (e.g. energy costs, capital costs, product mix) and is continuously affected by global trade streams of most major steel product categories. The primary extraction part of the iron and steel industry thus is potentially highly susceptive to "leakage" away from countries with high energy prices, carbon taxes or strict environmental regulations to areas with less restrictive conditions. Such relocations of primary production would give away many chances of energy optimised production close to the main markets.

Wherever EAF minimills are fed mainly with scrap significant CO_2 emission reductions occur relative to the primary blast furnace route if the same products can be produced with the same quality. During recent decades the occurrence of high quality (circulating and prompt) scrap has declined as a consequence of improved process control. The global consumption of scrap has thus basically stagnated with a tendency towards a higher share of obsolete and capital scrap of lower quality. Table 6.8 gives an overview of maximum residual metal contents in different steel products and typical contents in various scrap categories. It demonstrates that many scrap qualities have residual metal contents that preclude their usage for certain steel products.

Table 6.8 Residuals in steel and its raw materials. Quoted after Ullmann [1994].

	residual limits (Cu+Sn+Ni+Cr+Mo) [%]
carbon steels (maximum)	
tinplate for draw and iron cans	0.12
extra deep drawing quality sheet	0.14
drawing quality and enameling steels	0.16
commercial quality sheet	0.22
fine wire grades	0.25
special bar quality	0.35
merchant bar quality	0.5
charge material (typical)	
direct reduced iron	0.02
pig iron	0.06
scrap: no. 1 factory bundles	0.13
scrap: bushelling	0.13
scrap: no. 1 heavy melting	0.20
scrap: shredded auto	0.51
scrap: no. 2 heavy melting	0.73

Table 6.9 lists usage categories of finished steel products in 1995. It shows that only a limited share of steel went into automotive applications from which steel typically returns with high residual metal contents due to the shredding process. Table 6.8 and Table 6.9 together indicate that large volume applications exist for scrap qualities with higher residual metal contents. Lacking more detailed quantitative information on current and likely future supply and demand of different scrap qualities it is not possible to arrive at robust conclusions about a future need for primary iron, e.g. from DRI, to dilute high levels of residual metals in order to utilise a maximum level of scrap.

Table 6.9 Use categories for finished steel consumption in 1995. Quoted after UN/ECE [1997]

Sector	annual consumption [MT yr^{-1}]
Construction	229
Machinery	78
Automotive	72
Appliances	53
Ship / Transport	49
Elec. Equipment	41
All Other	131
TOTAL	653

Globally direct reduced iron (DRI) is increasingly used as a substitute of scrap in electric arc furnaces as scrap prices are too high, too fluctuating, or that shipments were too unreliable or qualities of scrap too poor. Chatterjee [1998] predicts a rapid expansion of DRI production (based on coal) in India because of the limited availability of domestic and imported scrap. The removal of trade barriers and the availability of inexpensive sea and land transport have certainly helped to significantly increase global trade in scrap. To promote a maximum future usage of scrap it will be of great importance to ensure that scrap is readily available to steel plants in the most dynamic steel markets, e.g. South East Asia. Free trade, the improvement of infrastructure, and appropriate site selections will play a major role in this context.

Technological options are much more limited. Electric arc furnaces are commonly using a maximum of scrap already, the energy balance of the basic oxygen furnace appears to preclude a substantial increase of scrap use per ton of steel. The fall of the open hearth technology has certainly diminished the capacity to flexibly vary scrap use. Significant technological potential may exist in the field of sorting of mixed (low grade) scrap and for modifications of the steel making processes to allow for a removal of trace elements that are detrimental on steel quality.

6.3 CARBON DIOXIDE RECOVERY FROM INTEGRATED STEEL PLANTS

This section deals with the opportunities for recovery of carbon dioxide from process gases produced in integrated steel mills. The carbon dioxide emission for the production of secondary steel is largely due to the production of electricity. Since this is generally not done at the site of the minimill we will not deal with minimills here. This section is based on a study of Farla *et al.* [1992]. Where no other references are given, data stem from this study.

6.3.1 Carbon in process gases of an integrated steel mill

In an integrated steel mill three major process gases are produced: coke oven gas, blast furnace gas and oxy-steel gas. About 70% of the carbon input for the process finds its way to the blast furnace gas; 7-9% can be found in the coke oven and oxy-steel gas. The composition of the gases is given in Tabel 6.10. The balance is incorporated in the steel, slag, sold by-products (breeze, tar) and emissions in other stages.

Table 6.10: Typical values for the composition and calorific value of process gases of an integrated steel mill (dry basis) [Farla *et al.*, 1992].

Components		Coke oven gas	Blast furnace gas	Oxy-steel gas
Hydrogen	% (v/v)	59	3	-
Nitrogen	% (v/v)	3	56	14
Carbon monoxide	% (v/v)	5	21	70
Carbon dioxide	% (v/v)	1	20	16
Methane	% (v/v)	28	-	-
C_2-C_6 hydrocarbons	% (v/v)	4	-	-
Hydrogen sulfide	g/Nm^3	8*	0.045	-
Calorific value	MJ/Nm^3	19.8	3	8.8
Carbon content	% of C-input	~ 9	~70	~2

* Before washing

Process gases are used as fuel in the power plant and at several heating operations, e.g. reheating furnace and blast stoves. After combustion the carbon dioxide content has increased considerably due to conversion of carbon monoxide. However, it seems advantageous to recover the carbon before the gas is used as a fuel because the gases are produced at a few sources only. Since 70% of the carbon input is present in blast furnace gas, we will describe decarbonisation of this gas.

6.3.2 Carbon dioxide recovery from blast furnace gas

The techniques required for carbon dioxide recovery from blast furnace gas depends to some extent on the configuration of the blast furnace, e.g. the presence of top gas turbines. The description is based on the configuration at Hoogovens, the Netherlands. This mill represents an energy-efficient mill. Since carbon dioxide recovery will probably be taken only after efficiency improvement options have been implemented, this mill seems to be a good reference.

The two blast furnaces at Hoogovens (capacities 6000 and 8500 ton of pig iron per day) are equipped with ring-venture scrubbers and top gas pressure recovery turbines. In these turbines the pressure of the gas is reduced from 2.2 and 2.8 bar to 1.12 bar. After pressure reduction, the blast furnace gas is further dedusted electrostatically and distributed internally and externally as a fuel.

For the recovery of carbon dioxide from gases several separation technologies are available, like pressure swing absorption, membrane purification and chemical and physical absorption processes. Because of the low CO_2 partial pressure in the blast furnace gas a chemical absorption method is required. With a chemical absorption process a high purity carbon dioxide van be generated at relatively low investment costs. However, the heat required for chemical absorption is relatively high compared to other CO_2 absorption processes.
Several absorbents can be chosen. Activated MDEA is suited as a solvent for the recovery of CO_2 from blast furnace gas. Recovery of MDEA requires a small energy input and it is selective for H_2S in the presence of CO_2. Typical operation temperatures for absorption range from 25 to 50°C.

In the proposed configuration the chemical absorption step is placed between the dust cleaning and the top gas turbines. The H_2S that is recovered together with the CO_2 will result in a H_2S content of approximately 0.5%.
For the recovery of carbon dioxide a one-stage chemical absorption seems the be the most economic design in this case. Because of the low CO_2 partial pressure no CO_2 can be flashed. The heat consumption is estimated at 140-160 kJ/mole CO_2 and the electricity consumption at 29 kJ/kg of CO_2.
The recovered CO_2 has to be compressed to a transportation pressure of 110 bar and dried to a water content of below 10 ppm. Compression is possible in a four-stage isentropic compression process. The compression energy is calculated to be about 265 –280 kJ/kg of CO_2. Most of the water will be removed during the first compression stages. However, additional drying in a drying tower with a solid desiccant is necessary. Hydration energy is 8 kJ/kg. Another 8 kJ/kg is required for cooling to 10°C.
Generally the compressed CO_2 will have to be transported to locations where it can be stored or used. The market for usage of CO_2 is small (e.g. enhanced oil recovery and urea production[9]). CO_2 can be stored in, for instance, empty gas fields and aquifers. Storage of CO_2 in an aquifer is being applied in Norway. Here CO_2 that is separated from natural gas obtained from the Sleipner-field is stored in a nearby aquifer [Andenaes, 1999]. The energy demand for transportation and storage is negligible compared to the energy required for compres-

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[9] Urea plants are usually located near ammonia plants where also CO_2 is produced. The CO_2-market for urea production is therefore already satisfied.

sion provided that the transportation distance is limited (several hundreds of kilometres).

The recovery of carbon dioxide will result in a lower power recovery in the top gas pressure turbines due to the pressure drop in the absorption tower and the recovery of CO_2 from the blast furnace gas. The pressure drop in the absorption tower is assumed to be 0.1 bar. If 90% of the carbon dioxide is recovered, the electrical power generation will reduce from 19 to 15 MW, resulting in a loss of electricity production equivalent to 43 kJ/kg of CO_2 recovered.

The carbon recovery may be enhanced when carbon monoxide is converted to carbon dioxide in a two-stage water gas shift reaction. It is estimated that this would result in higher costs per tonne of CO_2 recovered, because of the extra investment costs and the heat requirement for the shift reaction. This option will not be further elaborated here.

Economic evaluation

An economic evaluation of CO_2-removal from blast furnace gas is presented in Table 6.11. This evaluation is based on 8350 operating hours a year. 90% of the CO_2 in the blast furnace gas will be recovered, resulting in 8 ktonnes per day. Since the maximum train capacity is on the order of 1 ktonne per day, 8 trains will be needed. The capital costs for are estimated at US$120/annual tonne of CO_2 recovered.
The investment costs for the compressor are estimated at US$6/annual tonne of CO_2 and for the drying units 1 US$/annual tonne of CO_2.

Table 6.11: Economic evaluation for CO_2 recovery from blast furnace gas

		BF1	BF2
Characteristics			
Capacity	(kton CO_2/yr)	1200	1600
Electricity consumption	(MJ/ton CO_2)	319	303
Loss of electricity production	(MJ/ton CO_2)	38	47
Steam consumption	(MJ/ton CO_2)	3417	3417
Investment			
Total investment	(million US$)	152	203
Annual costs			
Capital costs	(million US$/year)	11	14
Operation and maintenance	(million US$/year)	3.5	5
Electricity (@ US@ 0.05/kWh)	(million US$/year)	5	6.5
Steam (@ US$ 2.5J)	(million US$/year)	10	13.5
Loss of electricity production	(million US$/year)	0.5	1
Total annual costs	(million US$/year)	30	40
Specific costs			
CO_2 avoided	(kton/y)	867	1175
Specific abatement costs	(US$/tonne CO_2)	35	34

From Table 6.11 it appears that recovery of CO_2 from blast furnace gas has specific costs of US$35/tonne CO_2. These costs will be lower when steam is available at lower costs, which will be often the case at integrated steel mills.

Furthermore, the CO_2-emission associated with steam production is avoided. A 50% reduction of the steam price will reduce the specific costs to US$28-29/tonne CO_2.

To transport CO_2 over 100 km requires about US$ 3-5/tonne for [Wilderborg, *et al.*, 1999]. Costs for storage are US$ 5-15/tonne, depending on for instance locations, depth, safety demands and amount km [Wilderborg, *et al.*, 1999]. Taking an average distance of 100 km from steel plant to storage location, transportation and storage of CO_2 will add US$ 8-20/tonne CO_2 to the costs of recovery. Total costs will therefore be US$ 43-55/tonne CO_2.

6.3.3 Conclusions

In the case of Hoogovens, with an annual pig iron production of 5 million tonne of steel, 0.4 tonne CO_2 per tonne of pig iron can be recovered. The recovery percentage is about 25% of the direct carbon input. The remainder is lost with other gases and solids and as carbon monoxide in the blast furnace gas (this will be converted to carbon dioxide during combustion).

If this measure were implemented at all integrated mills around the world, this would result in the recovery of 175 Mtonne of CO_2 now. In 2010 this amount could be increased to 260 Mtonne of $CO_{2.}$ and to 290 Mtonne in 2020.

The specific costs of carbon dioxide recovery from blast furnace gas are comparable to that for recovering CO_2 from stack gases of coal-fired thermal power plants with chemical CO_2-absorption, being US$35/tonne of CO_2. Transportation and storage of CO_2 will add US$8-20/tonne CO_2.

6.4 USING CHARCOAL AS FUEL AND REDUCER

Before the introduction of coke in the 18th century charcoal was the fuel and reducer in blast furnaces. Shortage of wood supplies in the UK encouraged iron manufacturers to use coke (see Chapter 2). Most other regions followed in the 19th century. Coke has the advantage over charcoal that it is stronger, allowing larger blast furnaces.

In Brazil the iron and steel industry developed mainly in the 20th century [Ackerman and Fernandes de Almeida, 1990]. Nevertheless, charcoal was the fuel of preference for many decades. There are two main reasons for this. First, Brazil has large ore deposits but lacks coking coal deposits. It does have large area of forests. Second, coke furnaces require a high capital investment, whereas charcoal production is labour intensive.

The share of charcoal in the total energy demand for pig iron production is shown in Figure 6.. The share of charcoal was as high as 45% in 1975 but is below the 30% since the beginning of the 1990s. This is due to the fact that more coke-based integrated steel mills have been taken into operation. The capital is provided by public enterprises century [Ackerman and Fernandes de Almeida, 1990].

The shift from charcoal to coke in Brazil, although not very pronounced at the moment, might continue in the future. The reason for this is a shortage of wood to make charcoal. In the state of Minais Gerais deforestation is a severe problem [Ackerman and Fernandes de Almeida, 1990]. Sustainable production of charcoal to supply the demand for industry is no longer possible.

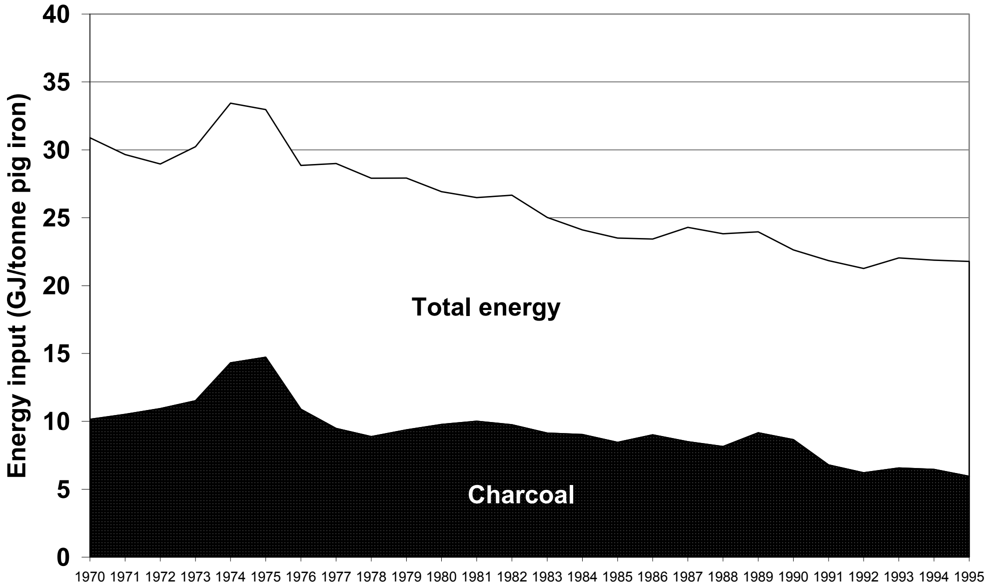

Figure 6.13: Development of the total energy input and the charcoal input for pig iron production in Brazil. Note: the pig iron production includes that based on coke.

Tabel 9.12 presents a tentative calculation that gives us insight in the area required for wood production if an average integrated steel mill would use charcoal. The capacity of Hoogovens in the Netherlands is taken. The area required is determined to be 1.2 million ha. This is about 30% of the area of the Netherlands.

Table 6.12 Tentative calculation of area requirement for charcoal production for an average integrated mill

Capacity integrated steel mill	5 million tonne of pig iron
Charcoal requirement	0.5 tonne/tonne pig[1]
	10 million tonne
Efficiency charcoal kilns	55%[2]
Wood requirement	18 million tonne
yield wood	15 tonnes/ha/year[3]
area required	1.2 million ha

[1] Ackermann and Fernandes de Almeida [1990] report that 2.8 m^3 of charcoal/tonne of pig iron is used in Brazil. Here we assume that this can be reduced to 2.0 m^3/tonne. The density of charcoal is assumed to be 0.25 m^3/tonne.

[2] Ackermann and Fernandes de Almeida [1990] report 53% for efficient kilns.

[3] Maximum assumed value for the cultivation of willow in the Netherlands [De Jager *et al*, 1998].

This example shows that production of charcoal for iron production requires large surface areas, which will probably not be available in the neighbourhood of most integrated steel plants. Production elsewhere and transport of charcoal is also an option. However, this would put high demands on a limited number of densely forested regions and it can be doubted whether sustainable production can be guaranteed.

Companies in other countries have also considered the use of charcoal. Elkram in Norway has been looking for cheap sources of carbon, including charcoal, Chinese coke, polish char for their ferro silicon units [Gale, 1999]. The driver was not the desire to use charcoal but the price.

It can be concluded that the use of charcoal to substitute coke is not an option that will have a serious contribution to the reduction of the emission of carbon dioxide of the iron and steel industry. No further study is done to determine the impact on greenhouse gas emission of the use of charcoal.

6.5 USING CARBON-FREE FUEL AND REDUCER

Traditionally carbon and carbon monoxide are used as fuel and reducer in blast furnaces. Carbon has the advantages that it is abundant (in the form of coal) and that is able to convert iron ore very efficiently.

Iron oxide can also be reduced by hydrogen. In direct reduction processes hydrogen is also used for reduction of iron ore (See section 3.1.3.2). Whereas most direct reduction processes also use carbon monoxide as reducer, the Circored process uses solely hydrogen [Daniëls and Moll, 1998]. If hydrogen can be produced by electrolysis from water with renewable electricity or from biomass, the hydrogen can be marked as carbon-free.
To produce 1 tonne of pure iron, about 650 Nm^3 of hydrogen is required [De Beer *et al*, 1998]. Hence, the energy consumption for iron ore reduction with hydrogen is in theory more or less comparable to that for using carbon (6.5 GJ/tonne iron).

A demonstration plant that used hydrogen was planned to in operation in Ireland from 1994 to 1996 [Stam, 1994]. However, no confirmation that this plant had actually been running has been found.
In this plant hydrogen and iron oxide are injected in a hot plasma, in which iron oxide is reduced. A plasma is a state of matter in which a significant number if the atoms or molecules are electrically charged or ionised. The behaviour of plasmas differs from that of liquids, solids or gases. Due to the high reactivity plasma chemistry offers new possibilities for chemical reactions. Plasmas can be produced by e.g. the release of chemical energy in flames, and electrical discharge and by lasers. To create and maintain a plasma can be very energy-intensive. The results of the demonstration, if taken place at all, are not known.

The advantages of the use of hydrogen for ore reduction are that it
- is potentially carbon free
- can be produced on site thus avoiding transport over long distances of coal

- avoids the use of expensive coke plants
- it fits in futuristic projections of a hydrogen-based society.

Disadvantages are that it
- is still in a very early stage of development
- the technology for iron ore reduction using a plasma seems complex
- the characteristics of the iron product change

Considering the complexity of the technology it is not to be expected that it will be commercialised before 2020. However, further study to this option may be appropriate in the light of studies to a hydrogen-based society. Since the interest of the industry in this option is negligible at the moment, such a study should be encouraged by other organisations.

6.6 CONCLUSIONS ON OPTIONS TO REDUCE THE CO_2-EMISSION

In Table 6.13 an overview is given of all options to reduce the emission of CO_2 of iron and steel production described in this chapter.

The economic potential, using a discount rate of 5%, of all options is estimated at 440 Mtonne CO_2 in 2010 and at 590 Mtonne CO_2 in 2020. These emission reductions correspond to 25% and 31% of the unabated CO_2-emission in 2010 and 2020 respectively according to a frozen efficiency scenario. When CO_2-removal from blast furnace gas is also taken into account, these percentages increase to 40% and 46% respectively. However, CO_2-removal costs about US$40-55/tonne CO_2.

Two main assumption that were required to make this estimate are:
1. It is assumed that new and emerging steel making technologies (smelt reduction and near net shape casting) make up 10% of the steel making capacity in 2020. It is assumed that the commercial introduction takes place in 2010 and the rate of penetration is 1% a year. This is in line with our optimistic estimate.
2. The shift from primary to secondary steel making depends heavily on market conditions for scrap and scrap substitute, and on consumer demands. An economic potential is therefore hard to estimate. Nevertheless, we assume that the following values for primary and secondary steel in 2010 and 2020, reflecting a 10% change in 2010 and a 20% change in 2020 with respect to the ratio in 1995.

	Primary steel	Secondary steel
1995	510	240
2010	550	325
2020	530	430

Table 6.13: Overview of the economic potential (discount rate is 5%) of options to reduce the CO_2-emission of iron and steel production.

Option	Economic potential		Remarks
	2010	2020	
Energy efficiency improvement available techniques	340	340[1]	Same potential assumed in 2020 as in 2010.
Energy efficiency improvement new and emerging techniques	not applicable	50	
Shift from primary to secondary steel	100	200	Assuming a 10% shift in 2010 and a 20% shift in 2020, compared to the ratio in 1995.
CO_2-recovery from blast furnace gas	0 (240)	0 (290[2])	Values in parenthesis can be achieved at costs of US$43-55/tonne CO2
Charcoal-based blast furnaces	negligible[3]	negligible[3]	
Iron ore reduction with hydrogen	0	0	Not expected to be commercial before 2020.
Total	**440** **(680)**	**590** **(880)**	

[1] Assumed that in 2020 20% of the CO_2-emission of conventional steel making processes can be avoided cost-effectively. It is assumed that new and emerging processes make up 10% of the steel making capacity in 2020, assuming a penetration of 1% a year from 2010.

[2] It is assumed that CO_2-removal can also be applied at smelting reduction processes.

[3] Applicable to niche markets. Impact on GHG-emissions not further studied.

7. NON-TECHNOLOGICAL ASPECTS

The development and implementation of emerging technologies is not only a matter of technological improvement. Other, non-technological, factors play a role in the successful implementation of new technologies. For example economics, environmental legislation as well as demand for product quality are important factors. These factors can both be a barrier and an impetus to the development and implementation of new technologies.

In this paragraph the main non-technological aspects and the assumed consequences will be described. (Technological) barriers to the implementation of specific technologies are already addressed in chapter 6. Now we will discuss more general factors.

7.1 ECONOMIC AND ORGANISATIONAL FACTORS

Most emerging technologies will be cost-effective. Steel producers must be able to do investments in development and implementation. The financial risk can be very high, which can result in a delay in development. An example is the postponement of the development of smelt reduction at Hoogovens (The Netherlands).

In western European countries some big companies are now merging, for example the Dutch Hoogovens and British Steel. Because of organisational and economic consequences of this fusion, implementation of new technologies is delayed. When this merging of big companies is a trend for industrialised countries, this could mean a barrier to implementation of new technologies. On the other hand, mergers can lead to rationalisation of production facilities in terms of allowing the most efficient plant to run at full capacity and older plants to close.

7.2 CURRENT AND FUTURE ENVIRONMENTAL LEGISLATION

A number of countries are considering programmes to control the emissions of the greenhouse gas CO_2. Many industrialised countries confirmed their national target of either stabilising or reducing the emission of CO_2. As the iron and steel industry accounts for about 7% of the global CO_2-emission these regulations and targets will certainly effect this industry.

The process of coke making, which has not changed very much over the last hundred years, is subject to strict environmental regulations. These regulations are pressuring the steel industry to improve its technology. The ageing of facilities is creating a need for replacement or new technologies.

Tighter environmental regulations, for example the Clean Air Act Amendments of 1990 (United States), threaten the economic viability of coke production. Hereby these regulations accelerate the speed of closures of plants, inducing a loss of about 30% of the current capacity in the USA. Other nations will probably follow these tighter regulations that will affect the world-wide coke production.

Some other environmental regulations concerning coke making in the USA are:
- more stringent air emissions requirements by January, 1998 for companies pursuing the U.S. Environmental Protection Agency's (EPA's) Lowest Achievable Emission Rate (LEAR);
- more stringent standards by January, 2003 for companies pursuing the EPA's Maximum Achievable Control Technology (MACT) and residual risks standard route;
- even more stringent air emission standards by January, 2020 for companies pursuing LEAR. These requirements are for charging, lids, off-takes and door emissions.

Sintering is the operation with the largest environmental burden in an integrated steel mill. Due to environmental regulation in the USA some sinter plants have been closed. Equipment to reduce emissions does not always perform well over the whole range of feed materials. There is a need for new control techniques.
Sinter plants also have an environmental benefit, because iron-bearing wastes from the plant can be recycled in the sinter plant.
Environmental concerns and high capital and operating costs have led to declining use of sinter plants. This has led to the development of other waste oxide agglomeration processes and of iron ore reduction processes that do not need sinter (e.g. smelt reduction).

There will continue to be regulatory pressures to reduce release of toxic and hazardous waste from BOF's. In response to the requirements of the Clean Air Act, EPA is working on Maximum Achievable Control Technology (MACT) standards for hazardous air pollutants from BOF's. Important is the emission of inhalable particulate matter.

The main emissions from the process of refining are particulates from different process steps and sulphur dioxide. In the process of vacuum degassing low concentrations of elements like zinc and lead are adsorbed by process water.
To comply with permits effluent limitations for these operations, suspended solids and metal discharges must be reduced. The pressure from the government to minimise hazardous waste, along with the costs of disposing, will lead to reduction and recycling of these wastes in the USA.

Air emission regulations will lead to reduction of NO_x emissions from the fuel cutting torches from the casting operations. Some continuous casting facilities have steam emissions that contain volatile organic compounds (VOCs) from leakage of the cooling system. So NO_x and VOC-control seems to be the main issue when looking at air emissions in the future of casting facilities.

Furthermore, EPA is planning to revise the water effluent guideline limitations. This may result in a reduction in the allowable discharge limits for waste water. This could lead to new water pollution control facilities.

The wastes from casting are coarse scale and sludge from the continuous caster's wastewater-treatment. These wastes are not hazardous and are good candidates for recycling, particularly to sinter plants. Some drivers to increase the use of caster wastes are increasing pressure for waste minimisation and pollution prevention programs and scarcity of landfill space and increasing costs of landfill disposal.

There is no strict European legislation on environmental issues. According to Kyoto-agreements all countries seek their on way of reaching their targets and have therefore their own legislation. There is an Integrated Pollution Prevention and Control (IPPC) Council Directive that wants to 'achieve an integrated prevention arising from activities in industry' and has as a goal to 'prevent or reduce emissions to air, water and land'. There is a treaty between EU members about new installations, investments and energy use etc. The members agreed to work according to the best available technology. Members have an obligation to inform each other on the best available technology and governments can use this treaty in agreements with the industry or to develop legislation. In general one can say that European governments make agreements with certain sectors of industry instead of implementing the strict environmental rules the USA is using. The environmental based aspects of getting emission or effluent permits are also becoming stricter and the monitoring and control will become more important.

In general every country has their own way of setting up environmental legislation, but there is a trend to solve environment and energy related problems on a world wide level (Kyoto Convention).

The impact of these environmental regulations and agreements will be the development of improved technologies and will lead to international agreements on the implementation of best available techniques. Also it will lead to a technology transfer from developed to developing countries, due to mechanisms agreed in the Kyoto Protocol.

7.3 CLEAN DEVELOPMENT MECHANISME, JOINT IMPLEMENTATION AND NATIONAL EMISSIONS TRADING

In the Kyoto convention (1993 mechanisms are described to reduce GHG emissions, the Clean Development Mechanism (CDM), Joint Implementation (JI) and national emissions trading. These mechanisms are not yet in practise, but will probably be of great importance to future developments of GHG emissions world-wide. In chapter 8 (scenarios) more will be said about CDM and JI.

7.4 MARKET TRENDS AND DRIVERS

The call for lighter products leads to the introduction of other materials as plastics and aluminium. Steel has to innovate to compete with these 'new' materials, so it must be lighter, thinner, thus stronger, but still flexible. What the effects would be on energy use and CO_2 emissions of producing lighter, thinner, steel products was not studied in the LCA study of IISI (IISI, 1998).

Two options for steelmakers to compete with these new materials are cost reduction and quality improvement.

Cost reduction can be achieved by making the steel mill more compact and flexible with regard to output. The development of smelt reduction and near net shape casting fits into this option.
Most important drivers for technological change related to blast furnace technology are to reduce its reliance on coke and to extend campaign life to reduce capital costs of repairs. The high capital cost of this technology is also an issue.
The major need for direct reduction is a low-cost and high quality alternative to low residual scrap for steel making. Secondary processes are becoming more important because of the increasing call for low-carbon steel.
The main drivers for smelt reduction are reduction in capital costs, elimination of coke making and reduction in agglomeration requirements. Although the COREX process is already in use, commercialisation of the second generation of smelt reduction processes is at least 5 to 10 years away.

Quality improvement is related to making steel that meets small margins concerning surface uniformity, with well-designed composition (low in impurities) and properties. More alloys with other metals or plastics are being produced. New casting technologies give the opportunity to meet with these quality demands.

7.5 PRODUCT DEVELOPMENT

The steel industry, which has been focussed on in this report, is a supplier of mainly semimanufactured goods. These half-finished products are used in building industry, to manufacture products like consumer electronics, cars and are used in the packaging industry. Product development on the level of end products is therefore important. Steel makers have to be able to meet the demands of their customers.

Some major product developments in the three main steel using industries (automotive, packaging and construction) are given.

7.5.1 Automotive industry

In the automotive industry the main trend is to make lighter vehicles that will use less energy during their lifetime. Safety (thus strength) and costs are of course also important factors. The competition in vehicle construction is mainly between steel and aluminium, but plastics can also be used.

For some time now there is a discussion going on whether a light aluminium vehicle or an ultra light steel vehicle saves more energy (CO_2) throughout the life-time of the vehicle. Several studies have been done on this subject, and some conclusions from different parties in the debate will be given.

ULSAB (Ultralight Steel Auto Body, a project by 35 leading steelmakers) developed an ultralight steel car, that is supposed to be 25% lighter, and 80% more rigid. The fuel consumption can be brought down to 5 litres per 100 km. By ULSAB no comparison is made with the use of aluminium [website ULSAB].

According to the aluminium industry, a CO_2 emission reduction of 20 tons could be reached over the life of an average vehicle, when 1 ton steel is replaced by aluminium in automotive applications. American Iron and Steel Institute (AISI) seriously doubts this conclusion. According to a MIT study (Massachusetts Institute of Technology) it would take 32 to 38 years of driving an aluminium vehicle to offset the amount of CO_2 emitted during the production of aluminium, compared to the ULSAB vehicle. (The production of 1 ton aluminium emits 10 to 15 times more CO_2 than the production of 1 ton steel [Global Environmental Change Report, 1999].

MIT compared the total CO_2 emission of the production and use of a current used steel car with a car with an aluminium body and with the ULSAB car. MIT states that it would take 10 years of vehicle-use to show a benefit for the aluminium car compared to the normal steel car. When the aluminium car is compared with the ULSAB vehicle it takes 12 years.

The Aluminium Association (Washington, DC) holds on to its claim that 1 ton of aluminium production leads to approximately 6,7 ton of CO_2 emission at today's recycling levels. They state that over 90% of car scrap is recovered and that 60-70% of aluminium used in cars is from recycled material. Using recycled aluminium instead of virgin aluminium generates 95% fewer green house gasses (International Primary Aluminium Institute, London). MIT reacts to this saying that the amount of aluminium scrap available is not enough to supply the quantities needed for a large scale introduction of aluminium vehicles.

The above described discussion will probably continue for some time, but it can be concluded that steel has to innovate to be able to compete with other materials.

7.5.2 Packaging industry

Steel for packaging is mainly used for cans (food-industry) and aerosoles and for containers used in transportation. Lightweighting is an important issue in the packaging chain, brought forth by the drive to save energy and to avoid waste from packaging. Using less material is of course also an economic advantage.

Steal for cans is recycled for over 45% in Europe and for 77% in Japan (data from 1996, [Hoogovens web-site 1999]), but this can theoretically increase up to 90%. As illustrated in figure 7.1 Japan has the highest percentage of recycled cans and Europe is certainly staying behind in development of recycling rates. Whether this is due to differences in legislation or level of facilities is not clear, but in general it can be said that the main reason for these relatively low recycling rats of cans is lack of infrastructure and facilities to collect.

The use of coatings (aluminium, tin, plastic) in packaging is increasing to improve the quality of the product. The lifetime of a product can increase (no rust formation) and higher surface qualifications can be reached. Research also focuses on techniques to make thinner coatings, as a result of environmental regulations and cost-savings. Consumer demands on the appearance of the product are of great importance to the choice of material and thickness of a coating.

Higher efficiency in distribution and logistics also leads to development of containers and cans (for example the square can, so more cans fit in a truck). Due to automation in manufacturing and distribution combined with changes in food-preservation the traditional way of (rigid) steel packaging may change.

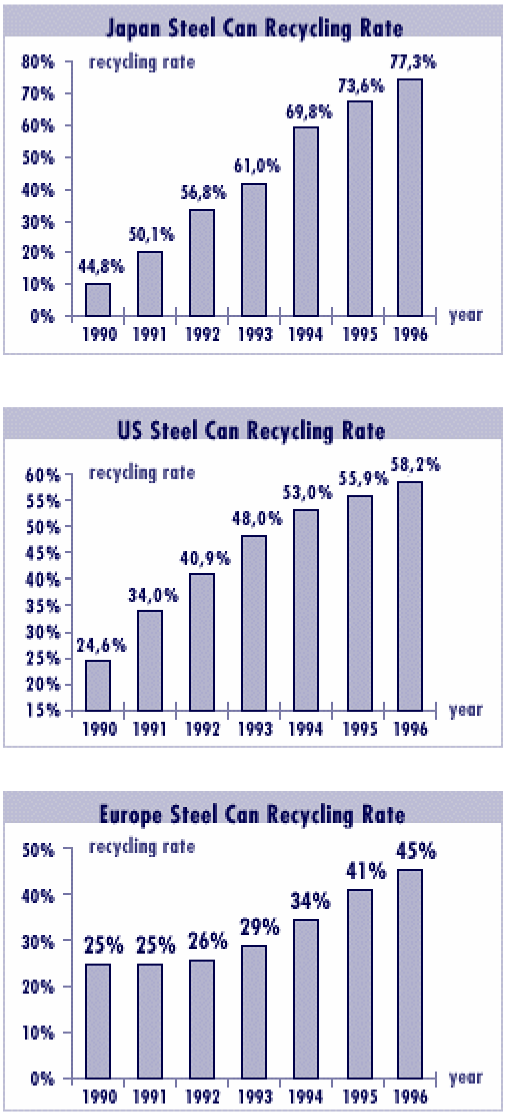

Figure 7.1:Steel can recycling rates [web-site Hoogovens Packaging Research Centre, 1999]

7.5.3 Construction industry

Also in construction industry, steel has competition of other materials like wood, aluminium and plastics. Some governments stimulate the use of more wood, out of a sustainable development perspective. Costs and market demands will be the most important factors for development in construction steel.

As steel becomes stronger, constructions can be designed with less material, and become therefore lighter. The effect on energy-use and CO_2 emissions is uncertain. Some recent LCA studies have been done on comparing different building materials, but the results of these studies are not publicly available.

7.5.4 Conclusions

Cost effectiveness and high quality market demands lead to product development. Environmental regulations of course are of influence, but are not the main reason why steelmakers innovate.

Minimisation of inclusions and zero cracked flanges or bead fractures, will lead to improved steel making technologies. Process control practises that reduce variability of surface finish (coatings), rolling practices that reduce physical surface defects and detection systems are essential to reducing defects.
More use of scrap leads to steel with less quality, so the use of scrap will be obstructed by high quality demands.
The use of different coatings is increasing. For some sorts of steel, impurities are not a problem, and a greater percentage of scrap can be added. One can say that the increasing use of all kinds of different coatings can become a barrier to recycling.

Competition from plastics and aluminium is evident for a lot of steel products. To compete with these 'new' materials steel must become lighter, stronger or cheaper. Downweighting leads tot less material use, but certainly not in all cases to net energy (CO_2) savings.

8. SCENARIOS AND EVALUATION

8.1 GENERAL REMARKS

Emission estimates for 1985, 1990 and 1995 were based on national aggregates of production technologies and regional default values for the energy consumption of certain process steps and the associated emissions. This approach has its own limitations as it tends to underestimate improvement options within one technology (retrofitting) and emphasises the benefits of switching between technological routes. A detailed technological database would certainly allow more precise estimates of emissions and a better definition of the global potential for emission reduction options. Unfortunately this type of database (on a site-by-site level) does usually not even exist on the national level.

A technology oriented methodology to estimate emissions cannot be expected to yield meaningful results for future emission projections, as all three types of input data (economic scenario, shares of specific technologies and their characteristics in terms of energy consumption and emissions) would remain uncertain. On the global level - as requested for this study - a completely different and more abstract route to emission projections until 2010 and 2020 had to taken.

8.2 METHODOLOGY

For the emission projections 2010 and 2020 the world was divided into four regions: 1) The European Union (EU) and the North American Free Trade Association (NAFTA); 2) the countries of the former Soviet Union (FSU) and the East European Economies in Transition (EET); 3) China and 4) all other countries of the world “Remaining Countries” (REMCO). It is important to note that REMCO is larger in this part of the study than “rest of the world” (ROW) had been defined for the emission estimates for 1985, 1990 and 1995 above.

The emission projections are based on a plausible estimate of the future production of steel and primary iron as described below. Associated emissions are subsequently calculated from emission factors per ton of produced steel and primary iron, respectively. Emission projections are calculated as the mean values of the two individual emission levels calculated from the projected emission factors for steel and primary iron. Both individual estimates lie within ±5 % of their mean, which is well below the overall uncertainty of this analysis. Four different scenarios are derived for different assumptions on the temporal evolution of initial regional values between 1985 and 1995.

These factors (Table 8.1) are calculated from the database, which was created for the emission estimates. On this level of aggregation little difference can be found between the technological performance of EU & NAFTA and REMCO. FSU & EET and CHINA in particular exhibit high CO_2 emission factors per ton of product. This is mainly due to high specific energy consumption, high carbon intensities of electricity generation and low recycling rates. It is important to keep in mind that the derived numbers are simply statistical indicators calculated by dividing the sum of CO_2 emissions from the iron and steel industry in one region by the regional output in terms of pig iron or rolled steel. These indicators are not to be confused with specific emissions per technological path of metal production.

Table 8.1 Regional CO_2 emission factors in 1985, 1990 and 1995 [T CO_2 / ton of metal] (pig iron and rolled steel).

	1985		1990		1995	
	pig iron	steel	pig iron	steel	pig iron	steel
EU & NAFTA	2.4	1.5	2.3	1.5	2.3	1.4
FSU & EET	3.1	2.1	3.0	2.1	2.8	2.0
CHINA	3.3	3.1	3.4	3.2	3.4	3.5
REMCO	2.1	1.6	2.2	1.7	2.4	1.8
WORLD	**2.6**	**1.8**	**2.6**	**1.9**	**2.6**	**1.9**

8.3 ECONOMIC SCENARIO

The projection of future industrial emission levels requires assumptions on the expansion or decline of underlying production processes. The authors of this study unfortunately lack the ability to precisely estimate the future demand for iron and steel. Basically a set of regionally differentiated growth scenarios of the iron and steel production has to be defined for a complete uncertainty analysis of projected emissions. A different approach was chosen in this study in order to avoid a model with multiple degrees of freedom. In this study the effects of technological change on emissions were studied based on only one, moderately optimistic projection of the future production of iron and steel until 2020. It was derived by considering past trends of production increase in EU&NAFTA, CHINA and REMCO and by assuming a certain economic recovery in the FSU & EET countries. For the former the regions it is assumed that growth of production continues until 2020 at half the expansion rate between 1985 and 1995. For FSU & EET a recovery of the iron and steel production from 1995 levels at a 1.5 % yr^{-1} growth rate is assumed. Production would still remain roughly 25 % below 1990 levels in 2020. Historical and projected production numbers for pig iron and crude steel are given in Figure 8.1 and Figure 8.2, respectively. Production is projected to remain basically constant in the EU & NAFTA. Most growth is projected to occur in CHINA and REMCO.

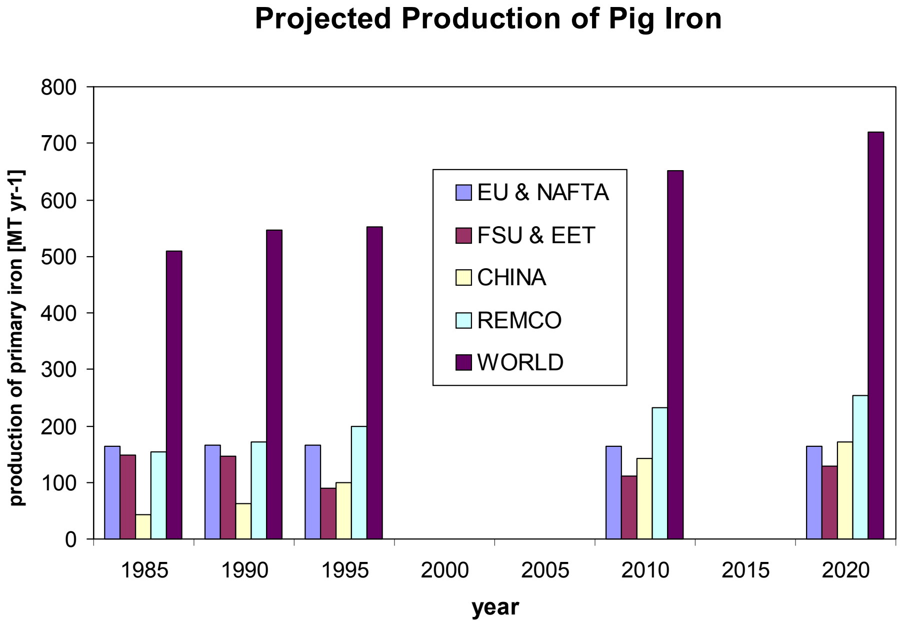

Figure 8.1 Historical and projected production levels of pig iron.

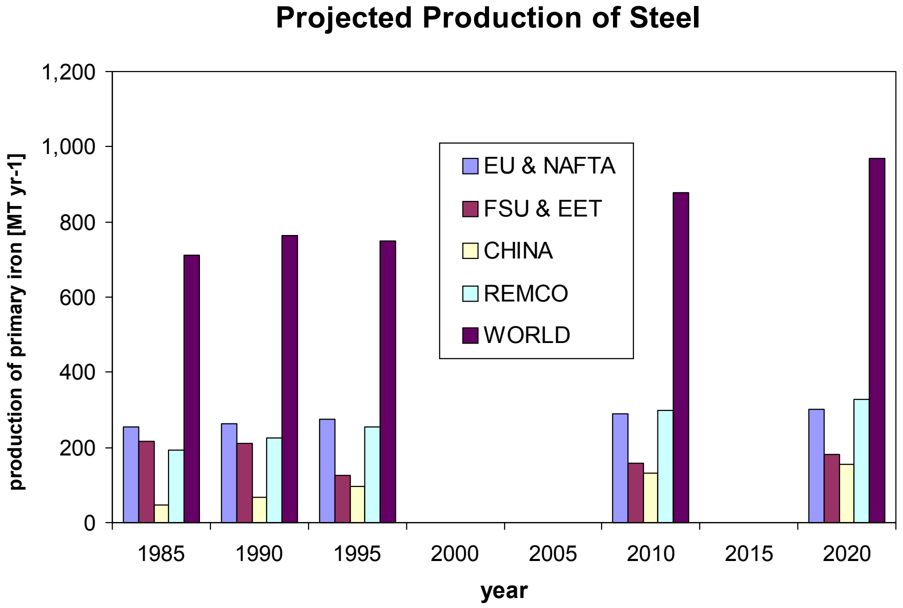

Figure 8.2 Historical and projected production levels of crude steel.

8.4 FOUR SCENARIOS

We calculate four different emission scenarios to describe the range of plausible regional emission trajectories. The four scenarios are not linked to specific climate change policies but refer to different assumptions of technological evolution and technology diffusion across regional boundaries. The scenarios are called “Frozen Technology”, “Moderate Change”, “Accelerated Change” and “Wonderful World”.

“Frozen Technology” is overly pessimistic and assumes that the mean of emission factors in Table 7.1 remains unchanged in time. This scenario is used in Chapter 6 to project the unabated CO_2-emission in 2010 and 2020.

“Moderate Change” assumes that emission factors in “EU & NAFTA” decrease by 5 and 10 % until 2010 and 2020 and that the difference of emission factors in the other regions narrows down to 5/6 and 2/3 of the original difference until 2010 and 2020, respectively. This can be achieved by implementation of energy-efficient techniques that are cost-effective at a discount rate of 30%.

“Accelerated change” assumes a 10 and 20 % reduction of emission factors in “EU & NAFTA” until 2010 and 2020 along with a reduction of the differences between the emission factors of the other regions and “EU & NAFTA” to 2/3 and 1/3 of the original value. This can be achieved by implementation of energy-efficient techniques that are cost-effective at a discount rate of 5%, and by the introduction of new and emerging techniques for new capacity especially in China, the FSU and EET.

In the overly optimistic scenario *“Wonderful World*” we assume that all regions converge at the same time at the reduced “EU & NAFTA” emission factors of 90 % and 80 % of the mean 1985-1995 factors in 2010 and 2020. To achieve this new and emerging technologies have to be implemented at an accelerated pace, CO_2-removal from blast furnace gas is required and a shift from primary to secondary steel is necessary.

8.5 RESULTS

The main results of the calculations are presented in the Figures below. The data for the scenario “Frozen Technology” are shown in Figure 8.3. Global emissions start to pick up their increase after the economic decline of FSU & EET and are projected to be 32 % above 1995 levels by 2020. EU & NAFTA is the only region with virtually stagnant emissions.

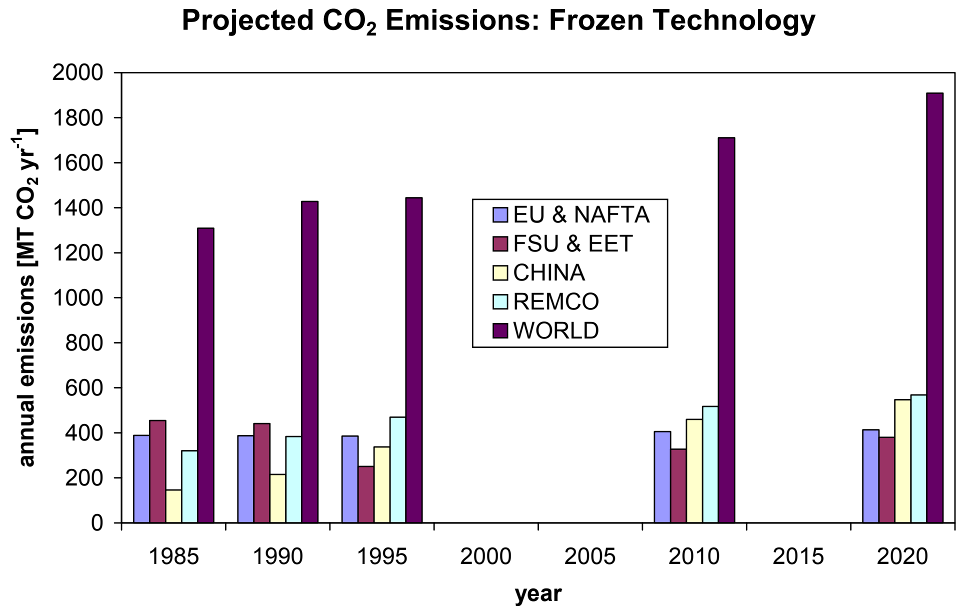

Figure 8.3 Projected emissions in scenario “Frozen Technology”

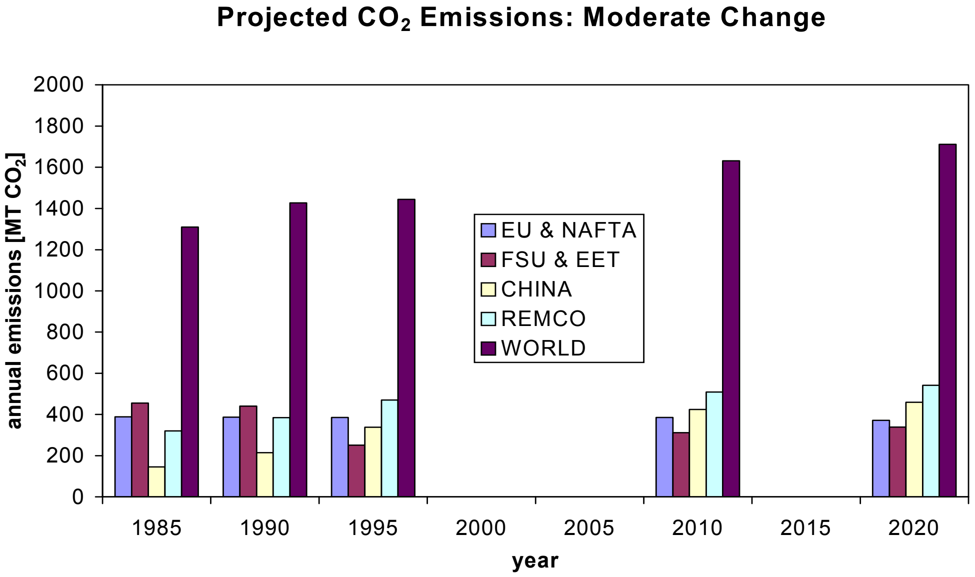

Figure 8.4 Projected emissions in scenario “Moderate Change”

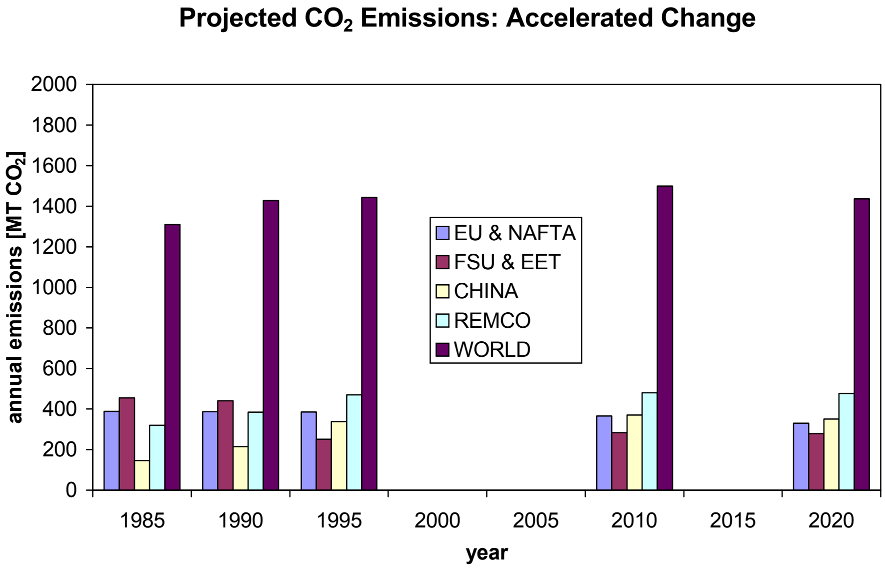

Figure 8.5 Projected emissions in scenario “Accelerated Change”

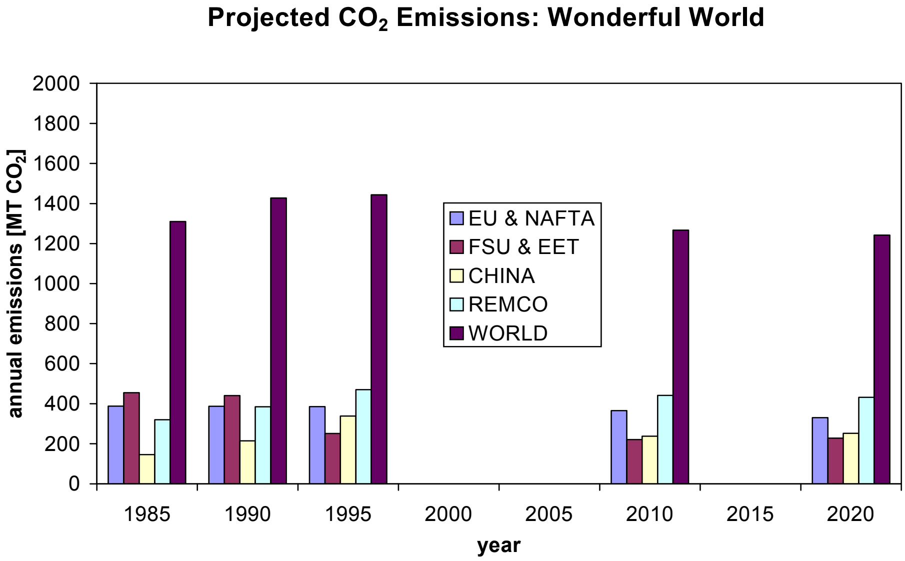

Figure 8.6 Projected emissions in scenario “Wonderful World”

The probably most realistic business-as-usual scenario “Moderate Change” leads to emission levels as presented in Figure 8.4. Global emissions are projected to increase by 19 % again basically driven by increases in CHINA, FSU & EET and REMCO. Figure 8.5 and Figure 8.6 visualise the results for scenarios “Accelerated Change” and “Wonderful World” which require significant efforts in terms of technological innovation and technology diffusion. Despite the projected 30 % expansion of global production until 2020 emissions are projected to remain at 1995 level or decrease 14 % below this level until 2020. Figure 8.7 summarises the global emission for all four modelled scenarios. It demonstrates the large effect of technology diffusion on the mid-term emission levels of the iron and steel industry. The widely varying projected emission levels of the four scenarios become even more obvious in the case of China (Figure 8.8).

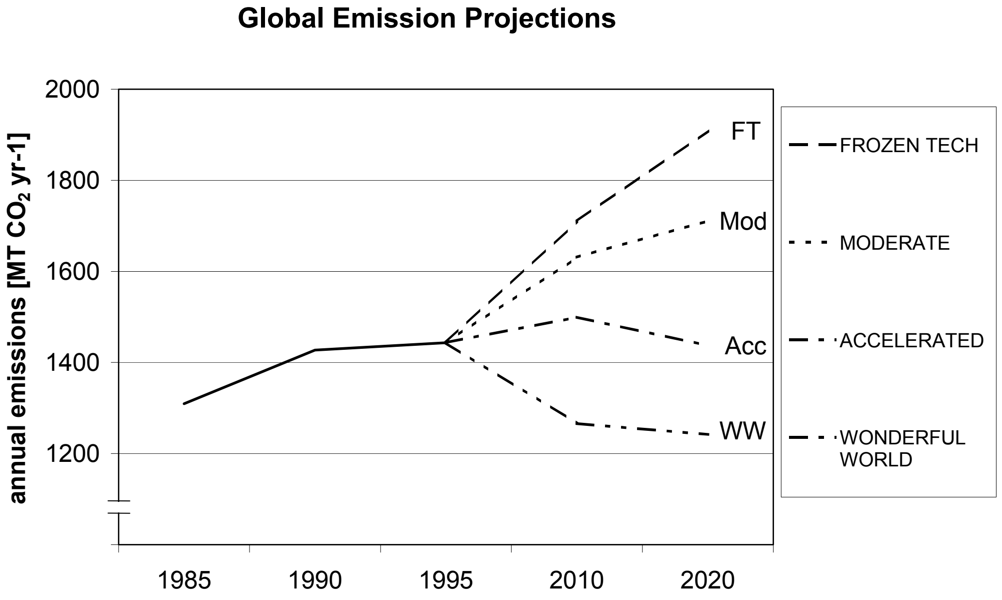

Figure 8.7 Projected global emission for the four scenarios

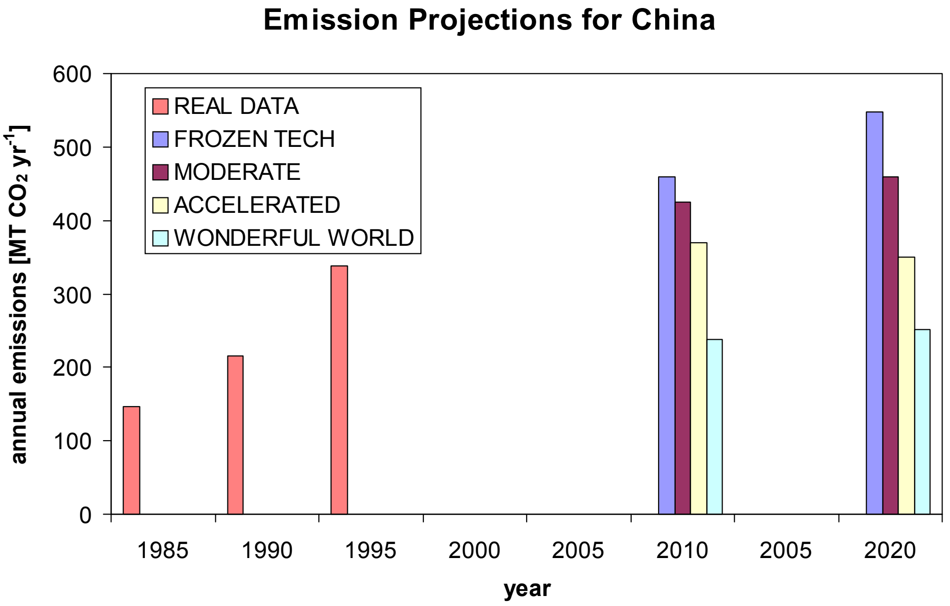

Figure 8.8 Projected Chinese emission for the four scenarios

8.6 DISCUSSION AND CONCLUSIONS

A comprehensive technological database on site-by-site level is required for reliable estimates of historical emissions and the projection of future emissions. Due to the unavailability of this information this study had to take more abstract routes towards emission monitoring and projection. This “top-down” analysis shows that considerable emission reductions may exist from a convergence of the technological performance of the iron and steel production particularly in China and the countries of the former Soviet Union and Eastern Europe with current western standards.

Four scenarios were defined to cover the full range of potential future emission trajectories. A projected growth of 30 % of the global production of iron and steel until 2020 in the four scenarios leads to emission decreases as well as emission increases of more than 30 % depending on how soon countries like China or the Former Soviet Union will be able to approach the energy efficiency standards of the most advanced western producers.

Scenario “Frozen Technology” assumes that energy efficiencies and emission factors will remain fixed at their mean 1985-1995 levels in each region. This is a clearly over-pessimistic assumption, as in areas with expanding production more recent technology will generally be used for new investments. The specific mean energy consumption and associated specific emissions will thus generally fall when production expands. “Moderate Change” is probably closest to an undisturbed “business as usual” case. The IISI [1996b] energy report describes the evolution of energy requirements for iron-making in several major western producer countries. It reports specific reductions of 5-10 % during the 1980's, which is at the higher end of what was assumed for “Moderate Change.” In dynamic developing countries like China the mean specific energy consumption value will also be reduced simply through a larger share of newer plants with advanced technology. These reductions are likely to be in the range of several 10 % until 2020 as assumed in “Moderate Change.” The third scenario “Accelerated Change” requires energy consumption reductions in the industrialised world, which would go beyond those, accomplished during the 1980’s. In developing countries like China “Accelerated Change” would imply that existing plants also undergo significant efficiency improvements and that a reasonable share of the least efficient and smaller plants be closed. The fourth scenario “Wonderful World” requires a rapid transition of production technology in developing countries towards standards, which are now accomplished in only few industrialised countries. Less efficient capacity will have to be retrofitted or closed. A significantly larger market for recycled steel also will have to be established to arrive at the required low energy consumption values per ton of steel product using the electric arc furnace route. It would certainly require considerable concerted global action to force the global iron and steel industry beyond “Accelerated Change” towards the path of “Wonderful World.”

Certainly a larger near term potential for emission reductions exists from an adoption of existing technologies via CDM and JI than from technological innovations which would be implemented in western countries. “Technology transfer and diffusion" are obviously more complex issues than a mere transfer of patents, licences and machinery is. Often they will require a prior economic and cultural convergence of societies to ensure comparable cost structures for products, energy, labour, raw materials of certain qualities. The energy efficiency issue in the iron and steel industry goes well beyond the choice of specific technologies in iron- and steel plants. It includes for example the availability of high-grade ores, coke quality coal and affordable high grade scrap. In cases in which a country decides to rely on domestic instead of world-market resources it will often not be able to even approach the energy standards of the more advanced producers.

9. CONCLUSIONS

This study resulted in the following key findings:

⇒ **The iron and steel industry is the largest energy consuming manufacturing sector in the world**. In 1990, its global energy consumption was estimated to be 18-19 exajoule (EJ), or 10-15% of the annual industrial energy consumption. The associated CO_2-emission is estimated to be 1425 Mtonne. In 1995 this amount had increased to 1442 Mtonne CO_2, equalling roughly 7% of global anthropogenic CO_2-emissions. When mining and transportation are included this share is expected to near 10% of total emission.

⇒ **In the last decade considerable changes occurred in the division of the CO_2-emissions over world regions**. This is due to a decline in production and emissions in the countries of the former Soviet Union and Eastern Europe on the one hand, and due to a rapid increase of production and emissions in China and other dynamic developing countries on the other hand.

⇒ **There are large differences between CO_2-emission factors of steel making between world regions**. This is due to differences in efficiency of the processes and fuel input and due to a different pace of penetration of new technologies. At the moment the CO_2-emission factor for steel of China is a factor 2 higher than in the European Union and Nafta-countries.

⇒ **In total about 590 Mtonne CO_2 can be abated cost-effectively in 2020, equalling about 30% of the unabated emissions in 2020.** Organisational, institutional and political barriers are not taken into account in this potential. The options to abate the emission of CO_2 that are considered are:

- *Improvement of the energy efficiency by the introduction of available techniques*. For integrated steel mills 16 techniques have been identified and for minimills 12. The technical potential for energy-efficiency improvement averaged over the world is 23% of the unabated CO_2-emission in 2010, which equals about 400 Mtonne of CO_2. Of this potential emission reduction, approximately 90% may be achieved in integrated steel mills. The remaining 10% has to be realised in minimills. The economic potential, using a discount rate of 5%, is 20%. In these potentials account is being made for regional differences in current penetration
- *Improvement of the energy efficiency by the introduction of new and emerging techniques.* The main techniques in this category are smelt reduction and near net shape casting. Commercial introduction is not expected before 2010. The specific energy consumption of an advanced integrated steel mill, consisting of smelt reduction and near net shape casting, can be im-

proved by about 45% compared to the word average. It should be noted that such a configuration can only be applied for the production of certain products (flat products). Furthermore, replacement of existing plants is in general not economically feasible and the technical viability of this routes remains to be proven.

- *Shift from primary to secondary steel.* The CO_2 emission factor of secondary steel is about 35% of that of primary steel. During recent decades the usage of secondary steel has stagnated. This was due to technological developments in smelting, casting and processing that led to a decline of amounts of plant and circulating scrap. Primary steel is certain to remain the preferred material for most high-quality products. Furthermore, a shortage of high grade scraps may limit further growth of the minimill capacity. To overcome this shortage plants that produce primary iron scrap-substitutes (e.g. direct reduced iron) have been set up exhibiting CO_2-emission factors similar to the conventional blast furnace route. Due to the complexity of steel product categories and qualities the reduction potential of a shift from primary to secondary steel is hard to project.
    - *Carbon dioxide recovery from blast furnace gas.* Decarbonising blast furnace gas before use can be done at costs of US$35/tonne CO_2. Transportation and storage of CO_2 will add US$8-20/tonne CO_2 (at a transportation distance of 100 km). In 2020 this could contribute 290 Mtonne to the CO_2-abatement.
    - *Charcoal-based blast furnaces.* A technology being used in Brazil. However, the potential is limited because the large surface area required for growth of wood for producing charcoal.
    - *Iron ore reduction with hydrogen.* This technology is still under development and not expected to be commercial before 2020.

⇒ **The uptake of CO_2-abatement options is affected by a number of non-technological factors:**

- *Environmental legislation.* Especially for sinter plants and coke ovens environmental standards force integrated steel manufacturers to look for alternatives. Since smelt reduction is an option that avoids the use of both sinter and coke, the uptake of this technology might be speeded by more stringent environmental standards.
- *Capacity development.* It is not expected that new primary steel making capacity will be built in developed countries. CO_2-abatement in these countries should therefore come from retrofit options. In developing countries new capacity is expected. Joint implementation can be used to ensure that the latest technologies will be used.
- *Market and product development.* Primary steel manufactures are innovating their products to keep an edge over secondary steel. Technological development is directed at steel cleanliness, surface appearance and gauge control. In the automotive industry steel has a competitor in aluminium. Although the discussion on the effect on CO_2-emission is still

ongoing, it forces the steel industry to pay attention to product innovation.

- *Cost reduction*. Processes in an integrated steel mill are very expensive. Eliminating one or more processes is therefore very attractive. This is a major driver for the development of smelt reduction and near-net-shape-casting technologies. Increased levels of pulverised coal injection may avoid new coke making capacity.
- *Investment risks*. The development of new and emerging processes often involves high investments. Steel companies are not always willing to take the financial risk alone. At least in one case this has lead to a postponement of the development of a new reduction technology.

⇒ **According to a scenarios in which the energy-efficiency is frozen at 1995 levels the possible CO_2-emission is 1900 Mtonne in 2020.**

⇒ **Three scenarios were developed to assess the effect of energy-efficiency improvement and different developments per world region.** The scenarios differ in the development of energy efficiency per world region. This reflects differences in assumed diffusion of technologies over world regions.
A scenario “Moderate Change” is designed to resemble business-as-usual. According to this scenario the CO_2-emission in 2020 will be 1,700 Mtons, equalling a 10% reduction compared to a “Frozen Efficiency Scenario” with 1,900 Mtons. In the “Moderate Change” scenario the CO_2-emission factors are reduced by 10% in the European Union and Nafta-countries and the difference in energy efficiency of the other regions with EU/NAFTA is reduced by 35%. The more radical scenarios “Accelerated Change” and “Wonderful World” assume that by 2010 the energy efficiency gap between further improved EU/NAFTA values and other world regions is reduced by 65% and completely disappears, respectively. The projected global emission levels for 2020 are 1,400 and 1,200 Mtons per year equalling reductions by 15% and 25% against business-as-usual and 25% and 35% against the “Frozen Efficiency Scenario.”

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