LONG TERM ENERGY AND MATERIALS STRATEGIES FOR REDUCTION OF INDUSTRIAL CO_2 EMISSIONS

A Case Study for the Iron and Steel Industry

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1 INTRODUCTION

Greenhouse gas emissions emerged in the last decade as a key environmental problem on the political agenda. The most important greenhouse gas is carbon dioxide (CO_2). This gas results from the combustion of fossil fuels (natural gas, oil and coal). As a consequence, greenhouse gas emission reduction is closely related to energy policies.

Even a stabilisation of the atmospheric CO_2 concentrations at a level of 750 ppm (parts per million), more than twice the current level, implies a reduction of global emissions by 50 % in the next century. The world population will simultaneously double and the capita energy consumption will increase. As a consequence, the Western industrialised countries will have to reduce their per capita emissions by more than a factor four. Such a policy goal will significantly affect the future industrial production structure.

Approximately 4% of the global CO_2 emissions can be attributed to the production of iron and steel [1]. This sector is the most important industrial source of CO_2. The case study for the iron and steel industry will be discussed in this paper in order to illustrate the impact of significant CO_2 emission mitigation on the industry. The goal is to show the consequences of CO_2 policies for R&D planning and investment decisions.

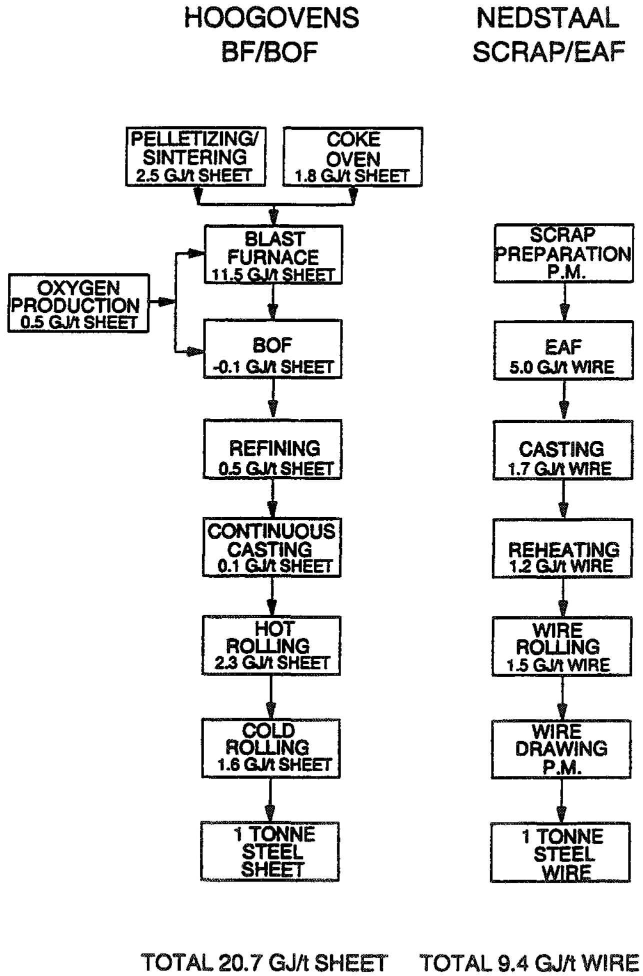
The notion that the iron and steel industry will be affected by CO_2 policies is not new; a number of studies have addressed this issue before (e.g. [2,3,4]). These studies have compared steel production technologies and emission reduction options within the iron and steel production sector. In this paper, the emission reduction in the iron and steel industry is analysed within the framework of the changing (inter-)national energy and materials system configuration. This includes all production, conversion and consumption processes. The impact of CO_2 policies on the optimal choice of steel production technologies and on the competitiveness of steel compared to other materials will be discussed.

This paper focuses on the Western European situation. The results can however also be applied to major foreign steel industries, as the technologies and applications are generally very similar.

2 CO_2 EMISSIONS IN THE IRON AND STEEL INDUSTRY

CO_2 emissions in the iron and steel industry are related to the use of fossil fuels. The fossil fuel consumption depends on the steel production technology. The current Western European iron and steel industry is mainly based on two technologies. The Blast Furnace (BF) is used to reduce iron ore into liquid iron, which is subsequently converted into steel in a Basic Oxygen Furnace (BOF). Electric Arc Furnaces (EAFs) are used to produce steel from scrap. Approximately two thirds of the Western European steel is produced in BOFs, one third is produced in EAFs.

Figure 1: *Primary energy consumption for BF/BOF and scrap/EAF in the Dutch situation*



Scrap based EAF production requires considerably less energy than the BF/BOF route, mainly because the chemical energy for the ore reduction can be saved. The preparation of coke, ore pellets, or sinter for the BF requires also considerable amounts of energy. Figure 1 shows an analysis of the energy consumption of the blast furnace and the electric arc furnace route. The data refer to the Dutch situation with relatively low energy consumption for the blast furnace route, compared to other Western European countries.

Table 1: *CO_2 emissions of fossil fuels*

	[KG/GJ]
COKE	108
COAL	95
OIL	73
NATURAL GAS	56

Blast furnaces are predominantly fueled with coal and coke (a coal product). The specific CO_2 emission coefficient of coal is in the range of 95-105 kg CO_2/GJ (GigaJoule), depending on the content of volatile matter. This emission coefficient is high compared to other fossil fuels (see Table 1) [5]. As a consequence, the coal based steel industry is an important source of CO_2. CO_2 is also emitted during iron production because of the decarbonisation of limestone ($CaCO_3$). Limestone is added to the blast furnace charge in order to reduce the impurity content of the iron product. The decarbonisation represents approximately 0.075 t CO_2 emissions per tonne steel (1 t = 1 metric tonne).

The specific CO_2-emissions per tonne steel cannot be calculated straightforward from the energy balance of the steel industry because of the significant amount of energy by-products: coke oven gas, blast furnace gas and BOF-gas. If these gaseous energy carriers are sold, their CO_2-emission can either be allocated to the user of the gas (generally a power producer) or to the steel industry. In this study, the emissions related to the use of the off-gases for power production are allocated to the steel industry.

However, the simultaneous reduction of the emissions because of the reduced power production elsewhere is also attributed to the steel industry.

In Europe, national electricity production ranges from nuclear or hydropower plants with zero CO_2 emissions to coal fired power plants with 0.3 t CO_2 per GJ electricity. On average, electricity is produced with a specific CO_2 emission of approximately 0.1 t CO_2 per GJ electricity. With such a reference value, the CO_2-emissions per tonne cast BOF-steel are approximately 1.8 t/t, the emissions for one tonne cast EAF-steel are approximately 0.3 t/t.

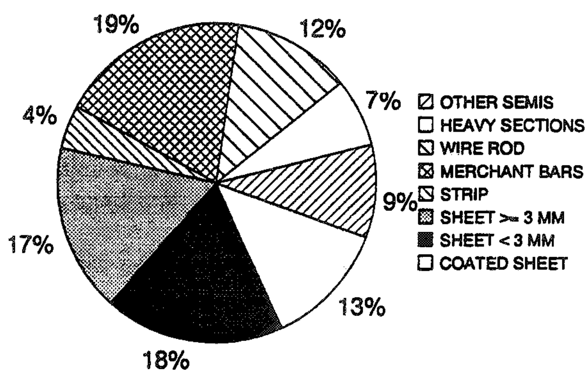
However, the cast steel is not the final product. Steel slabs and blooms are further processed into sheets, tubes, wire etc.. The CO_2-emissions of steel rolling and finishing depend to a large extent on the product type, and ranges from 0.1 t/t for hot rolled sheet to 1 t/t for thin drawn wire. An average emission for rolling and finishing of 0.4 t/t results in a total emission of 2.2 t/t for the blast furnace route and 0.7 t/t for the EAF route. The total emission (assuming best practice steelmaking) for the Western European steel industry is approximately 250 Mt per year (Megatonnes = 10^6 t). As the total Western European CO_2-emission is approximately 3500 Mt per year, this represents 7% of the total Western European emission. This contribution is well above the global average of 4%. The difference is related to the strong European export position for steel, steel products and steel scrap that is discussed in Section 4.

3 THE STEEL MARKET

A division of the steel consumption into semi-finished steel products is shown in Figure 2 [6]. The bulk of the steel is consumed as wire rod (12%), merchant bars (19%) or sheet (48%). Wire rod is used for wire drawing and reinforcement bars, merchant bars are especially used in the building sector. Sheet is used in a number of consuming branches like tube production, mechanical engineering, transportation equipment production and the metal goods sector.

While steel has been used for more than 100 years, the number of steel qualities is still rapidly increasing. Because of competition from aluminium and plastics in certain market segments, steel producers have developed a large number of new steel qualities with increased strength, enhanced fracture toughness, improved formability etc.. Over 50% of the products that are sold by many steel companies today could not have been produced ten years ago. New steel qualities are based on new combinations of alloying elements and finishing techniques. The secondary steel metallurgy with technologies like vacuum oxygen degassing (VOD) and ladle refining furnaces (LF) has allowed the production of steel with much lower impurity contents and the improved control of the chemical composition. The corrosion resistance of steel has been significantly increased by development of metal and organic coatings.

Figure 2: *Steel consumption in the European Union, 1990 (weight fractions)*



Steel meets in each consuming branch different quality criteria. The criteria are determined by the product specifications and the manufacturing process. The minimum amount of steel is in most applications determined by the strength requirements, ductility and weldability. The steel properties depend on the crystal structure, the chemical composition and the grain size. These parameters can be influenced by the steel production conditions (see Section 4).

4 ANALYSIS OF CO_2 MITIGATION OPTIONS

A number of strategies exist to reduce industrial CO_2 emissions. The Intergovernmental Panel on Climate Change (IPCC) lists the following options for mitigation of industrial CO_2 emissions [7]:

- fuel switch
- increased energy efficiency
- CO_2 removal and storage
- recycling and reuse
- dematerialisation and materials substitution

This generic list of improvement options can also be applied to the iron and steel industry.

Fuel switch

The main CO_2 emissions in the iron and steel industry arise during the production of steel from iron ore. The current blast furnace iron production is based on coal as energy source. Other fuels can however also be used for production of either iron or DRI. Oil, natural gas, hydrogen, electricity, plastic waste and biomass can either partially or completely replace coke and coal in the production of steel from iron ore. Hydrogen, electricity and biomass are CO_2-free energy carriers. The use of oil, natural gas, and plastic waste (an oil product) results in lower CO_2 emissions than the use of coal and coke (see Table 1).

Oil injection in blast furnaces has been common practice up to the oil crises in the 70's. In a similar way, plastic waste can be injected into the blast furnace. Natural gas can be used for production of DRI (Direct Reduced Iron). DRI is produced through reduction of iron ore in its solid state. This product can substitute scrap in EAF steel production. 23 Mt DRI was produced in 1993, representing 5% of the total global pig iron production for steelmaking.

With regard to the CO_2-free energy carriers, hydrogen can also be used for DRI production. Electricity based plasma can be used to heat the blast furnace. It substitutes the injection of fossil fuels like coal or oil. Biomass can be converted into charcoal, a product with a similar chemical structure as coke. The Brazilian iron production is currently still to a large extent based on the use of charcoal (7 Mt iron per year, 1.2% of the global iron production). If the biomass is renewable, this route allows the production of iron without (net) CO_2 emissions, because the CO_2 that is released has previously been stored by the tree.

Increased energy efficiency

Significant energy efficiency improvements are still possible in the steel production process. First of all, the average European steel producers use 25% more primary energy than the best practice steelmaking would require [8]. But even the best practice steelmaking can be further improved.

The theoretical minimum energy consumption for steel production is only 6.7 GJ/t (Haematite iron ore, Fe_2O_3). If this figure is compared to the actual energy consumption for steel production in Figure 1 (from ore to BOF-liquid steel), the theoretical saving potential is still two thirds of the current energy consumption. Hoever, this value overestimates the saving potential. The sensible heat of liquid steel cannot be recovered, the decarbonation of $CaCO_3$ requires considerable amounts of energy. 10 GJ/t is a more realistic estimate for the minimum energy requirement. This leaves a long term energy saving potential of 50% compared to the current best practice steelmaking in Western Europe.

Such significant savings would however imply radical changes in the steel production process. The current relatively high energy consumption of the blast furnace steelmaking is not related to the inefficiency of the actual chemical reduction process that takes place in the blast furnace. The energy consumption of coke and ore preparation processes and the steel finishing processes are the main causes (see Figure 1). As a consequence, current research focuses on steelmaking with fewer and more efficient preparation and finishing steps.

Examples are the smelting reduction processes like Corex that can use coal instead of coke to produce liquid iron from iron ore. The Cyclone Convertor Furnace (CCF) is another promising technology that uses coal and ore fines for liquid iron production. Such a design would replace both coke making and ore agglomeration.

Similar radical improvements are currently being introduced in the finishing section. Continuous casting has replaced the ingot casting process in the last two decades. Thin slab casting, strip casting and direct rolling will further reduce the energy consumption and materials losses in the rolling sections.

A reduction in energy consumption from the 21 GJ/t for cold rolled sheet in Figure 1 to 15 GJ/t seems possible in the next 25 years. In practice, these reductions will not be introduced at once due to the very high investment costs and the long remaining life of the existing capital equipment. A gradual decline in the average specific energy consumption for iron and steel production in Western Europe seems however certain for the next decades.

CO_2 removal and storage
CO_2 can also be removed from off-gases before they are emitted into the atmosphere [9]. This CO_2 can be stored in empty gas and oil fields or in aquifers (underground water reservoirs). CO_2 injection into depleted oil fields is a technology that is currently widely applied for enhanced recovery in the oil industry. The storage potential of aquifers is equivalent to the global anthropogenic CO_2 emission of decades or even hundreds of years.

In principle, CO_2 removal can be applied for all off-gas types. However, the removal costs are lower per tonne CO_2 if the off-gases contain higher concentrations of CO_2. The concentrations are higher for the oxygen blown Corex and CCF processes than for the blast furnace, that operates with (oxygen enriched) air. In DRI production, CO_2 removal is currently already applied in order to allow the recycling of off-gases. This recycling enhances the energy efficiency of the process. Because CO_2 is already removed, the additional costs for CO_2 removal and storage (per tonne CO_2) are lower for the HYL DRI production processes than for the iron production processes.

Recycling and reuse
Scrap based steel production results in considerably lower CO_2 emissions than ore based steel production. If the fraction of scrap based EAF steel production could be increased, this would also reduce CO_2 emissions. The potential of this option is limited by the scrap availability.

Figure 3: *Western European (EU+EFTA) iron and steel balance, 1992 (figures indicate material flows in Mt per year)*

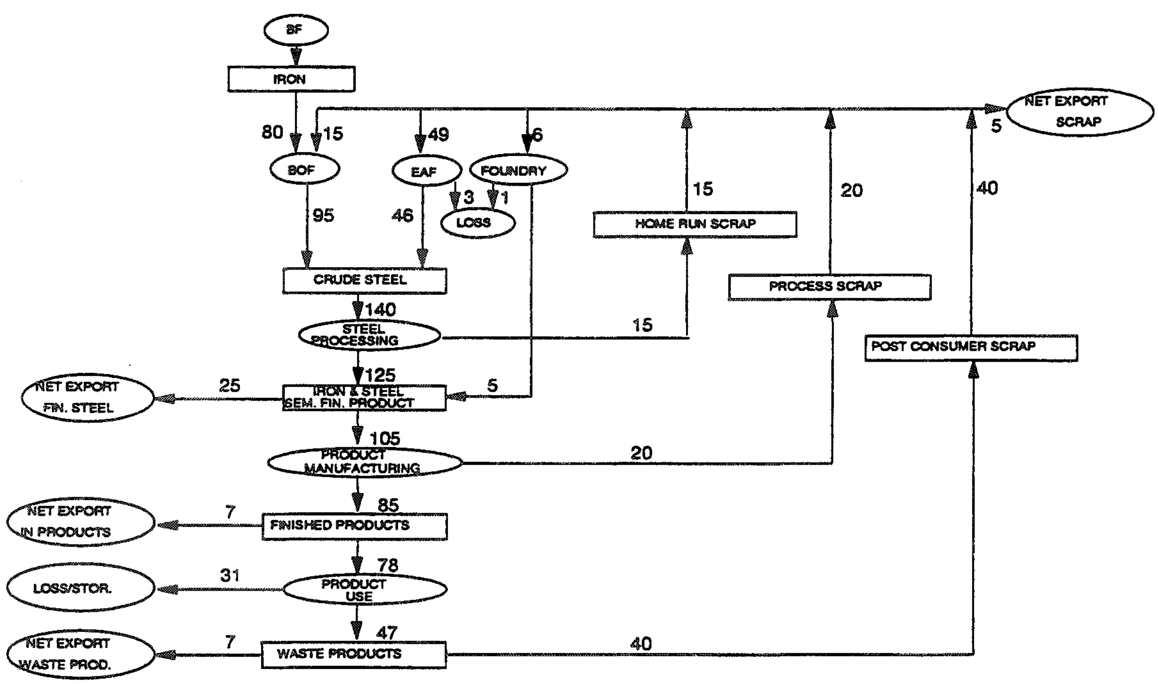


Figure 3 shows a steel balance for Western Europe. Significant amounts of steel, steel products, used products and even steel scrap are exported. Moreover, significant amounts of steel are stored in the still increasing stock of buildings, infrastructure and other long life capital equipment: the number of new buildings exceeds the demolition of old buildings by a factor four. Scrap recovery can be increased through improved waste separation systems, for example for municipal solid waste (MSW) [10]. However, the potential for increased scrap recovery is probably less than 10 Mt per year.

Another main barrier for increased scrap use is the product quality. The impurity content (Cu+Sn+Ni+Cr+Mo) of the feed material (scrap or iron ore) determines the steel quality. The impurity content of scrap can significantly differ for different scrap qualities. The quality is the highest for home run scrap (that is generated within the steel industry) and the lowest for certain types of post consumer scrap, like shredded cars [11]. Especially for the high purity steel qualities, like cold rolled sheet, impurities pose a serious problem. Post consumer scrap cannot be used to produce steel with very low impurity contents, unless expensive scrap purification technologies are applied.

Dematerialisation and materials substitution

Apart from the reduction of the CO_2 emissions related to the production of one tonne of steel, a reduction of the amount of tonnes can also reduce the emissions from the iron and steel industry. This reduction can be achieved through increased efficiency in the use of steel (deliver the same or even more product service with less material, which is called dematerialisation) or through substitution of materials (also called transmaterialisation).

Product specifications that determine the materials consumption can be split into the specifications for semi-finished products like steel sheet, steel tubes etc. and the specifications for the product service to the consumer, like for example the transportation service from A to B or the shelter service of a dwelling. The product services offer much more potential for increased materials efficiency than the steel products because of the much wider scope of options that can be considered. However, the substitution of passenger cars by trains and buses (substitution of product services) is not the same as the substitution of steel by aluminium in passenger cars, because many consumers perceive that their lifestyle is affected in the first case. The following analysis includes only materials options where technical constraints dominate the long-term improvement potential.

Improved materials quality has also significant potential for light weight product design. New Dual Phase steel qualities can be applied for bulk products like steel reinforcement bars. They can result in a 20% weight saving [12]. UltraHigh-Carbon Steels (UHCSs), consisting of fine ferrite grains with fine spheroidized carbides have higher tensile strength but the same ductility as high-carbon steels that are currently used. They can be used for wire, reinforcement bars and machining equipment. They can increase the tensile strength by more than 25%, while keeping the ductility at the same level. This results in significant weight saving in situations where strength determines the minimum amount of material [13]. New qualities of cold-resistant micro-alloyed higher strength steel for welded pressure vessels reduce the weight by 17-30% compared to the conventionally applied steel qualities [14]. New steel qualities for beverage cans reduce their weight from 24 to 18 grammes, a reduction by 25%.

Steel quality can be increased through improved control of the chemical composition and the grain size. Thermo-Mechanical Control Processing (TMCP) can be applied for improved control of the formation of the steel microstructure, a key parameter for steel strength. The introduction of thin strip casting and new rapid solidification processes shows also a significant potential for development of new steel qualities that can increase the materials efficiency.

Re-design can reduce the weight of steel car bodies by 40% [15]. Honeycombed indentations in food cans ("Hexacans") reduce their weight by 30%. Similar design improvements can be introduced for many other products.

Less rigid product standards and improved quality control pose also a significant potential for increased materials efficiency. The minimum proof strength quoted by manufacturers may be significantly underestimated, especially for thin plate. In one random example, out of 36 tests on stainless steel, the average strength was 40% greater than the quoted minimum and the lowest exceedence was 26% [16].

One type of dematerialisation concerns the increased life of products and product parts. If products are discarded before the end of their technical life, increased product life can reduce the steel consumption. Second hand shops, product dismantling schemes or renovation schemes can increase the economic product life through reuse. If the technical product life is limiting longer product use, improved steel qualities, coatings, or improved product maintenance can increase the product life.

In conclusion, it is assumed that the average saving potential through improved materials quality and product design is still in the range of 25%.

The production volume of steel may also be affected by intermaterial substitution. The major competitors of steel are aluminium and plastics in the transportation market and concrete and wood products for the building and construction market. It is beforehand unclear how CO_2 emissions will influence the intermaterial competition, and if steel will benefit or suffer. An increasing CO_2 emission in the iron and steel industry may result in a decreasing total CO_2 emission, if other materials with high specific CO_2 emissions per unit of product service (like cement or aluminium) can be substituted. A product life cycle approach is required for proper assessment.

5 THE MARKAL MODELING APPROACH

An integrated energy and materials system MARKAL model has been developed [17]. MARKAL (an acronym for MARKet ALlocation) is a tool that is used in many countries in the framework of IEA/ETSAP (International Energy Agency/Energy Technology Systems Analysis Programme). This techno-economic optimisation model can be used to develop national RD&D and investment strategies that take environmental policies into account. The model is widely used to develop long-term technological strategies for regions or countries.

The modeling approach is based on linear programming. The final demand for product services and environmental, technological, and financial constraints are in MARKAL defined by the user. Based on a database of technologies, the model calculates the least-cost system configuration for a set of time periods that satisfies the final demand and complies with the constraints. The capital stock transfer from one period to the next period is considered. This is one type of dynamic relation. The changing demand during these time periods, changing environmental constraints or, for example, changing energy and resource prices can also be included. Originally developed as a tool for energy systems analysis [18], the model has been extended for materials systems analysis [19]. The main difference between energy and materials from a modeling point of view is the storage of materials in products during the product life and the waste release after the product life. This is another type of dynamic relation.

The model consists of a database of several hundred supply, conversion and end use technologies that cover the whole energy system (energy production, conversion and use) and the materials system (materials production, conversion, use, and waste handling). These technologies are defined by the model user. Technologies can range from nuclear power plants, refineries, and steel production plants to cars or light bulbs. They are modeled as black boxes that are characterised by their energy and material inputs and outputs, their costs and their environmental impacts.

Because the whole system is modeled, technology interactions in a changing system configuration are automatically considered in the calculations. This is of paramount importance for analysis of the performance of technologies with multiple inputs and outputs from other parts of the system. Conventional analysis tools like chain analysis and life cycle analysis cannnot provide conclusive answers for such situations.

Environmental constraints are defined by the model user. The calculations that are discussed in the next section consider only CO_2 emissions. The analysis is confined to this single one emission because it is thought that significant CO_2 emission reduction will have a much more significant impact on the economy than all previous environmental policies.

Figure 4: *The materials life cycle model*

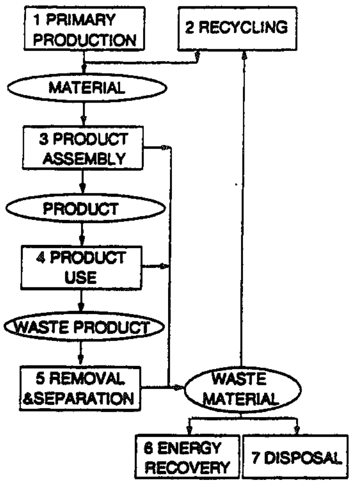
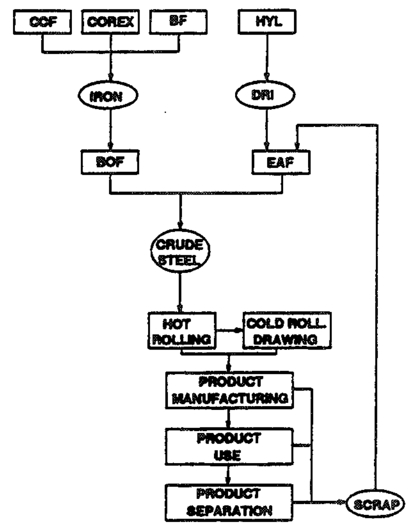


Figure 4 shows the model structure for products and materials. More than 30 materials like steel, aluminium, cement, paper, nitrogen fertilizers and wood are included. A large number of products are modeled, representing the application of these materials. This includes several types of buildings, cars, and household equipment. Auxiliary materials like fertilizers, solvents, and chlorine that do not end up in products are also considered. The model contains several hundred technologies in the energy system with a significant number of improvement options.

Based on the database of technologies, the model calculates the least cost-system configuration that satisfies the demand for products and services for a certain period, while taking CO_2 taxes into account. Future costs are expressed in current prices, based on a discount rate of 5%.

Figure 5: *Model structure for the iron and steel industry*

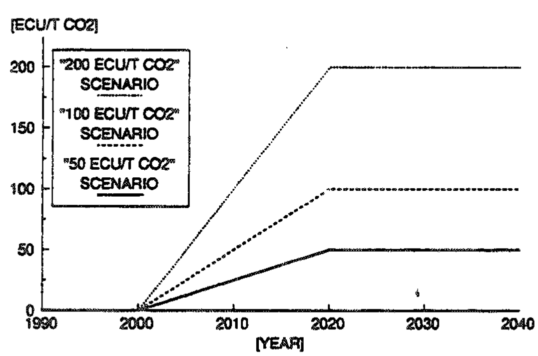


The MARKAL approach allows the comparison of completely different options like e.g. energy efficient steelmaking technologies, increased scrap recycling and dematerialisation for emission reduction. Interactions between technologies are taken into account, e.g. the interaction between electricity savings in EAF steel production and CO_2 emission mitigation in electricity generation.

Model structure

Figure 5 shows the model structure for steel production. Three technologies are considered for ironmaking: the blast furnace, Corex and CCF. Increased coal injection is considered as autonomous development for blast furnaces. Charcoal and waste plastic are considered as substitutes for (limited amounts of) coal in ironmaking. Two steelmaking routes are considered: BOF and EAF. DRI can substitute scrap in EAF steelmaking. Three steel qualities are considered: very pure (e.g. sheet < 3 mm and coated sheet), pure (e.g. sheet > 3mm, wire and tubes) and conventional (e.g. bars, castings). The more scrap is added, the lower the steel quality. Scrap based EAF can only be used for the pure and the conventional quality. The very pure quality can only be produced from iron or from DRI. Cast iron is considered as separate quality.

Figure 6: *CO_2 tax scenarios*



The steel applications include bulk products like cars, steel frames for buildings, steel reinforcements, machinery and other capital equipment, household equipment. Competing materials like concrete (for buildings), aluminium (for cars and trucks), plastics (for cars and household equipment), and glass (for food containers) are considered.

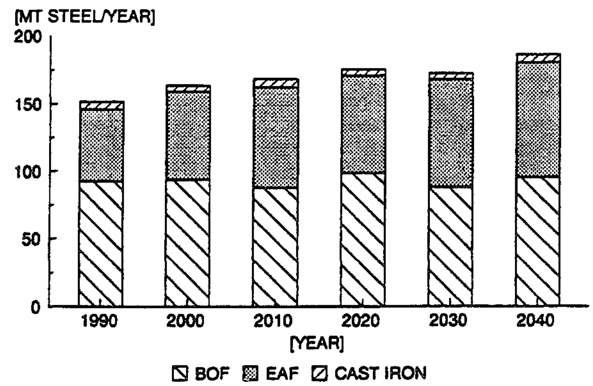
Model calculations

Model calculations have been done for the base case without CO_2 emission reduction and for a number of CO_2 tax scenarios that are shown in Figure 6. One set of calculations included CO_2 removal and storage, another set lacked this option. This represents the uncertainty whether this key option will become technologically feasible and socially acceptable.

6 RESULTS OF THE MARKAL CALCULATIONS

Figure 7 shows the iron and steel production in the base case without CO_2 emission reduction. There is still some growth in the total steel demand. Individual sectors are shown in Figure 8. The BOF steel production remains at a constant level, the growth is completely covered by increasing EAF steel production, based on increasing scrap availability.

Figure 7: *Iron and steel production in the base case* [17]



If CO_2 reduction is initiated, the steel industry is significantly affected. Especially the production structure for iron and steel changes. Figure 9 shows the iron production structure in 2020 in the scenario with CO_2 storage with increasing CO_2 taxes. The total iron production is hardly affected. As the tax level increases, there is a switch from Corex in the base case to increased CCF to Corex with CO_2 removal. The solution is rather sensitive for the removal and storage costs. In the calculations, it was assumed that the costs are in the range of 30-40 ECU/t CO_2 (ECU=European Currency Unit; 1 ECU≈1.2 US$). If the costs are raised to 50-60 ECU/t CO_2, the production shifts to a mix of CCF and DRI. In the scenario where CO_2 removal is not included (Figure 10), the iron production volume is significantly affected. DRI based steel production is introduced on a large scale. Corex iron production is especially negatively affected, CCF becomes the dominant iron production technology.

The CO_2 impact of smelting reduction technologies is significantly affected by the production structure for electricity. For example Corex produces more than 15 GJ of gas and steam by-products per tonne iron. These products will generally be used for large-scale power generation. Figure 11 shows that power production in the reference energy system becomes virtually CO_2-free at higher emission reduction penalties. Coal is substituted by natural gas, nuclear energy and renewables, so power production based on the energy by-products of steel production saves no CO_2 emissions in power production.

Figure 8: *Iron and steel consumption, base case* [17]

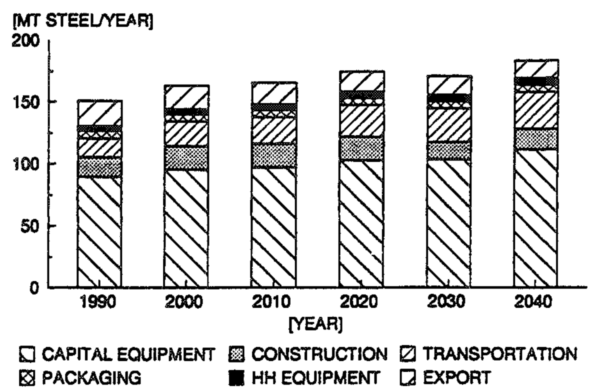


Figure 9: *Changing iron production 2020 due to CO_2 tax, including CO_2 storage option* [17]

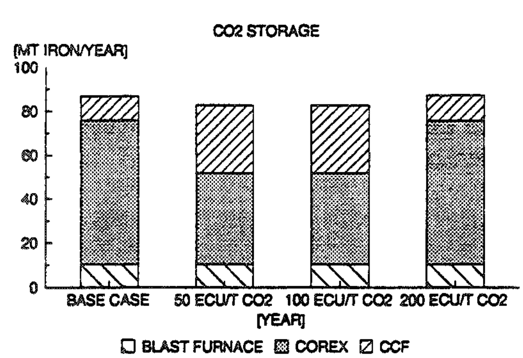


Figure 10: *Changing iron production 2020 due to CO_2 tax, no CO_2 storage option* [17]

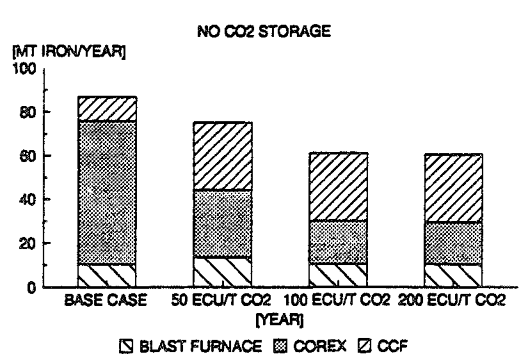


Figure 11: *Power production in 2020 with increasing CO_2 taxes*

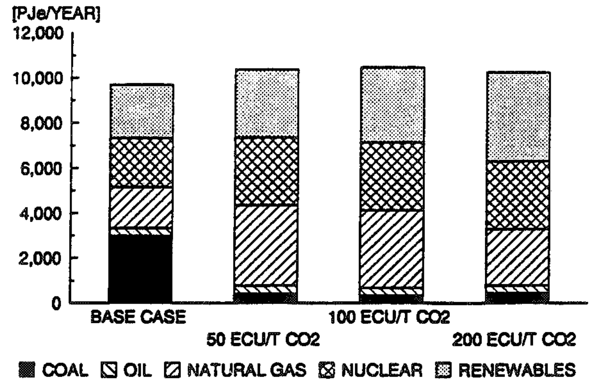
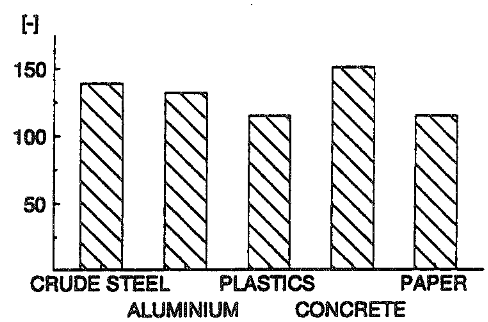


Figure 12 shows the impact of a 100 ECU/t CO_2 tax on the prices of some materials in 2020. The price increase, compared to the base case without emission reduction, is the lowest for plastics and paper and the highest for concrete. Steel is in an intermediate position. It gains competitiveness compared to concrete, but loses competitiveness com-pared to plastics and paper. The position relative to aluminium is hardly affected. Based on these figures, the impact on different markets can be predicted: steel will become more attractive for the building sector and less attractive for the packaging and transportation sector.

Figure 12: *Materials prices in 2020, 100 ECU/t CO_2 (base case =100)*



7 CONCLUSIONS

The iron and steel industry is one of the energy intensive industries that will be significantly affected by the imminent CO_2 policies. The Western European steel industry emits 7% of the total CO_2 emissions in this region. Blast furnaces will in the next century be replaced. One option are energy efficient smelting reduction technologies with significant amounts of energy by-products. The other option is EAF technology. The best choice will be significantly affected by future CO_2 policies. The development of CO_2 removal and storage technology is also of key importance in the strategy selection. The use of coal based smelting reduction processes is optimal in case of weak CO_2 policies or in case of strong CO_2 policies and low removal and storage costs. However, if CO_2 removal proves to be infeasible and strong CO_2 policies are introduced, the gas based DRI production processes will become more attractive. In both cases, the energy efficiency of the iron and steel industry will further increase in the next decades.

There is a significant potential for improved materials efficiency. This potential is generally neglected in energy efficiency and CO_2 reduction studies. However improved steel qualities are of similar importance for CO_2 emission reduction as increased energy efficiency. It remains to see if this potential will be used to its full extent in the next decades. Preliminary MARKAL model calculations indicate that the impact of CO_2 policies on the competition with other materials will be limited.

The MARKAL approach provides additional information regarding the changing system configuration. Especially smelting reduction processes produce significant amounts of gaseous energy by-products that will be used for electricity production. This development has significant consequences for the energy system configuration, especially for electricity production planning. The beneficial CO_2-balance of energy efficient smelting reduction technologies will however be off-set by competing power producers in a situation with high CO_2 taxes. In case CO_2 policies are initiated, the reference electricity production will become CO_2-free. As a consequence, power production with energy by-products from the steel industry becomes less attractive. This does significantly influence the optimal choice of steel production technologies. MARKAL can be used to analyse this type of system interactions.

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