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Technological Competition, Time, and Windows of Opportunity – the Case of Iron and Steel Production Technologies

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Technological Competition, Time, and Windows of Opportunity – the Case of Iron and Steel Production Technologies

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Abstract

This case study within the SUSTIME project analyses technological competition between iron- and steel-production technologies, steel production belonging to the most energy- and environment-intensive industrial activities. It shows that techno-economic time windows can be of relevance for competition between old and new technologies as well as between several new ones and clarifies some conditions. After the description of relevant technologies and a historical analysis of technological competition in steel production (between basic oxygen furnaces and electric arc furnaces), the analysis of old-new competition between the traditional blast furnace ironmaking technology and the new smelting reduction technology demonstrates that investment cycles and market entry barriers seem to be constituent for the time dependence of techno-economic windows. Given this importance of scale, such instable phases of competition can already be important before market introduction of the new solution takes place. An outlook on new-new competition between several new ironmaking technologies points out that even if direct network effects are absent, scale and learning effects may provide for pressure towards one dominant technology and thus the relevance of time windows. Finally, some implications for future climate policy are discussed.

Zusammenfassung: Technologiewettbewerb und Zeitfenster im Fall Eisen- und Stahl

Die Eisen- und Stahlherstellung ist eine der energie- und umweltintensivsten Industriebranchen. Die vorliegende Fallstudie im Rahmen des SUSTIME Projekts analysiert den Technologiewettbewerb zwischen verschiedenen Eisen- und Stahlherstellungsverfahren. Die Studie zeigt, dass Zeitfenster - verstanden als instabile Phasen des Technologiewettbewerbs - sowohl für den Wettbewerb zwischen alten und neuen Technologien als auch zwischen neuen Technologien untereinander von Bedeutung sein können. Nach einer Beschreibung der relevanten Technologien sowie einer historischen Analyse des Technologiewettbewerbs in der Stahlproduktion (Sauerstoffstahl vs. Elektrostahl) wird aufgezeigt, dass im Alt-Neu-Wettbewerb zwischen dem Hochofen- und dem Schmelzreduktionsverfahren der Eisenherstellung Investitionszyklen und Markteintrittsbarrieren konstituierend für die Zeitabhängigkeit von technisch-ökonomischen Fenstern sind. Angesichts der Kapitalintensität können solche instabile Phasen des Wettbewerbs auch schon von entscheidender Bedeutung sein, bevor die Markteinführung der neuen technischen Lösung stattfindet. Ein Ausblick auf den Neu-Neu-Wettbewerb verschiedener neuer Eisenherstellungstechnologien deutet darauf hin, dass auch bei Abwesenheit von Netzwerkeffekten Skalen und Lerneffekte für Druck in Richtung Dominanz einer Technologie sorgen und somit Zeitfenster relevant sind. Schließlich werden Implikationen für die zukünftige Klimaschutzpolitik diskutiert.

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1. Introduction

Steel production is one of the most consuming industrial activities in terms of energy and the environment. Today steelmaking is marked by two dominant production routes based on different technologies: the coke oven, blast furnace, basic oxygen furnace route and the scrap, electric arc furnace route. The first route takes place in so-called integrated steel mills at a quite high production scale, while the latter is typical for so-called minimills which work on a much lower scale. In the last years, the ironmaking stage as well as the stage subsequent to crude steel production have seen important innovation processes. Time criticality of the innovation dynamics might result, e.g., from the importance of economies of scale and the related longitude of investment cycles. Luiten (2001) puts forth the hypothesis that smelting reduction technology, a new process of ironmaking which skips the coke oven stage and substitutes for the blast furnace, leading to environmental benefits, is locked-out from commercialisation by the dominance of the blast furnace route in integrated steel mills.

In the SUSTIME project (Nill/ Zundel 2002, Erdmann 2003), two types of technological competition marked by partially different dynamics are distinguished: old-new and new-new-competition (see Nill 2002 for details). This example looks like a typical case of competition between an old and a new, environmentally beneficial, technology. However, a closer analysis shows that there are also interesting aspects of competition between the new technologies. For instance, there are several technologies making use of the smelting reduction principle where the environmental record seems to be different. Moreover, hot metal produced by smelting reduction can also be used in place of scrap in electric arc furnaces. But in this function it competes with other, also rather new alternatives. Thus a detailed analysis promises to be instructive. As in the other case studies of the first phase of the SUSTIME project, the study is based on a review of the empirical literature.

Before the analysis of technological competition at the ironmaking stage, the relevant technologies are described and for two reasons a closer look is taken at the first phases of the competition between integrated steel mills and minimills, implying a "competition" between basic oxygen and electric arc furnaces. First, as will be shown, this competition has considerable influence on the ironmaking competition. Second, it is of considerable conceptual interest, because, although the same sector is tackled and thus some framework conditions are similar, for reasons which are described in more detail below, this competition seems to be less time critical and virtual techno-economic windows thus less important.

2. Description of competing technologies

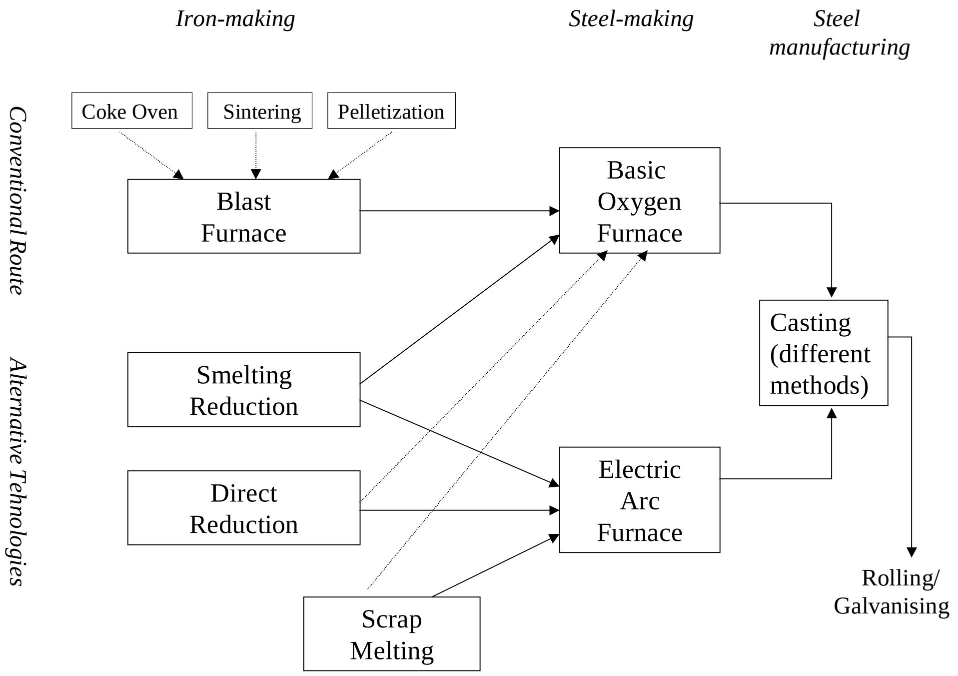
2.1. Technical changes in steel production - an overview

Steel is one of the most important industrial materials of the 20th century. Basically, the production of iron and steel is a three-stage process, which has not changed much since the early days (Moors 2000, p. 227):

1. *Ironmaking*: production of pig iron, based on the input coal and iron ore
2. *Crude steel production*: purification of iron to produce crude steel and
3. *Finished steel production:* casting and rolling or galvanizing the semifinished steel into plates, sheets, tubes etc., e.g., in hot-strip rolling mills.

The following figure 1 presents an overview of the different production technologies:

Figure 1: Different iron and steel production technologies



Source: Luiten (2001, p. 169), modified

Historically, all three stages have been combined in so-called integrated steel mills. In the last 50 years, however, at every step of this process, important innovation processes took place. This study focuses on the first and second step of steel production during certain time spans. Due to interlinkages between the stages, the third step also has to be considered to a certain extent. The *first* production step, ironmaking, has up to now remained largely unchanged, the coke-oven-and-blast-furnace route being the dominant technology. Only recently alternatives to this route, namely the direct reduction of iron, mainly with the help of gas, and smelting reduction technologies have emerged (section 2.2.).

Concerning the *second* step, several steel production technologies dominated the market. At the beginning of the 20th century, the Thomas process and the Bessemer as well as Siemens-Martin open hearth processes, were dominant. The Thomas process was outdated in the 1970s; the last Siemens-Martin ovens were taken out of operation at the end of 1993 (EC 2001, p. 244). Starting in the 1950s, the oxygen process was introduced to the market and diffused rather quickly. As a result, the basic oxygen furnace (BOF) is nowadays the most important steel production technology. However, a second method to produce steel based on steel scrap instead of iron emerged with the rising quantities of steel scrap, i.e., the electric arc furnace (EAF) (see 2.3.).

The resulting technological dynamics, however, can only be understood taking the *third* production step into account, especially the evolution of casting technologies (section 2.4.). After being of marginal importance for a long time, the opportunity to combine the EAF production process with continuous casting in small-scale steel mills, the so-called minimills, gave a push to this technology from 1950 onwards. It gradually won market shares in the lower end of the steel markets, in industrial as well as in emerging countries. The main appliance has been long products. Only recently, minimills working with EAF have been able to combine this process with new thin slab casting processes, giving them the opportunity to also supply the lower ends of the flat steel market. Today, the BOF process accounts for roughly two thirds of steel production and the EAF process for the remaining third. They are the only processes in use for producing steel in the EU (EC 2001, p. 244).

2.2. Ironmaking technologies

2.2.1. The conventional blast furnace route

Iron has already been produced in blast furnaces since 1300. Since 1718, coke has been used as a main input instead of charcoal (Luiten 2001, p. 170). Coke is made from coal in coke ovens, requiring a certain quality of the coal input (metallurgic coal). Coke is used instead of coal because of its better physical and chemical characteristics, serving both as a reducing agent and as fuel during iron production. The other main input is agglomerated ore. It is produced from iron ore in *agglomeration* plants. The agglomeration of ore is needed to optimise blast furnace operation and to make maximum use of less suitable iron ore types. In modern blast furnaces, only relatively large iron ore particles can be used, so that small iron ore particles need to be baked into larger pieces in so-called *sintering* plants or, to lesser extent, in *pelletisation* plants (Moors 2000, p. 228, EC 2001, p. 383).

In *blast furnaces*, coke and ores together with limestone are reduced to produce pig iron. They have been continually optimised, resulting in very efficient large-scale operating facilities. Nearly all integrated steel mills still use blast furnaces as a first step in the production of oxygen steel.

2.2.2. Direct reduction technology

An alternative technology to the dominant blast furnace route of ironmaking is the so-called direct reduction of iron (DRI). The concept dates from about 1950; the first direct reduction facility dates from 1952. The basic process consists in the production of solid primary iron from iron ore with the help of a reducing agent, mainly natural gas (sometimes also coal). A variety of processes exist for this. However, product quality depends directly on feedstock quality, as direct reduction does not include any physical change of state or separation of chemical impurities (EC 2001, p. 329). DRI can serve as feedstock for small-scale EAF, thus allowing for the production of higher-quality steel with this technology. Moreover, DRI can be used in BOF in order to permit increased scrap utilisation, and in blast furnaces when increased quantities of hot metal output are required (Hogan 1994, p. 142; EC 2001, p. 322).

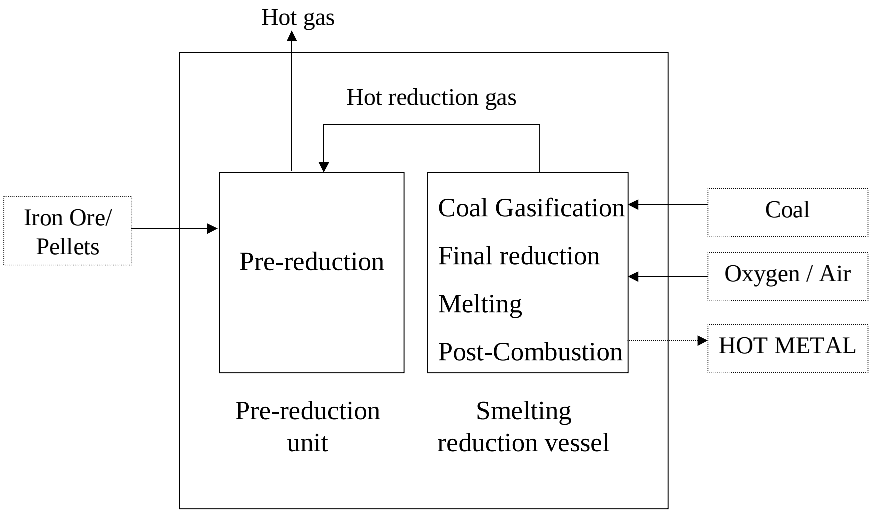
DRI has been commercialised in several variants since the 1970s but has not yet achieved a significant breakthrough, due to several reasons such as technical problems (e.g., high reactivity of solid-state DRI) and the high prices of natural gas. E.g., in the EU in 1990 it only had a market share of 0,3 per cent (Worrell et al. 1997, p. 9). In the 1990s, the share of DRI in worldwide pig iron production rose from 3,5 to 6,7 per cent (Luiten 2001, p. 170). In the mid- 90s, three major processes were in commercial use (MIDREX, HyL (I, II and III) and FIOR), while five new techniques which provide better quality iron input, e.g., iron carbide or HBI, or the use of fine ores, e.g., FINMET, were about to be commercialised. The biggest producer of directly reduced iron is ISPAT. Concepts are also increasingly developed to integrate DRI production, which usually takes place separately, with other steps in steel production.

2.2.3. Smelting reduction technology

A direct competitor of the blast furnace route came up with the so-called smelting reduction technology (SRT). The theory underlying smelting reduction, i.e., to convert iron ore directly into crude steel in just one step by using the principle of gasifying coal in a molten bath has been known since the 1930s. However, notable R&D efforts only started in 1975. Compared with blast furnaces, the sequence of gasification and reduction is changed. Several technology variants which apply this principle have been developed. This ironmaking technology may be combined either with basic oxygen furnaces or with electric arc furnaces.

Smelting technology allows for the reduction of iron ore to pig iron using coal instead of coke, thus avoiding coke oven operation. Most SRT also omit the agglomeration of iron ore to agglomerated ore. The process involves both solid-state reduction and smelting, i.e., melting involving chemical reactions (see figure 2). Hence, it comprises two different stages: the pre-reduction unit and the smelting reduction vessel, exploiting the principle that coal can be gasified in a bath of molten iron.

Figure 2: Smelting reduction technology



Source: Luiten (2001: 171)

In the smelting reduction vessel, coal is gasified, delivering heat and hot gas containing carbon monoxide, which has a high chemical energy. Heat is used to smelt the iron, whereas the hot gas is transported to the pre-reduction unit to pre-reduce iron-oxides (in a solid state), fed directly into this unit. Subsequently, the pre-reduced iron, which is quite similar to DRI, is transported to the smelting reduction vessel for final reduction. Moreover, carbon monoxide can be oxidized in the smelting reduction, in order to deliver additional heat to smelt the iron. This stage of the process is called post-combustion, which decreases the reduction potential of the hot gas in the smelting reduction vessel. After post-combustion the hot gas is transported to the pre-reduction unit where the remaining carbon monoxide is used for pre-reduction. Since the degree of pre-reduction is determined by the richness of carbon monoxide in the hot gas, there is a trade-off between pre-reduction and post-combustion (Luiten 2001, p. 172).

High levels of pre-reduction are characteristic of the first generation processes. The first commercial application and best-known example of these is the COREX process. High levels of post-combustion determine second generation processes; the lower degree of pre-reduction needs less coal, because extra heat is generated and used in pre-reduction. However, SRT is not a homogenous technology; there are a variety of smelting reduction processes, whereas only one operates on a commercial basis (Luiten 2001, p. 173).

2.2.4. Functional comparison of ironmaking technologies

Quality and technical performance: The pig iron produced in blast furnaces is of stable good quality, being similar to the pig iron produced by SRT, whereas directly reduced iron can be of significantly lower quality in accordance with the quality of the ores used as input.

Feedstocks and energy inputs: One advantage of the conventional blast furnace route over DRI and some SRT is that metallic feedstocks and reductants of variable quality and specification can be used, without reducing product quality (EC 2001, p. 329). In some, SRT fine ores cannot be used directly as yet, and, in DRI, high-quality pellets and lump ore are required. Moreover, the traditional blast furnace route provides many recycling and disposal opportunities for downstream waste, for ferruginous arisings, filter cakes and oils that may not (yet) be available in reduction processes (EC 2001, p. 329). In turn, coal quality requirements of DRI and SRT are more flexible than in the traditional blast furnace route. Both use natural gas or coal as a fuel and therefore dispense with a coke oven plant, which also reduces energy requirements.

Of major importance for DRI is the availability of cheap natural gas, while the main advantage is that DRI can serve as feedstock for small-scale EAF, especially if there is a shortage of high-quality scrap. One drawback is the danger of fire hazards. Hence, most plants are situated in developing countries in the oil-and-gas-rich belt around the equator.

Power consumption of *direct reduction technology* is estimated as 10,5 to 14,5 GJ/ ton solid DRI (EC 2001, p. 339), compared to a consumption of 17–18 GJ/t of liquid iron in efficient blast furnaces. Unlike blast furnaces, DRI counts with gas, steam and heating credits from carbon in iron (EC 2001, p. 331). However, DRI needs to be in molten form to be directly comparable to blast furnace iron; otherwise the additional energy requirements and emissions connected with this physical change of state need to be considered.

The International Iron and Steel Institute (IISI) estimates that *smelting reduction technology* has a similar specific energy consumption as optimised blast furnaces, but is reported to be more efficient overall because of the omission of coke ovens and sintering plants (Luiten 2001, p. 188). However, there are important differences between the SRT variants: One vessel, second generation processes have a high specific energy consumption, and especially the first generation COREX process is relatively energy intensive with 17 to 20 GJ. Second generation SRT with a pre-reduction unit and SR vessel in separate vessels is more efficient, the pilots reaching 15 to 17 GJ, and, in the future, a reduction to 11 to 15 GJ is expected (Worrell et al. 1997, p. 9, Luiten 2001, p. 187). However, SRT shows varying energy efficiency, because, on the one hand, it needs higher coal input and, on the other, produces larger amounts of fuel gas. In general, the latter authors expect a 20–30 per cent reduction of (net) energy consumption, whereas the EC document on best available techniques (BAT) speaks only of 5 to 10 per cent (EC 2001).

Environmental effects: The primary environmental benefits of the emerging technologies DRI and SRT as compared to the blast furnace route is that they avoid coke production, which implies avoided emissions to air of dust and VOCs from the ovens and a variety of organic chemicals to air and water from by-product plants as well as reduced specific CO_2 emissions. If SRT and DRI also dispense with sintering, the emission of metallic and non-metallic dust and gaseous pollutants such as sulfur-dioxide is avoided (EC 2001, p. 330). Although blast furnaces have reduced their coke consumption significantly, there is a technical minimum for the coke rate for blast furnaces, because of its burden-supporting function (EC 2001, p. 347). The amount of CO_2 emission reduction by SRT, however, is debated. The commercialised first generation COREX process has up to now no CO_2 emission advantages (EC 2001, p. 332). However, Worrell et al. (1997, p. 13) expect for the Cyclone Converter Furnace (CCF) SRT process in the future about 15 per cent less CO_2 emissions than with the blast furnace route. For the so-called HIsmelt SRT process a CO_2 emission reduction of 10 per cent is reported (Bates 1998). And a recent Belgian study even points to bigger advantages of SRT processes, namely 1,3 tons CO_2 (COREX) and 1,2 tons CO_2 (CCF) per ton hot metal compared to 1,7 ton CO_2 of the blast furnace route, the off gases of each process being excluded (Institut Wallon 2001, p. 26). Some SRT, especially COREX, produce large amounts of top gases and have high oxygen requirements, whereas environmental advantages are the reduction of dust and sulfur emissions by more than 15 per cent.

The impact on the environment of a direct reduction unit itself is very limited. There is little dust emission, which is easy to collect. The water need is low and water can largely be recycled. Furthermore, a methane-based direct reduction unit produces much less CO_2 than a coal-based unit.

2.3. Crude steel production technologies

2.3.1. Oxygen steel production in basic oxygen furnaces

The conceptual origins of oxygen steel date back to Bessemer in the 19th century. The objective of oxygen steelmaking is to burn, i.e., oxidize, the undesirable impurities contained in the metallic feedstock. An important step was the invention of the Linde-Frankl process for liquefying oxygen and the separation of air in 1928/29. This served as a basis for the invention of the basic oxygen furnace *(BOF)*, patented in 1943 (Faber et al. 1999, p. 269). It uses mainly gas and electricity as an energy input. Commercialisation took place rather quickly; in 1949 the first successful experiment took place (VÖEST, Austria), and market introduction already started in 1952. In comparison with the Thomas and the open hearth processes, BOF allowed for major efficiency gains, e.g., the conversion took only 45 minutes instead of 8 hours in open furnaces. However, only a maximum of 20 per cent of scrap can be used in this process, which is much less than in the precursors (Binder/ Schucht 2001, p. 250).

2.3.2. Electro steel production in electric arc furnaces

The electric arc furnace route goes back to an invention in the year 1878. First commercialised in 1899 (Faber et al. 1999, p. 269). The technique is quite similar to the formerly used open hearth process, only that it uses electricity and not natural gas as an energy input. Unlike the BOF process, it mainly uses scrap to produce new steel, whereas a slag is formed from lime to collect undesirable components in the steel, which is similar to the BOF process. Another possible, but not yet widely used input in electric arc furnaces is directly reduced iron (see below).

Since the 1950s, EAF steelmaking has been combined with casting in so-called minimills. If only scrap is used as input and thus there is no iron-making step, steel production in minimills is much simpler than in integrated steel mills. Minimills operate on a much smaller scale. Output typically ranges from 0.5 to 1.0 million tons of crude steel per year, compared to the production of 2–3 million tons of steel per year in integrated mills (Luiten 2001, p. 179).

2.3.3. Functional comparison of crude steel production technologies

Quality and technical performance: Mainly due to scrap impurities, EAF deliver lower-quality steel than BOF (Bartzokas/ Yarime 1997, p. 29). In the past, BOF have been used to produce high-quality steel and high-tonnage carbon steel while EAF have been used for lower-quality steel, low-tonnage alloys and specialty steels. Due to innovations in casting methods this started to change. Nevertheless, Bartzokas and Yarime (1997) estimate that still more than 50 per cent of quality steels are beyond EAF capacity.

Feedstocks and energy inputs: One advantage of BOF over EAF is that a wide range of feedstock of variable quality and specification can be used (EC 2001, p. 331). However, BOF only allow a maximum of 20 per cent of scrap to be used as input. As mentioned before, the quality of EAF steel is highly dependent on feedstock quality, i.e., scrap quality, and on the share of scrap used in relation to DRI and/or pig iron produced by smelting reduction.

As far as energy consumption is concerned, information is sometimes contradictory or not yet completely available. In BOF (converter), electricity consumption is estimated at 0.08 GJ/t LS, including the production of oxygen and the operation of the converters (EC 2001, p. 242) However, when the energy from the BOF gas is recovered (waste heat recovery and/or BOF gas recovery), the basic oxygen furnace becomes a net producer of energy. In a modern plant, energy recovery can be as high as 0.7 GJ/t LS (EC 2001, p. 242). In EAF, total energy consumption lies at 2.3–2.7 GJ/t, 1.25–1.8 GJ of which is electricity (EC 2001, p. 281).

More data is generally obtained for integrated steel mills or the electric arc furnace route comprising both iron and steelmaking production stages and sometimes also casting. The most energy-efficient integrated steel mills (ISM) need 18 to 19 GJ primary energy/ t crude steel, whereas in reality consumption varies up to 40 GJ/t. 75–85 per cent of this is needed for the blast furnace including coke and ore production (Luiten 2001, p. 170, Moors 2000, p. 234). The most efficient minimills (EAF) need 5 GJ/ t, owing to scrap being used as input. In case they are fed to 100 per cent by DRI, though, energy consumption rises to 18,5 GJ/ t, i.e., to almost the same level as in integrated steel mills (De Beer 1998; Luiten 2001, p. 170). The most consumed form of final energy in EAF and BOF is electricity.

Environmental effects: The biggest advantage of EAF is that carbon dioxide emissions are only one third of BOF (Bartzokas/ Yarime 1997, p. 29). Based on the Belgian electricity generation structure, another study estimates CO_2 emissions of 0,34 tons per ton cast EAF-steel compared with 1,32 tons CO_2 per ton cast BOF-steel (Institut Wallon 2001, p. 25). This is due to lower energy consumption because of the substitution of iron by scrap as input. At the same time, also other emissions are substantially lower. Further on, emissions in electricity generation using fossil fuels need to be taken into account, but often depend on the country specific energy mix specific to the country.

In BOF, during oxygen blowing, converter gas is released from the converter, which contains carbon monoxide (CO) and large amounts of particulate matter (mainly consisting of metal oxides, including heavy metals), relatively small amounts of sulfur oxides (SO_2) and nitrogen oxides (NOx). Dust releases from the various processes are in the range of 1–275 g/t LS. Emissions to air after abatement are in the range of 0.1–10 g/t LS (EC 2001, p. 236). In EAF the primary off gas contain 14–20 kg dust/t liquid carbon/steel or low alloyed steel and 6–15 kg dust/t in case of high alloyed steel (EC 2001, p. 289).

However, if DRI (or potentially also SRT) is used in EAF, the overall emission advantages become smaller. Thus for a complete picture, all the production routes combined with EAF and BOF need to be taken into account.

2.4. Steel manufacturing: the evolution of casting technologies

Until a few years ago, the standard casting method consisted of pouring the molten steel into ingot moulds and, as a second step, reheating and forming it into final shapes like billets, blooms or slabs. Thus, so-called *ingot casting* represents a discontinuous process, whereas in *continuous casting* the steel is cast in a continuous strand. Here, instead of going through the ingot stage, the molten steel is poured directly into a casting machine to produce the required shapes, eliminating the primary and intermediary rolling mills as well as the reheating furnaces and the storage of ingot moulds.

Continuous casting techniques were developed after World War II and commercially introduced in the early 60s. In the beginning, continuous casting was only suitable for small plants, which provided the possibility to combine EAFs with casting facilities in so-called minimills. From 1970 it was used also in a growing number of integrated mills, replacing ingot casting except for certain special applications that require ingot casting. Hence, its share in overall steel-output has risen to over 95 per cent (EC 2001, p. 227).

However, a new search process for new strip casting methods, ideally allowing the direct casting of the metal into (or near to) the final shape, e.g., strips or sections (*near net shape casting)*, thus replacing hot rolling, began in the mid-70s in the wake of the first steel crisis. The conceptual beginnings date back to the end of the 19th century. The motivation was to reduce capital and operating costs; thus a lot of integrated producers also invested in R&D. The innovation race intensified in the 80s, driven by the rising availability of R&D money due to increasing profits, but also to some government support in the US and Europe, further fuelled by the first claim of a solution by Allegheny in 1984 (Luiten 2001, p. 149). However, no commercially viable solution was developed by this point. The current state in Europe is at the prototype stage prior to demonstration.

Parallel to these developments, an intermediate form of new casting technologies was developed: *thin slab casting*. Instead of slabs of 120–300 mm thickness produced in continuous casting, slabs of 30–60 mm thickness can be cast with this new method. The cast thin slabs are reheated in a coupled furnace and then directly rolled in a simplified hot strip mill. The technology was mainly developed by German machinery producers. Thin slab casting promised to reduce the total cost of sheet steel making by about 20 per cent (Christensen 1997, p. 92). Again, in 1989 the first commercialisation took place in minimills, the pioneer being the rather large US producer Nucor which had built up in-house capacity and resources for its own R&D efforts (Hippel 1988, p. 79). Now it is applied on a commercial scale (Worrell et al. 1997). In combination with a higher input of hot iron, e.g., on the basis of DRI, this technology paved the way for minimills to enter the high-quality, flat-market segment. Nevertheless, the high investment required for thin slab casting is beyond the scope of many minimill producers.

Despite the success of thin slab casting R&D in new methods which allow further reductions, cast thickness went on (Luiten 2001, p. 137). One advantage of strip casting technology is that hot-rolled coils require considerably less capital than a conventional casting and rolling mill (Luiten 2001, p. 134). The lower capital costs of strip casting technology therefore allow smaller firms (e.g., minimills) to process the steel themselves, dispensing of outsourcing for hot rolling. Besides, strip casting technology opens up the cold-rolled market for minimills. And again Nucor seems to have been the first steel producer to have introduced strip casting to the market. In 2000, Nucor started a joint venture with the Australian steel producer BHP and the Japanese supplier IHI, one of the networks which had developed a pilot strip caster, and planned the start up of the first commercial facility via license in 2001 (Luiten 2001, p. 143).

3. Dynamics of technological competition I: Steel production

3.1. The revival of technological competition in the 1950s/60s

The conventional steel production process took (and takes) place in integrated steel mills and is characterized by extreme economies of scale. Typical facilities have a capacity of 2 to 3,5 million tons of crude steel per year. The commissioning of new plants is very time consuming, alone taking 5 to 10 years. Once installed, the facilities are used for decades without major changes, involving important sunk costs (Binder/Schucht 2001, p. 245). With the emergence of the new basic oxygen furnace (BOF) technology, since the 1960s, all new integrated steel mills are equipped with oxygen converters (BOF), while the phasing out of the outdated Thomas and open hearth processes took until the early 70s and 80s respectively.

The use of electric arc furnaces (EAF) had been for a long time restricted to a rather small niche market, mainly for some specialty steels. This changed, however, with some important technical progress in electro steel production and the commercialisation of new continuous casting methods suitable for small EAF plants. Thus after the Second World War minimills using EAF, characterized by capacities well below 1 million tons per year, emerged as a potential alternative for steel production.

Both innovations had tremendous consequences. In the one case, a gradual technological substitution process of traditional production technologies took place, being replaced either by BOF or by EAF. For quite a long time, both new steel production technologies diffused in a quite parallel manner. This was also due to one complementarity of both technologies, i.e., reduced scrap reuse capacities of BOF, and scrap being the main input of EAF (Faber et al. 1999, p. 283). This corresponded with a market segmentation along quality lines. On the other hand, on a larger level, technological competition between integrated steel mills and minimills emerged.

Until the 1990s, this competition only took place in the market for long products, which was gradually left by the integrated producers which concentrated on the higher-valued flat segments. Recently, however, also within the flat segment, competition became fierce.

3.2. The diffusion of EAF as a result of competition between minimills and integrated mills

Minimills made it possible to produce steel for local markets without the huge investment and capital cost of integrated steel mills; the first plants only needed an investment of $5 million. Also today, the share of capital cost in total cost is much lower in minimills than in integrated steel mills (about 10 per cent vs. 25 per cent, Reppelin-Hill 1999, p. 296). This allowed EAF to enter the low-quality end of the market for long products which are mainly used in construction. At the same time, steel production also became affordable for small countries with small local markets as well as for developing countries. Pilot markets of the EAF/minimill competition with Thomas- or open hearth-based integrated steel mills were the US and Italy, while other countries followed later. Over time, minimills considerably improved product quality. This enabled them to enter ever larger segments of the market for long products (Hogan 1994). For example, in the US they conquered 80 to 90 per cent of the market for reinforcing bars until 1980, increased their market share in other bars and rods from 30 per cent in 1980 to almost 100 per cent in 1985 and took the market for structural steel until the mid-90s (Christensen 1997, p. 90).

The *first phase* of this technology diffusion and substitution process, which can be dated from 1950 to 1970/75 was not very time-critical. Put loosely, the techno-economic window for EAF/minimills opened by the commercialisation of new casting technologies remained open. The reason is twofold:

1. It is a period of massive global market expansion, which reduces the role of sunk cost etc., combined with the market entry of a lot of new firms and countries – due to the greatly reduced entry barriers as well as national industrialization programs of emerging countries (including Italy and Spain).
2. The integrated steel firms did not compete too much, because in their view the market segment conquered by minimills was the least profitable one, in comparison with the more profitable and technologically demanding flat steel products for which the market also grew (Hogan 1994, Christensen 1997). Instead, they themselves renewed their facilities, introducing the basic oxygen furnace instead of the traditional processes, which, in 1970, already reached a market share of more than 50 percent (Grübler 1998, p. 211).

As a result, the EAF route, mainly applied in minimills strongly increased production (in the 60s, in the US, EAF production more than doubled, Hogan 1994, p. 77), and continuously gained market shares, as is shown in figure 3. The absolute shares, however, differ quite a lot, usually, with the remarkable exception of the US, being a lot lower in countries with important integrated steel producers. Most of the new facilities for long products were EAF; as a result, by the eighties minimills largely dominated the world market for long products. The total market share of EAF in 2010 is projected at 45 per cent.

Figure 3: Diffusion of Electric Arc Furnace technology in different countries

Market share of EAF in %	**1970**	**1985**	**1990**	**1995**	**2000**
USA	15,3	32	36,8	ca. 40	47
Germany	ca. 7	18,5	18,5	24,1	28,7
EU	15	25	30	34,4	39,7
Japan	16,7	29	31,4	32,2	28,8

Sources: Barton (1999, p. 25), Christensen (1997), EC (2001, p. 2), Herrigel (2002), Labson/Gooday (1997, p. 919), OECD (2002: 13), Schleich et al. (2002)

Looking for the techno-economic reasons behind this development, several factors can be mentioned. The general advantages of EAF steel production are high-technical efficiency, high automation and low investment and R&D cost. Moreover, every type of scrap steel can serve as input (Kerz 1990, p. 4). Minimills are able to produce crude steel at 200 US $/t, while in integrated steel mills the prices vary between 200 and 300 US $/t (Luiten 2001, p. 170).

However, in a *second phase*, lasting perhaps until 1990, characterized by the steel crisis and stagnating steel demand, marked differences occur. The overall diffusion process continues quite steadily, for example between 1970 and 1990, 75 per cent of the increase in global steel production is produced in EAF (Labson/ Gooday 1994, p. 917). And, as two diffusion studies found out, this phase is marked by considerable inertia, i.e., changes in input prices do not seem to have played an important role (Labson/ Gooday 1994, Reppelin-Hill 1999). Nor the age of the conventional integrated capital stock, i.e., measured by the decommissioning of outdated open hearth processes, seems to have played a decisive role, as EAF production rose as well in the shrinking and not modern US market (OH share 1970: 36,5 per cent) as in the growing *and* modern Japanese market (OH share 4,1 per cent) (Labson/ Gooday 1994, p. 918). But given these properties of the competing technologies, this picture is hardly surprising. In general, EAF producers, though also hit by the steel crisis, envisage less economic difficulties than integrated producers with large and often outdated facilities. For example, in 1991 in the US minimills are reported to have made a profit of 10 $/ ton of steel sold, while integrated steel producers had an average loss of 27 $/ ton (Faber et al. 1999, p. 284).

Nevertheless, it is interesting to take a closer look at the divergent processes in the *US* and *European* markets which have both been hit by a steel crisis. In the US, between 1975 and 1993, the number of integrated plants halved from 50 to 23 while the number of minimills remained roughly constant. And 5 integrated steel producers switched to small-scale EAF production (Hogan 1994, p. 86). Between 1970 and 1994, the EAF share in North America rose by 183 per cent and in Europe by only 66 per cent (Reppelin-Hill 1999, p. 299), and even more slowly in countries with important ISM producers. This different pattern could be attributed to different investment cycles, but is also partly due to policy interventions. From the technological side, one could argue that the window remained open in the US, because the sunk cost of the integrated producers was low due to outdated capacities, while at the same time they could not afford costly reinvestment. The situation in Europe is different, because here, on average, rather modern ISM plants and thus high sunk cost and stagnating markets coincided. The political argument is that in the US there was no *relevant* direct policy intervention (Barnett/ Crandall 1986). Of course, there were important trade restrictions and political lobbying as well

(Lenway et al. 1996). Perhaps, these trade restrictions, while generally working to the benefit of more lobbying and less R&D spending firms (Lenway et al. 1996), even indirectly helped minimills by driving the competitors into higher value products (Barnett/ Crandall 1986, p. 111).

In Europe, the European Community crisis policy, which involved cartelisation, quotas and joint capacity reduction with the help of subsidies to integrated producers, made more difficult or even prevented the entry of new minimill firms or their enlargement of capacities (Barnett/ Crandall 1986, pp. 109-11, Hogan 1994, p. 116). Indeed in the European Union the share of EAF remains the smallest in those countries where the influence of integrated steel producers is high, e.g., in 1990 4 per cent in the Netherlands, 9 per cent in Belgium and 19 per cent in Germany (Worrell et al. 1997, p. 9). In the latter country, the subsidisation of the use of coal as input for steelmaking (valid until 2005) is an important political obstacle for further EAF diffusion; instead in 1993 a new blast furnace was blown on (Faber et al. 1999, p. 283). Sometimes, in the EU obsolete facilities have been subsidized (Gieseck 1995), in some cases also based on environmental arguments. At the same time, environmental performance of integrated steel mills has been considerably improved, mainly by end-of-pipe upgrading (Binder/ Schucht 2001).

Nevertheless, policy did not hinder that further diffusion also took place in Europe, resulting in a European Union EAF market share of 34,4 per cent in 1995, produced at 246 sites (EC 2001, p. 2). One reason behind this is that innovation and increased technological competition had lowered market entry barriers and led to increasingly divergent producer interests which weakened producer networks and made the enforcement of private and public cartels very difficult. For example, Italian and German minimill producers refused to comply with the EUROFER cartel of 1976 (Binder/ Schucht 2001, pp. 251-2, 275). Also some integrated producers switched: for example, ARBED Luxembourg shut down their BOF facility and installed three EAF to produce long products on the basis of scrap (Binder/Schucht 2001, p. 279). However, a more detailed analysis is beyond the scope of this case study.

3.3. Conclusion

The presented overview about technological competition in steel production provides some preliminary insights concerning dynamics of innovation, preconditions for techno-economic windows of opportunity and possible conclusions for policy.

In the first phase between 1950 and about 1970/75, not many time-critical factors could be detected. It has to be emphasized that it was a phase of dynamic market growth. This allowed for a rather unproblematic yet long-lasting, old-new technological substitution process of the outdated Thomas and open hearth processes by the far better BOF and EAF technologies. Environmental concerns did not play any role yet. Between the two new technologies, for quite a long time there was a rather complementary development in different market segments, network effects being rather negligible. And though large economies of scale and long investment cycles may considerably hinder the fast diffusion of new techniques, this was upset by the innovation breakthrough of continuous casting which led to significantly lower entry barriers for new producers and innovators.

In the second phase between 1975 and 1990, the market stagnated and competition thus became stronger. However, technological improvements allowing for the entrance of more segments of the long product market and economic performance were in favour of minimills so that the bulk of the adjustment was on the integrated producers. Put loosely, the techno-economic window remained open and, on a global level, diffusion continued, leading to the dominance of minimills in the market for long products. However, there are some hints that this environmentally beneficial diffusion has been considerably slowed down by political interventions in the European Union. There are also some hints that integrated producers partly successfully tried to protect their technologies, thus acting against the political utilisation of the techno-economic window (e.g. Herrigel 2002, pp. 37-41). A substantiation of this educated guess, however, would require more detailed research which is beyond the scope of this case study.

However, in the end, diffusion of EAF continued, and, since the end of the 1980s, has received a new drive due to new casting technologies which enabled minimills to enter the flat markets.

4. Dynamics of technological competition II: Blast furnace route vs. smelting technologies for ironmaking

SRT is considered one of the most important process technologies in industry for increasing energy efficiency (e.g., Martin et al. 2000, p. 5). This part of the study takes as its starting point Luiten's claim (2001, p. 167), that the new smelting reduction technology is locked-out by the dominance of integrated steel mills. Need this be the case or was or will there be a window of opportunity for an environmentally beneficial radical change in ironmaking technology?

In the late 50s and 60s, commercial interest in SRT arose for the first time, but development activities were stopped, because, on the one hand, not all technical problems could be solved and, on the other, steel demand expansion made giant high-capacity blast furnaces economically the most attractive, especially after the BOF had been introduced in 1952. At the same time, market expansion also made production on a smaller scale attractive. The first candidate at the time, in the mid-60s, was gas-based direct reduction technology, though smelting reduction technology was also already under discussion as an open hearth substitute (Moors 2000, p. 241). However, inherent drawbacks such as the high reactivity of the solid iron produced and the high price of natural gas prevented a breakthrough and incited actors to look for coal-based alternatives. From 1975 onwards, R&D activities in smelting reduction technology were undertaken by a number of actors (Luiten 2001, pp. 172-3). In the following, the general picture is provided and, each time, if possible, detailed by the very interesting example of a specific SRT, namely the Cyclone Converter Furnace (CCF) process developed by the Dutch firm Hoogovens (for an overview on the Dutch case, see figure 4, p. 18).

4.1. Setting the stage of the techno-economic competition

SRT was developed by a range of competing technology networks that were initiated by different types of actors: three times by suppliers (Corex, AusIron, Tecnored), twice by mining companies (HISmelt, AusIron), and four times by integrated steel producers (DIOS, CCF, DSM, Jupiter). In every one of the four latter cases competing producers were involved, often fuelled by substantial governmental R&D support (the empirical data are based on Luiten 2001, pp. 180-9).

Although there was a heterogeneity of actors and motives, broadly two different types can be distinguished: For most of the networks which were not initiated or led by integrated steel producers, a market entry motive prevailed. For *machine suppliers/ engineering firms* and *mining companies*, a new process or a new market could be potentially exploited, e.g., VOEST who initiated the COREX process used to sell DRI technology. For *integrated steel producers*, one main incentive to engage in substantial R&D effort was the search for cheaper and less capital intensive alternatives to the traditional blast furnace route. The threat of environmental regulations usually delivered an additional, but alone not sufficient incentive.

In principle, SRT can be used in integrated steel mills as well as in minimills. This results in two possible market introduction routes, which are driven by quite different factors and patterns of technological competition:

1. The utilisation of the process in minimills mainly depends on their expansion into higher quality markets. This is closely linked to the deployment of new casting technologies. A necessary precondition are higher quality inputs in EAF which can be provided by DRI or SRT technologies. This could be described as new-new competition dependent on the market-segment entry opportunities of minimills. A critical hurdle is the investment amount already necessary for a SRT demonstration plant which surpasses the usual investment capacities of minimill producers.
2. For utilisation in integrated steel mills, SRT has to compete with the traditional blast furnace route of ironmaking. This old-new competition is time-critical for two reasons: the window of opportunity for change, at least in already existing steel mills, mainly depends on the end of the long investment cycles of the old technology, and the commercialisation of the new technology also has to overcome the rather high investment hurdle.

A general factor influencing time-criticality is the general world market situation for steel, which is marked by a rather stagnating demand, which, in principle, even until 2010 can be easily satisfied with existing capacities (Hogan 1994). Thus, at least in industrialised countries, reinvestment and not additional investment is the main competition arena. Moreover, perhaps also the dynamics of new-new competition between several smelting reduction technologies will be of environmental relevance. In fact, while most of the SRT alternatives still struggle to reach the demonstration stage, one SRT, COREX, which does not seem to be the most promising option concerning environmental considerations, was able to get a head start and is already commercialised. The next section shows that this is due to an apt combination of both market introduction routes.

4.2. The COREX case: making successful use of a market niche

The first, and up to now only commercially used process, COREX, was developed by the Austrian technology supplier VOEST (the following is based on Luiten 2001 and VAI 2002). A first pilot plant was installed in Kehl, Germany, in 1981. Commercialisation, however, was reached together with the South African minimill EAF steelmaker ISCOR. For this first generation SRT, in effect a market niche was of decisive importance. It was mostly driven by the particular South African conditions. The main drivers were a dynamic local market, providing the incentive for a new steel plant, and the non-availability of technical alternatives due to limited access to metallurgical coal as well as a scarcity of scrap. After the installation of a pilot plant in 1985, it was already introduced to the local market in 1989, with a capacity of 300,000 metric tons per year. The general applicability of this first generation process was limited and a lot of technical problems had to be solved. Nevertheless, it helped to overcome the critical demonstration stage for this smelting reduction technology.

Building on this experience, VOEST also succeeded in raising interest of an integrated steel producer, the expanding Korean firm POSCO, thus using the second market introduction route. In emerging countries, there is less need for huge plants, and therefore the capital cost advantage of COREX in comparison with blast furnaces is important. Worrell et al. (1997) estimate the capital costs of COREX at 210-250 $/ton hot metal while the coke-oven plus blast furnace route is estimated at 330-350 US $/ton hot metal. The second COREX plant was commissioned in 1992 and commercialised in 1996 by POSCO. Here, COREX was combined with a BOF, producing 750,000 metric tons per year. Investment costs for the larger plant are given as only 160 US $/ thm (VAI 2002). After that, further plants have been built or commissioned in India, Korea and South Africa (EC 2001, p. 324). Today small COREX versions explicitly aiming at minimills as well as even larger types than the ones installed, able to produce 1.4 million thm (with an expected investment cost of 147 US $/thm) and thus to replace existing blast furnaces, are available. However, due to the off-gases the direct replacement of blast furnaces at the same site is not yet possible.

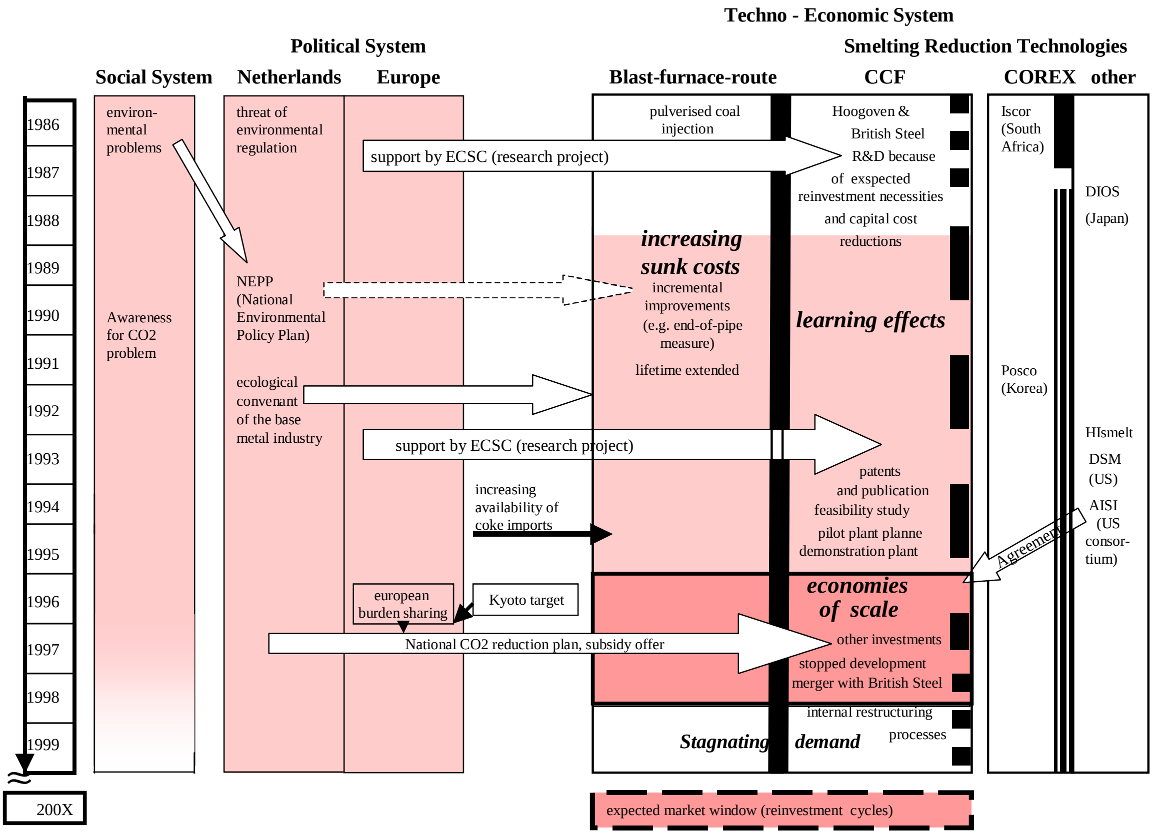
Environmental benefits due to the skipping of a coke oven played a role, too, while the non-existence of advantages concerning CO_2 emissions – in effect the actual COREX route is blamed as having even higher CO_2 emissions (EC 2001, p. 323) – was not (yet) of relevance. In the following, a closer look at the less dynamic but environmentally more promising SRT competitors, whose fate seems to be more closely linked to the second route, is taken.

4.3. Preparation for an anticipated techno-economic window

Besides COREX, the main driver introducing dynamics into the innovation process was the anticipation of a *window* of opportunity for technology substitution in integrated steel mills (ISM) since the mid- 80s. The future window was constituted by the *replacement necessity of obsolete coke ovens and blast furnaces* and the expectation that a *better alternative*, namely SRT, could be technically and economically feasible (promise of solution).

For the Dutch integrated steel producer *Hoogovens* as well for *British Steel* the threat of an expensive replacement of obsolete coke ovens was the starting point for joint intensified R&D efforts into the development of alternatives to the traditional blast-furnace route in 1986 (details concerning this example are mainly based on Moors 2000, pp. 238-45). Another general research incentive in the 80s was constituted by rigorous pressure from the Dutch authorities. Coke ovens are reported to have a depreciation period of 40 years which had almost expired in the 80s. E.g., Hoogovens projected that its two coke ovens would become obsolete in 2005 and 2015 respectively. Besides the capital intensity, the threat of environmental regulation also raised the reinvestment costs. Thus they started joint research long in advance, financially supported by the European Community of Steel and Coal (ECSC). An overview on the Dutch case is given in figure 4:

Figure 4: Competition of ironmaking technologies: the Dutch example



Source: own presentation

The situation in Japan was quite similar: In view of replacement necessities for about 40 per cent of the coke ovens and/or blast furnaces between 2000 and 2005 respectively, the cooperative DIOS project was started in 1987 (Hogan 1994, p. 150).

Given the anticipated windows of opportunity, an intensive R&D phase from the mid-80s to the beginning of the nineties started. According to Luiten (2001), nine technology networks developed 10 variants of different smelting reduction processes.

4.3.1. Techno-economic determinants

The technological preferences for a particular smelting reduction process were mainly related to earlier R&D experiences. SRT being a quite radical process change requiring a large amount of process automation and training (Worrell et al. 1997), a horizon of up to 20 years before (intended) commercialisation was important.

The main driver of R&D activities was the expectation that the cost price of a ton of hot metal would be reduced. The major driving forces behind this are lower capital investment (by avoiding coke ovens and agglomeration plants and replacing blast furnaces) and the replacement of expensive metallurgical coals as input by normal coal. Moreover, smaller scales, larger flexibility concerning raw materials and environmental advantages are hoped for.

Considering the economic stake, not surprisingly at this stage of development – and due to differences between processes – quantitative estimates vary considerably between +10 and -25 US $ per thm price change (for the Cyclone Converter Furnace (CCF), Worrell et al. (1997) estimate a reduction of operating costs of 18 $/ ton pig iron), leading to cost prices of 80 to 160 US $/ thm. Worrell et al. (1997) estimate the capital costs of an integrated steel mill at 330-350 US $/ton hot metal and for CCF 150-180 $/thm; moreover they expect a reduced construction time (3 vs. more than 5 years). For CCF they expect a size of 500,000 to 1,000,000 tons hot metal/ year and a life span of 30 years. The actual costs for a CCF demonstration plant of 125 million, however, are still above the costs of an *isolated* replacement of a blast furnace which is reported to cost 100 Mio US $ (Hogan 1994, p. 186). A feasibility study for a large-scale DIOS steel work (6000 thm per day) concludes that in comparison with a best standard blast furnace route construction costs will be reduced by 35 per cent and hot metal production costs will be 19 per cent less (Kitagawa 2000). Further, the economics highly depend on the use of the energy (off gas) released in the process (EC 2001, p. 323). Overall, however, the economics are still uncertain.

None of the nine micro-networks involved set the rate and direction of technology development, mainly due to the heterogeneity of the processes. None of the networks merged, which may be a sign that the competitive importance of the technology was esteemed considerable. Unfortunately, concerning several processes detailed information is rather scarce, e.g., for the Italian case.

Luiten (2001, p. 186) estimates that the total expenditure for SRT development up to now is between 600 and 700 million US $, i.e., 30 to 45 million per year, of which about 25-30 per cent was provided by governments. Compared with an overall average expenditure on industrial energy efficiency of 220 million US $ per year in OECD countries in the last 15 years, this is no insignificant amount.

But in the last years, SRT seems to have lost ground to the incrementally improved conventional iron production route (Luiten 2001, p. 179). Three networks led by integrated producers in industrial countries lost interest, because the existing capital stock was being continuously improved and upgraded and thus its lifetime extended so that there was no longer a pressing need to replace the existing coke ovens. Moreover, the introduction of pulverized coal injection in the blast furnace, combined with the increasing availability of coke imports, reduced the need for coke production. For example, with pulverized coal injection, the minimum coke rate required was reduced from 400 kg/ t pig iron in the beginning of the 90s to nearly 200 kg/ t pig iron in the future (EC 2001, p. 319). Secondly, they did not need an additional or new ironmaking capacity. And finally, cleaner coke ovens were developed. All in all, the cost advantages of SRT became smaller and smaller (Luiten 2001, pp. 184-5). And the existing environmental requirements could be met with incremental improvements. This was also true for the Dutch long term agreements on energy efficiency, in which 1998 the projected intermediate efficiency improvement of 16 per cent compared to 1989 was fulfilled (Michels 2000, p.3).

This looks a bit like another illustrative example of the so-called sailing ship effect induced by increased or renewed technological competition, leading to significant and unexpected advances of the old technology. Some producers, such as British Steel, Thyssen and Usinor, even recently invested in new coke ovens. The same is true for some American producers (Martin et al. 2000, p. 107). One developer of the Jupiter process stated: "[H]uge investments in smelting reduction processes would have been premature. Smelting reduction was possibly studied at the wrong time." (Lassat de Pressigny 2000, cited in Luiten 2001, p. 185). Put in other words, at least for some firms there was not yet a window for SRT and the anticipated window did not materialize (yet). And for a continuation without an application in sight, the expenditures needed for further developing the process are too high. In effect, only one Japanese integrated steel producer continued R&D activities concerning the DIOS process (see below).

Also the Dutch example reflects these developments. In 1989, Hoogovens, British Steel and now also the Italian Ilva focussed their efforts on the Cyclone Converter Furnace (CCF) technique, allowing for larger cost reductions than the previously favoured CBF process. There was time left for further research because improvements in the existing iron production route had improved the coke situation in both firms. The consortium was also involved in the development of pulverized coal injection as a more incremental alternative. Ongoing improvements in the latter as well as financial restrictions, however, were a major reason that British Steel left the network in 1992. Ilva left the consortium for other reasons, continuing research on their own under the label CleanSMelt. Hoogovens research resulted in patents and a publication in 1994. The Hoogovens pre-reduction process raised the interest of the US consortium led by AISI. After the failure of the latter, Hoogovens took over the complete knowledge and continued development by constructing a small pilot plant of 20 tons/ hour in 1995, having invested up to this point 6,5 million US $ (Moors 2000, pp. 241-4).

4.3.2. Institutional and political determinants

As already mentioned above, due to the amount and complexity of the R&D needed for the development of SRT, it is uncertain if government support or environmental regulation alone would have sufficed to open a window. Nevertheless, the application of SRT would make redundant some other environmental investments. But environmental regulation was not selective, e.g., it did not prevent steel firms from investing in new coke ovens.

In the late 80s and, particularly, in the 90s, the need to reduce emissions played an important role for the continuation of activities of integrated steelmakers, in Japan, South Korea, the US and in the European CCF network (Luiten 2001, p. 183). For Hoogovens, also the 1992 long term agreement on industrial energy efficiency improvement (ecological covenant of the base metal industry, see figure 4, p. 18), which was based on the National Environmental Policy Plan (NEPP) of 1990, played a role (Luiten 2001, p. 195). The steel industry agreed to improve energy efficiency from 1989 to 2000 by 20 per cent (Michels 2000, p.2).

Government R&D support played a role in almost every technology development process. It has been very substantial in the Japanese DIOS and in the US DSM development, delivering over two thirds of the expenditures. Also in CCF development, ECSC support was substantial, although it was financed by a levy on steel prices, not by the budget. In the US and in the Dutch case, the government also played an important role in initiating cooperative research projects, respectively continuing the activities (switch from CBF to CCF). In most cases, the support led to additional research and the enlargement of networks, although probably not in the most advanced one. Moreover, Luiten (2001, p. 191) concludes that an *acceleration* of the development might only have taken place in the DIOS process, but she only applies this category to processes near commercial use.

4.4. An early time-critical phase of technological competition

The rather successful development of pilot processes demonstrated technical feasibility and clarified the conditions of economic feasibility. Thus one precondition for an instable phase of technological competition, i.e. a techno-economic window, was reached. Moreover, the very important economies of scale of ironmaking in integrated steel mills make a commercial demonstration plant costly. Therefore from a business perspective a decision to invest in such a plant depends on expectations that a window utilisation, i.e. the successful commercialisation of the new technology, will be possible. Thus, there is a time-critical instable techno-economic phase of "old-new" competition even before the potential new technology is commercially available.

However, also the reinvestment prospects changed, so that at least in some countries no instable phase occurred. First, worsening economic prospects due to uncertain market demand and increasing world market competition can lead to a lengthening of the old investment cycle respectively delayed reinvestments or even the abandon of reinvestment plans. E.g., in the EU, steel production rather stagnated in the 1990s, with a steadily falling share of the world's steel production. The general trend in the US is similar or even worse. One example is the stopping of a planned demonstration plant project of the US steel producer Geneva Steel first based on COREX, and later on HISmelt technology due to the steel producer's having gone bankrupt. Second, revived technical progress along the old trajectory, which might partly also be due to end-of-pipe environmental regulation, reduced the performance difference between old and new technology. In some cases it made an upgrading of the existing facility necessary which increased sunk cost and thus lengthened the investment cycle.

Both factors make an investment into the new option economically more risky. What had been anticipated as substitution process with a rather clear timing now seems to be rather an open competition. And while the latter may well constitute a techno-economic window from a system-oriented policy perspective, this need not be the case from a firm perspective any longer. As mentioned above, at least some firms decided not to pursue the new option and reinvested into the old trajectory. Luiten (2001, p. 198) attributes this behaviour of integrated firms to a preference for incremental solutions, too.

As a result, only in two countries, the Netherlands and, albeit to a lesser extent, in Japan, the conditions lead to an instable phase of technological competition between blast furnace and smelting reduction technology in integrated steel mills. An indicator are the planned SRT commercialisation activities of Hoogovens and NKK.

4.4.1. The Dutch case: techno-economic and political determinants

The most important attempt to commercialise SRT in integrated steel mills has been undertaken in the Netherlands. Here, steel industry is largely identical with the integrated producer Hoogovens. From 1996 on, the firm planned a demonstration plant on an industrial scale, i.e., 700,000 tons a year. After efforts to find a cooperative investor to supplement its own CCF pre-reduction unit had failed, Hoogovens went for its own. In 1997, the Dutch government announced the so-called National CO_2 Reduction plan in response to the Kyoto Protocol, which involved substantial budgets. Hoogovens applied for government support for a demonstration facility and was awarded 30 million US $ which was about 25 per cent of total expenditures.

Hoogovens wanted to provide the same amount but failed to find another investor for the remaining 60 million, e.g., HISmelt actors refused. Hoogovens, however, was not willing to invest more, given the rather high risk of the project. There was no steel expansion phase, and the firm decided to first invest in thin slab casting technology that was also new. Despite government support, Hoogovens thus first postponed and two years later, in 1999, stopped development due to financial reasons (Moors 2000, p. 244). In between, there has been a merger with British Steel, further reducing the reinvestment needs.

Thus in spite of political support the techno-economic window was not utilised by the economic actor, and later on restricted by deteriorating economic prospects. There is some speculation that if Hoogovens and Ilva had continued joint development, during the better economic situation in the mid-90s, the story could have ended differently (Luiten 2001, p. 177).

A further critical factor cited in the Japanese case, where only NKK seems to pursue the commercialisation of the DIOS process might be the loss of knowledge: "DIOS will die as the people who have the knowledge hidden in their heads retire from NKK. We thus have to commercialise the technology as early as we can," states an NKK developer (cited in Luiten 2001, p. 194). But after some attempts, i.e. via extended demonstration in the small scale pilot plant and a promising feasibility study, the economic situation of Japanese integrated steel producers forced NKK to rather explore the minimill market introduction route for DIOS (Kitagawa 2000) – but without success so that commercialisation efforts were stopped 2001.

4.4.2. Germany: a special case

German steel producers were largely absent of the analysed innovation processes. They were only involved in the beginning of SRT research processes but later on did not further pursue this path. One reason might be a much greater stickiness to the old coke oven - blast furnace path, resulting i.e., from a long-term agreement with the coal industry (the so-called Hüttenvertrag) to buy a certain amount of coke which was valid until the end of 1997. Due to the exemptions for energy extensive producers, the German eco-tax did not generate much further incentives. German steel producers acknowledge that the CO_2 emission reduction potential of integrated steel mills is nearly exploited and thus consider R&D in new processes as important in the long term (Ameling/Aichinger 2001). In 1997 in a policy document they listed plans to e.g., participate in one SRT commercialisation project (VDEH/ WV Stahl 1997). However, up to now there are no signs for materialisation. Unlike in the US, where government provided substantial support for a demonstration project even though using foreign technology, German policy makers do not push into this direction. Obviously, German steel producers expect to fulfil their renewed – and compared with the German industry average rather modest - voluntary CO_2 reduction obligation, a reduction of the CO_2 emissions of crude steel production of minus 22 per cent between 1990 and 2012, with a range of optimising measures as well as an increasing share of electro steel (Ameling/ Aichinger 2001).

4.5. Minimill expansion as new framework for technological competition?

Thus the question arises of the extent to which *minimills* striving for higher quality market segments could be better able to provide a market niche in which SRT can successfully compete. At present, this route is favoured also by developers which focused primarily on large steel mills, e.g. NKK trying to commercialise the DIOS process (Kitagawa 2000). Minimill producers rarely contributed to the risky and expensive development, but in three of the five micro-networks not led by integrated steelmakers, minimills became involved when an operation on an industrial scale was envisaged (Luiten 2001, p. 180); COREX is one example. For minimills, some techno-economic conditions seem to be more favourable, i.e., the ongoing penetration of new flat steel market segments which demand higher-quality inputs. Their need for smaller production facilities coincides with the smaller units at the beginning of the commercialisation phase. Moreover, rising levels and volatility of scrap prices in the 90s let minimills think about other inputs (Bartzokas/ Yarime 1997, p. 28). However, in this segment SRT compete with the already established cold DRI technology as well as with other hot metal inputs such as hot DRI (HBI) and even compact blast furnaces (Haissig et al. 2002). Therefore the main question is, if a minimill producer is able to capitalize on the progress of SRT and is willing to invest substantially in a demonstration plant when already commercialised alternatives are available.

In fact, two US minimill producers seem to be prepared. North Star Steel has undertaken a joint venture with the Brazilian TECHNORED developers in order to construct a demonstration facility. However, the current status is unclear. The biggest US minimill producer, NUCOR, wanted to build a near commercial facility based on the HISmelt process in the US (Luiten 2001, p. 177). After that was postponed, Nucor recently announced a joint venture with the Australian Rio Tinto Group and others to build a (state-subsidized) commercial-scale HISmelt plant in Western Australia with a capacity of 800,000 metric tons per year at a cost of about 200 million US dollars. Construction shall commence in early 2003. While Rio Tinto intends to construct a full HISmelt-based steel mill with a capacity of 1,5 million tons in 2006 or 2007, Nucor takes 25 per cent of the costs and has the right to use the technology in its own plants (Chemlink 2002, Nucor 2002). Also this commercialisation project is quite heavily supported by the Australian federal government as well as by the government of Western Australia. The support amounts to about 80 million US $, a part of it being contingent on the later construction of a commercial steel plant (Chemlink 2002).

5. Conclusion and outlook

The case analysis has shown that time windows can be of relevance for competition between old and new technologies as well as between several new ones and has clarified some conditions. In *old-new competition,* investment cycles and market entry barriers (due to sunk cost, investment scale or else) seem to be constituent for the time dependence of techno-economic windows. Given this importance of scale, such instable phases of competition can already be important before market introduction of the new solution takes place. In *new-new competition*, even if direct network effects are absent, scale and learning effects may provide for pressure towards one dominant technology and thus the relevance of time windows.

Luiten (2001, p. 197) concludes that in integrated mills, the application of SRT – respectively a new instable phase of competition with blast furnaces - has probably been postponed for at least ten years, while an application in minimills may in the meantime be a first niche. However, in emerging countries at least the COREX process is already in use in integrated steel mills. Thus Luiten’s conclusion has to be specified towards other, probably environmentally more beneficial, SRT technologies. It seems that techno-economic determinants alone do not suffice to utilize the innovation window opened by successfully overcoming the pilot stage. The reasons are the reduced urgency of replacement as well as deteriorating economic perspectives.

In the present case, the political utilisation of the early techno-economic window, and thus, at the same time, preparation of a future competition in the market place, did *not* require a specific policy window. Almost everywhere where the utilisation of the techno-economic window has been intended, governments seemed to be ready to support the respective projects, even with substantial amounts of money. This is not surprising because only incremental policy change was needed. The incrementalism holds for the economic effects on integrated producers – in the end SRT is rather a competence and thus also a competitiveness-enhancing radical technology – as well as for the applied procedures which could draw on well-established instruments such as subsidies. However, the political incentives seemingly could not outweigh the increasing techno-economic doubts.

Moreover, the case illustrates the beneficial side effects for innovation induced by renewed technological competition leading to a more open market structure. With the emergence of minimills the close oligopoly of steel producers has been destroyed, in industrialized countries as well as in the world market, by allowing further countries to enter the market. Today minimill producers seem to be prepared to take the lead and market conditions seem to be favourable for the use of SRT for producing the necessary high-quality input. Nevertheless it is still uncertain if commercialisation will be successful. Certain promising processes developed by integrated producers, however, seem to be locked-out by this constellation.

Given this situation, there is a certain danger that the new-new competition between different SRT does not yield the success of the most energy-efficient – and thus also less CO_2 -emitting – technologies. COREX seems to profit from its head start, and given that significant cost reductions may be reached due to economies of scale and learning effects, this advantage may well prevail. On the other hand, due to minimill involvement, at least the HISmelt technology still seems to have chances for commercialisation.

An important role in this new-new competition, as well as in the old-new competition with the blast furnace route in integrated steel mills will be played by future climate protection policy (see also Schleich et al. 2002, Quirion 2002), as the Dutch example already indicates. For example, a trading system for CO_2 emissions in Europe, which is expected to include iron- and steelmaking, could in principle enhance the chances for a successful competition of SRT. But given that the CO_2 balance of gas-based technologies is better than of coal-based ones, a stricter CO_2 policy might predominately benefit the upgrade of minimills using the Direct Reduction technology route.

As a political recommendation on appropriate timing strategies, Luiten's (2001, p. 196) conclusion can be confirmed: Government support at the demonstration stage is appealing because it can be additional and greatly accelerate development and thus make use of an early techno-economic window. In other words, in capital intensive technologies the market introduction stage may indeed be the main bottleneck and an instable phase here the most suitable object for political timing strategies. They could aim for increasing the number of options in the first place and, if the new technologies generate sufficient environmental benefits, enhance the chances of successful competition. In large scale industries, however, even for a rather small impulse quite a substantial budget may be involved.

Emissions trading would also give an incentive to reduce CO_2 emissions for those who can do this most efficiently. Moreover it allows companies to choose the timing appropriate to their re-investment cycles. But the way it is implemented is decisive because in comparison with a subsidy, it is marked by a dilemma: Either, if auctioning is used as allocation mechanism, it involves a more cost for the industry in general (the same is true for substantially increased eco-taxes). In stagnant markets this might not stifle innovation in ironmaking. Or, if the initial allocation of emission permits will take place by "grandfathering", probably allowing existing integrated producer to sell permits, this would make a market introduction of SRT by minimills as innovators more difficult, because they would have to buy new emission permits for adding an ironmaking stage. The same is true for the use of DRI instead of scrap. However, if there is a political window for a policy design which would advantage innovators others than integrated steel producers is not obvious. The resistance of, e.g., German steel industry to any type of emissions trading rather casts doubts. But from an innovation perspective, the proposed continuation of voluntary agreements is no alternative.

6. References

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