CO_2 mitigation technologies in the steel industry: a benchmarking study based on process calculations

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CO_2-Minderungstechnologien in der Stahlindustrie: Eine Benchmarking-Studie basierend auf Prozessberechnungen

Global warming presents an enormous challenge to the steel industry, which is both carbon-intensive and energy efficient. Lean production can provide some short-term emission mitigation, at the level of the Kyoto requirements. In the middle term, more use of scrap will also help alleviate emissions. But to reach much larger reductions in GHG emissions, on a par with the likely targets that will be set after the Kyoto period, the steel industry will have to imagine new production paradigms, which constitutes its most formidable challenge for the years to come. Carbon capture and sequestration, processes leaner in carbon use, electricity and hydrogen from green sources will have to be added together in a patchwork of process routes, which will have to be developed at great risk in the next decade, hopefully through broad international cooperation.

Die globale Erwärmung stellt eine erhebliche Herausforderung für die Stahlindustrie dar, die zugleich kohlenstoffintensiv und energieeffizient arbeitet. Kurzfristig können Maßnahmen wie Lean Production dazu beitragen, dass die Emissionen etwa auf das im Kyoto-Protokoll verlangte Niveau verringert werden. Mittelfristig wird der verstärkte Einsatz von Schrott ebenfalls zur Emissionsminderung beitragen. Um jedoch eine deutlich höhere Reduzierung der Treibhausgasemissionen auf das Niveau zu erreichen, das voraussichtlich nach Ablauf des Kyoto-Zeithorizonts vorgegeben wird, ist ein Paradigmenwechsel in der Stahlerzeugung notwendig. Dies wird in den kommenden Jahren die gewaltigste Herausforderung für die Stahlindustrie darstellen. Im Laufe der nächsten zehn Jahre werden vielfältige Verfahrenswege zu entwickeln sein, die die CO_2-Abscheidung und -Lagerung, weniger kohlenstoffintensive Prozesse sowie den Einsatz von Strom und Wasserstoff aus umweltfreundlichen Quellen einbeziehen. Die Entwicklung dieser Verfahren ist mit einem erheblichen Risiko verbunden, so dass zu hoffen ist, dass sie im Rahmen einer breit angelegten, internationalen Kooperation erfolgt.

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Steel is one of the pillars of the well being of our modern societies in developed countries and it will definitely continue to play this role long into the 21st century, both in post-modern economies and in the developing world. Steel is also a mature basic material, which has incorporated accumulated knowledge to the point where its production technology has reached very high levels of efficiency, in terms of usage of raw materials and of energy.

This dichotomy sets the stage for the challenge that global warming poses to the steel industry in terms of managing the short term, where strong reduction of greenhouse gases (GHG) and more particularly of CO_2 emissions are out of reach – as most of what is achievable has already been achieved by the most efficient producers, and the long term, where the development of process routes, which would drastically reduce emissions, raises questions that are very open on possible technologies and their expected cost of production. But challenges, formidable as they may seem, do turn out to be a strong driver for change and progress. This is indeed what is expected, in a more general way, of the adoption of Sustainable Development policies by the steel business.

Short-term GHG emission mitigation

The concept of sustainability was first introduced by Ms Brundtland, in her famous 1987 report [1], but industries – and the steel industry more particularly – have been practicing the concept, nolens volens, since the 1960's at least.

Indeed, led by the drivers of mass production, quality control and cost reduction, technical progress has led to large energy savings and to the systematic use of lean and clean processes. The time evolution of CO_2 generation in the French steel industry, over the past 40 years, bears witness to that tendency, **figure 1.** It has indeed decreased by 60 % over that period of time. The trend has been leveling off because the reservoir of achievable stepwise improvements has been almost exhausted.

In the short term, improving efficiency and resource use has at best a further potential of decreasing emissions by 10 – 15 %, depending on local conditions. Any stronger pressure from governments, in terms of a carbon tax for example, would not topple this "physical" barrier but, on the contrary, would severely damage the competitiveness of the most efficient producers.

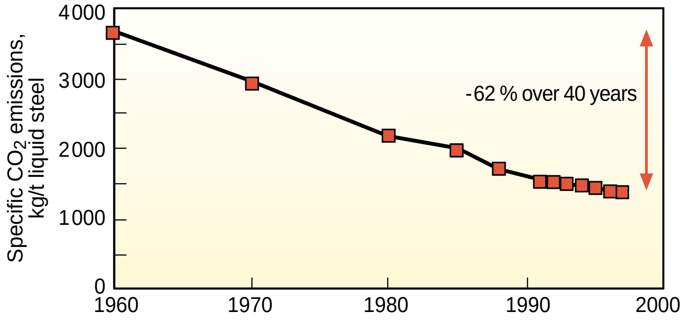


Fig. 1. Evolution of GHG emissions in the French steel industry 1960-2000

Bild 1. Entwicklung der Treibhausgasemissionen in der französischen Stahlindustrie 1960-2000

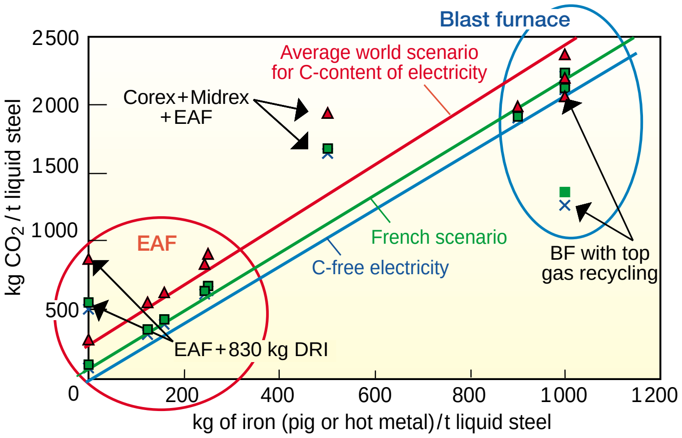


Fig. 2. CO_2 emissions of various steel production processes

Bild 2. CO_2-Emissionen von verschiedenen Stahlerzeugungsverfahren

Middle-term GHG emission mitigation

Figure 2 shows the results of a simulation study, where the CO_2 emissions of all the existing steel production routes have been investigated. Emissions are primarily related to the amount of hot metal or of pig iron used as iron units and, to a lesser extend, to the carbon-intensity of electricity [2].

In the middle term, a very attractive solution thus consists in further increasing the use of scrap by increasing the amount of available scrap through an improved recycling of steel. This means investing in electric arc furnace (EAF) technology rather than in integrated steelmaking as far as new capacity is concerned, but also introducing more scrap in the converter, at least up to the natural limit of 250 kg/t, beyond which the introduction of extra carbon would be needed.

On the other hand, this solution has limitations, because the amount of scrap available is directly related to production and can only become very significantly larger if and when production increases eventually. Quality issues due to scrap pollution by tramp elements are also a concern.

Another attractive solution is to make use of natural gas as a reducing agent in place of carbon. Limitations are not technical, as technologies in the area of prereduction are very mature, but economic in the shorter term due to gas prices, and related to the volatile issue of resource depletion in the longer term.

Long-term GHG emission mitigation

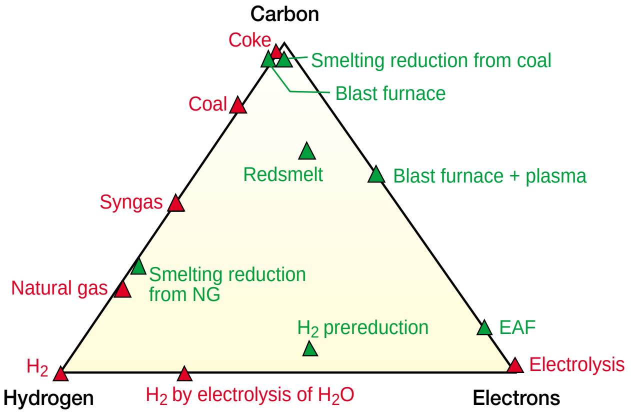
In the longer term, there are a number of paths that may be explored to produce steel with lesser carbon emissions. Very large reductions can be imagined, although the technologies that come to mind are still in their infancy or even merely conceptual and therefore exhibit a level of technical and financial risk on a par with the high reductions that can be envisioned.

Exploring these possibilities will probably require a coordinated effort of the world steel industry as well as a long-term commitment of a number of players and stakeholders, over 10 to 20 years, a typical critical time for radical innovation in the steel industry.

Figure 3 presents the spectrum of the candidate radical technologies, along with existing ones, in a conceptual ternary diagram, where fuels/reducing agents occupy the three apexes.

Their actual performance in terms of GHG emissions and energy needs are shown in **figure 4.**

The novel concepts include a more efficient use of carbon in the blast furnace, by recycling the top gas after decarbonatation for example, or a refreshed look at smelting-reduction (SR) processes, especially those, which foster in-process gas recycling. CO_2 capture and sequestration would be further needed to reach the high levels of mitigation that need to be targeted.



Other reducing agents: Al dross, etc.

Fig. 3. Radically new steel production processes
Bild 3. Völlig neue Stahlerzeugungsverfahren

Capture and sequestration of CO_2 has now become a credible technology, which can already exhibit some limited but large-scale examples, particularly in relation with enhanced oil recovery.

Large R&D programs are under way to develop the technology further and cut down its cost. In the meantime, other avenues than geological sequestration are being explored, such as ocean sequestration or the entrapment of CO_2 in mafic rocks.

Hydrogen. Replacing carbon or natural gas by hydrogen, derived from technologies that exhibit a low carbon intensity – such as water electrolysis with green or otherwise carbon-free electricity, or coal gasification with subsequent CO_2 capture and sequestration, is another promising path depending very much on the availability of green electricity and on the future price of CO_2.

This is a future, in which hydrogen is considered as a potential energy carrier by a large spectrum of economic players, including the transportation, the chemical, the oil refining and the power generation industries. Their time horizon is also the next 10 years to bring the necessary technologies to maturity and the next 20 years to reach a sizeable level of implementation. In such a future, hydrogen would become a ubiquitous energy carrier, like electricity today, and synergies would arise from the high level of demand.

Biomass and charcoal. Using biomass is a third area open for investigations. Indeed, carbon, in such a concept, cycles thanks to a natural biological process, where the regeneration of CO_2 to C is carried out by photosynthesis in plants. It is therefore invisible in terms of global warming effect, as long as the process is carried out in a steady-state manner, with a careful tree husbandry policy, for example. About 8 million t of pig iron are already produced in this way in Brazil today, with eucalyptus trees, charcoal ovens and small blast furnaces fed with this charcoal.

The present technology of charcoal blast furnaces needs to be upgraded from its present low-tech level, if it can expect to compete with more mature high-volume technologies. The charcoal can also be used to produce powdered coal, which can be injected at the tuyeres of state-of-the-art blast furnaces. Many technologies to produce other fuels, including hydrogen, from biomass can be imagined.

Energy recovery from waste can moreover be considered as a variant of these botanical biomass concepts.

Electrolysis. Finally, electrolysis of iron ore is a further possibility, which needs to be explored because little informa-

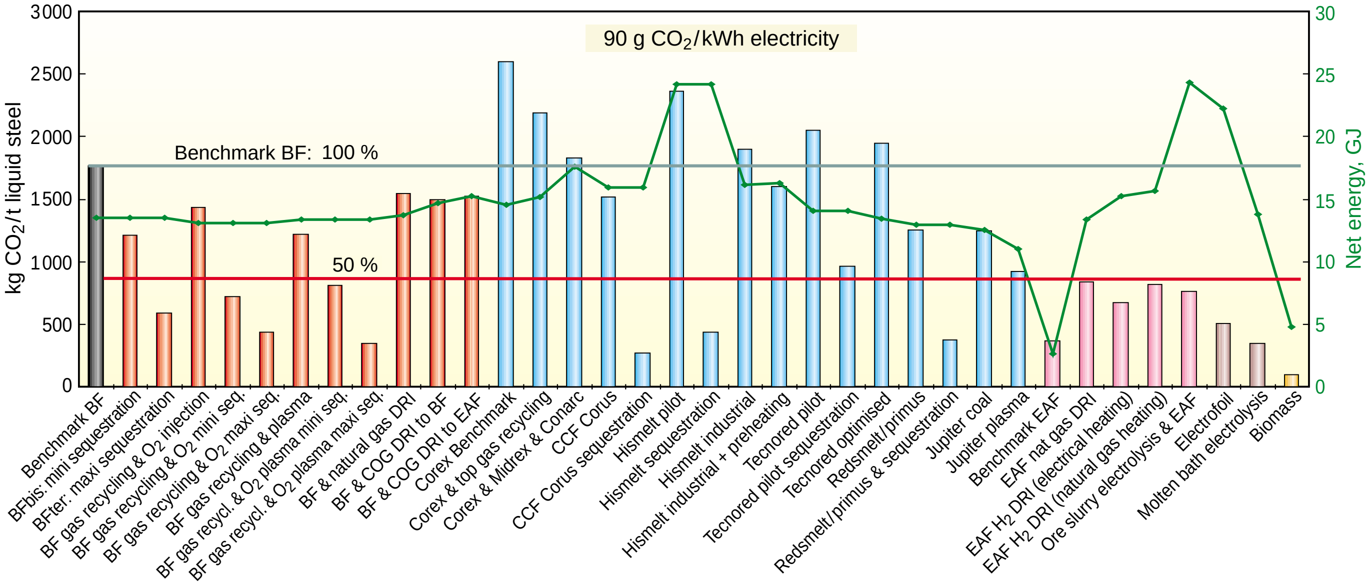


Fig. 4. Present and radically new steel production processes in terms of CO_2 emissions and energy consumption
Bild 4. CO_2-Emissionen und Energieverbrauch von gegenwärtigen und völlig neuen Stahlerzeugungsverfahren

tion is available on these potential technologies in the case of steel, as they were not seriously envisaged in the past. Electrolysis, in principle, produces greenhouse gases only through its use of electricity, provided electrochemical reactions are carefully designed to avoid the generation of GHG. It can therefore in theory be as green as the electricity that it uses.

Various concepts have been explored to produce steel by electrolysis. Aqueous solutions of Fe^{+++} ions obtained by leaching iron ores or scrap by HCl can be electrolyzed directly into a foil, 10 to 150 µm in thickness. A pilot plant based on this concept was experimented on at CRM under the name of Elofoil, with an output of 4.5 t/h and a drawing speed of 31 m/min for the 0.15 mm thickness [3]. The solution was either replenished with scrap or with sulfide ore. A soda solution, where iron ore pulp was dispersed, was also experimented upon at Irsid [4]. Electrolysis was assumed to dissociate water into OH-ions and free hydrogen, which would then reduce Fe_2O_3 and regenerate water. The iron deposit had to be melted, casted, rolled and finished. Iron ore can also be dissolved into liquid salts (e.g. Na_2CO_3+B_2O_3) at high temperature and the electrolysis carried out in the salt. Depending on the temperature, solid iron can deposit on the cathode, or liquid iron can flow down to the bottom of the cell, thus mimicking aluminium production. These routes are being studied at MIT, still at the laboratory scale [5].

Putting these various possible futures into perspective provides a picture of the formidable challenge that the steel industry might and most probably will have to face in the post-Kyoto era, which is starting almost tomorrow.

Scenarios

To peek deeper into the future, we have imagined a basic scenario, which can be considered as a long-term trend scenario for the middle of the century.

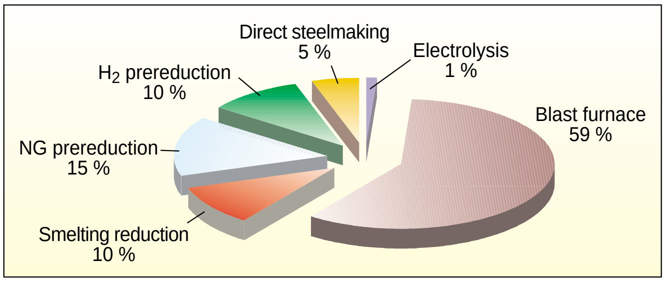


Fig. 5. Steel production routes: long-term scenario
Bild 5. Verfahrenswege in der Stahlerzeugung: langfristiges Szenario

In 2050, the world has a population of 9 billions, steel production would by then have reached 2300 million t/a from today's 850 million t, if steel is to play its role and accompany the improvement of the standard of living in China, the Indian subcontinent, Indonesia, Russia and South America [6; 7].

The first strong determinant concerns iron units. A large increase in steel production will generate a lot of scrap, the amount of which will become so important that it will have to be recycled at a high level, both volume and quality-wise. This would drive the scrap/ore ratio to 60 %. Scrap goes naturally into a modern version of an electric arc furnace, but is also largely used in converters, which will also be around in 2050, because steel will continue to be produced through a hot-metal phase in large quantities.

The virgin iron routes, beyond the blast furnace, have been complemented by: smelting reduction, which could replace some of the obsolete blast furnaces, and low-C intensive routes, i.e. prereduction from natural gas, hydrogen prereduction, electrolysis (provided hydrogen and electricity are CO_2 lean) and direct steelmaking, **figure 5.** We have also provided for the possibility of assuaging GHG emissions of C-intensive processes by carbon sequestration. The blast furnace remains at 59 % of the ore routes. This implicitly assumes that conventional integrated mills will still be built in the next 10 to 15 years, before any credible alternative is actually developed.

This 2050 scenario would lead to a reduction of GHG emissions of 39 %, without CO_2 sequestration and of 65 %, with CO_2 sequestration. This means either that sequestration is absolutely necessary to go beyond a target of 50 % reduction in CO_2 emissions or else that a more rapid migration to the ”breakthrough“ technologies introduced in the previous section would be needed.

Conclusions

Global warming and sustainability are challenging our society at a global level. This will call for major paradigm shifts in every sector of human activity, including the industrial sector. The general public and decisions makers are only slowly discovering the scope of the task lying ahead.

There are no solutions available to improve performance beyond 10 or 15 % in the future within the present economic framework, where low steel prices constrain process technologies to be based mainly on coal, with the very optimized solutions being used.

In the longer term, if one assumes a positive view of the future allowing for growth of the world economy, steel production will continue to increase and will generate large amounts of scrap, which, when properly reused, will reduce the specific GHG emissions. This, however, might not be at the level of the needs that might arise in the post-Kyoto period. Breakthrough process technologies, based on radically new routes as compared to today's technologies, would then become attractive and probably necessary.

Their potential, if it is to be realized, will need a strong and voluntary development program, with the perspective of making these processes available 10 years in the future. (S 31004)

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