

CO₂ Emissions and the Steel Industry's available Responses to the Greenhouse Effect

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1. INTRODUCTION

The issue of Global Warming has matured significantly since the Climate Conference of Rio in 1992.

On the scientific side, climate modeling has complexified by taking into account the coupling between atmospheric and ocean circulations and a number of interactions with the ecosphere. This has resulted into a better prediction of temperature projections caused by increased atmospheric CO₂. Moreover, analysis of historical data on CO₂ accumulation in the atmosphere and correlated temperature pick up has confirmed that the trend is due to human activities while other natural explanations were discredited. The connection between Global Warming and anthropogenic CO₂ emissions has therefore been accepted by a broad majority of scientists, although dissenting opinions still exist. The strong input of research funding in the field is continuing and more delicate issues such as the connection between CO₂ enrichment, plant life and overall ecosphere retroaction are being actively investigated. Similarly, regional studies on the impact of Global Warming on local weather pattern, tree survival or impact of ocean level rise on coastal shape are being commissioned all over the world.

On the political and societal side, Global Warming has been accepted by the world community as a scientific fact and considered as a mortgage on the future, mainly since the Kyoto Conference. The matter at hand is now to implement global policies that would restrict CO₂ emissions while allowing the less developed countries to continue their growth. The Buenos Aires Conference has not reached any consensus decisions on the issue.

The analysis of the consequences of Global Warming on the activities of economic sectors and of specific firms remains mostly a task for the future. The insurance business may be an exception: it has been looking into the possible connection between recent natural disasters and the weather instability that is expected to result from Global Warming. Of course, CO₂ emissions by sectors of activities are well known (Figure 1) and global macroeconomic simulations

have measured the immediate impact of potential countermeasures such as ecological taxes on CO₂ emissions or energy consumption. But longer-term predictions would require a true technological forecasting approach, whereby contrasted scenarios incorporating major technological changes would be taken into account. Although this may have been done in a few cases [1, 2, 3], the issues are too involved to be settled in a short period of time.

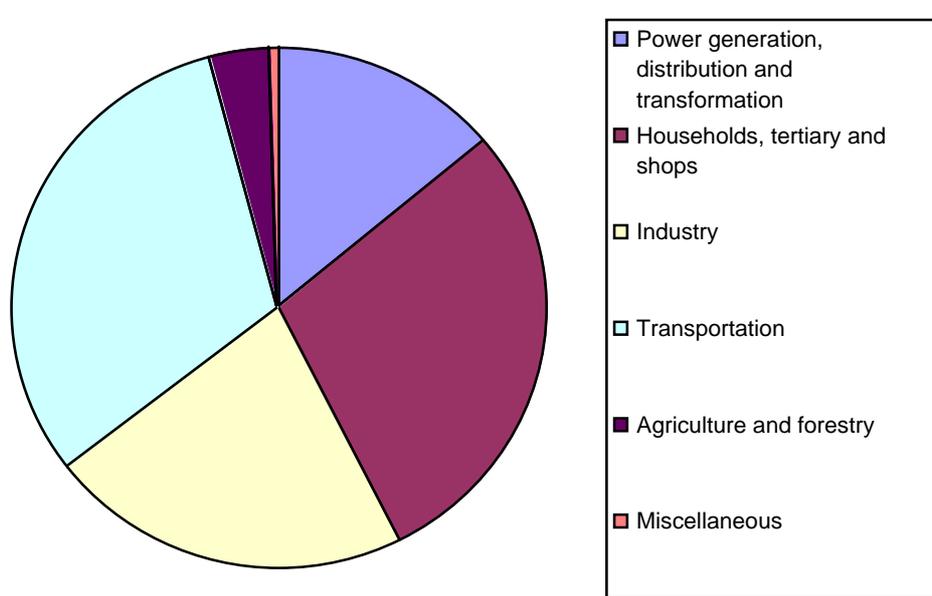


Figure 1: CO₂ emissions in France in 1995. The total amounts to 465 Mt/year, i.e. about 1.6 % of world anthropogenic emissions.

We will now present the views of the French Steel Industry in terms of possible worldwide futures for the industry. We shall also discuss the framework in which the issue should be tackled, thus, hopefully, bringing some more arguments to a complicated issue, that will need more time to be clarified fully.

2. CARBON CONSUMPTION FOR STEEL PRODUCTION

Materials in our civilization play an essential role in our well being. A combination of special properties and of a low cost, built up by research and development, lies at the root of their usefulness. Steel, which is a generic name for what is probably the widest ranging set of alloys available to the industry, is currently the second most used material: without steel our present technology simply could not exist.

In the present section, we shall review what are the CO₂ emissions of a Steel mill in a straightforward manner based on energy and mass balances. This is falling short of what would be necessary to measure CO₂ emissions against the functions that Steel performs, but this point will be brought up again in section 4.

2.1. Physical Chemistry basics...

Carbon has been used traditionally in the Steel Industry to provide the chemical function of reducing oxide ores and the energy function of heating up the reagents to the temperature where reaction kinetics are economically and technologically suitable.

¹ tls: ton of liquid steel

Some basic thermodynamics figures can help set the framework of this study, although actual operational figures will be larger - due to the yield of the various Steel production reactors and to the energy and reagents needed to handle the gangue:

- the energy requirement for reducing hematite (Fe_2O_3) at room temperature is 7 400 MJ/t of iron. The minimum amount of carbon that is needed for reducing it is 320 kg, if CO is formed and would be only 160 kg, if CO_2 were formed.
- the energy requirement for melting clean scrap into 1 t of Steel is 1350 MJ. A few kg or tens of kg of carbon are necessary to reduce the oxidized surface of scrap,

Carbon dioxide emissions depend primarily on the source of iron: using recycled iron or scrap is much less energy and carbon intensive than using virgin iron by reducing iron ore. This is the obvious and basic difference between the Integrated Route and the Electric Steelmaking Route.

A second factor is the carbon intensity of electricity generation. Renewable energies and nuclear power have virtually no carbon content. Fossil fuel electricity has a carbon content that depends on the fuel. In our simulations, we have basically used two scenarios:

- a French scenario, where 6% of electricity is carbon-based: the equivalence ratio between carbon and electricity is 16 g C/kWh or 4.5 t C/GJ (60 g CO_2 /kWh or 16.5 t CO_2 /GJ).
- an average World scenario, where 50% of electricity is assumed to be carbon-based: 127 g C/kWh or 35.3 tC/GJ GJ (466 g CO_2 /kWh or 129.4 t CO_2 /GJ).

As a reducing agent, carbon can, in theory, be replaced by hydrogen, electrons (in electrolytic processes) or raw heat, i.e. dissociation of the iron oxide at high temperature and subsequent capture of the free oxygen by physical (mass spectroscopy) or chemical means. These alternative Steel production routes will be discussed in section 3.

2.2. Simulation of carbon consumption of model mills...

In order to discuss the CO_2 emissions of a Steel Mill, we have chosen to use model mills. A model mill is a virtual mill, where process conditions can be varied in order to study the influence of important process parameters. The simulations are based on heat and mass balances, based on actual operational data of French mills or on published information on other technologies. The method had already been used in [1].

The system for which the balances are calculated includes all the reactors of the hot metal plant - including coke ovens (CKO), sinter plant, pellet plant, lime plant and blast furnace (BF), and the steelshop reactors until raw liquid Steel. All energy and carbon needs are taken into account. All input carbon is assumed to leave the system as CO_2 , a conservative assumption that ignores the use of CO as a fuel in downstream reheating furnaces or in a power plant. An example calculated for the case of a reference blast furnace representative of today's operation is given in Appendix 1.

There are many kinds of Steel Mills depending on the nature of energy and raw materials, the planned production of the mill and, as a result, the specific investment.

We have carried out the simulations of CO_2 emissions on a representative sample of them, that is given in Table 1. The two basic routes, integrated and electric, are represented with variants of interest for the issue at hand:

- **the blast furnace route** is explored in the range of pulverized coal injection (PCI), from 150 to 250 kg/thm². Feed material goes from 100 % sinter, to a mixture of sinter and pellet and of sinter, pellets and DRI.
- an extreme case is examined, **whereby the top gas of the BF is recycled at the tuyeres** in order to recover its chemical energy: the gas is initially decarbonated and the extra thermal energy required by the reactor is provided by plasma torches, i.e. electricity. The main elements of this technology were studied and used in commercial operation in the past in France [4, 5].
- **the EAF route** is explored as a function of scrap input, supplemented by 0 to 650 kg/tls of either pig iron (solid), hot metal (liquid) or DRI/HBI. When pig iron or hot metal is used as feed material to the EAF, the CO₂ emissions due to their production in a blast furnace are attributed to the EAF route.
- a number of so-called new Steel production routes has been included, mainly **Smelting-Reduction (SR) processes**:
 - a converter type of process, namely the CCF process [6], which has published more information than Hismelt;
 - a rotary hearth-submerged arc route followed by an EAF, in this case the Redsmelt process, It makes use of 250 kg/tls of scrap.
 - a shaft furnace Smelting Reduction route, specifically a COREX complemented by a MIDREX unit to make use of the top gas and followed by an EAF, a scheme in operation at Saldanha Bay in South Africa.

The main results of the simulations are given in Table 2, which presents the CO₂ emissions for each of the process routes and in Figure 2, which plots carbon consumption as a function of hot metal or pig iron input per ton of liquid steel.

The major trends are clear to see. **The amount of iron input is the main parameter controlling emissions. The relationship is roughly linear, in spite of the variety of processes and technologies involved. Input electricity is the second control parameter**, although much less important than the first one, as the lower curve in Figure 2 demonstrates, where the contribution of electricity to emissions has been altogether omitted. Taking into account the type of electricity generation is certainly important, especially in the EAF routes, but of second order when the whole range of processes is considered.

² thm: ton of hot metal

<i>Blast Furnace route</i>	
1	Reference Blast Furnace: 153 kg PCI , 1357 kg sinter & 103 kg pellets/thm
2	Same as 1, 1600 kg sinter/thm
3	5 Mthm/year, 200 kg PCI, 1290 kg sinter & 168 kg pellets /thm
4	Same as 3, 250 kg coal / t hm
5	5,3 Mt hm/year, 190 kg PCI, 94 kg DRI,& 115 kg pellets /thm
6	Same as 1 , 900 kg hm / t steel, instead of 1000
7	Blast Furnace with top gas decarbonatation & recycling, & plasma torches at tuyeres
8	CCF Process
<i>Electric Arc Furnace Route</i>	
9	EAF scrap & 125 kg pig iron
10	EAF scrap & 160 kg pig iron
11	EAF scrap & 250 kg Redsmelt hot metal / t steel
12	EAF scrap & 830 kg DRI / t steel
13	EAF scrap & 244 kg hot metal / t steel
14	EAF no scrap, 45% Corex hot metal and 55% Midrex HBI
15	EAF100% scrap

Table 1: process routes of the model Steel mills used for simulation of CO₂ emissions.

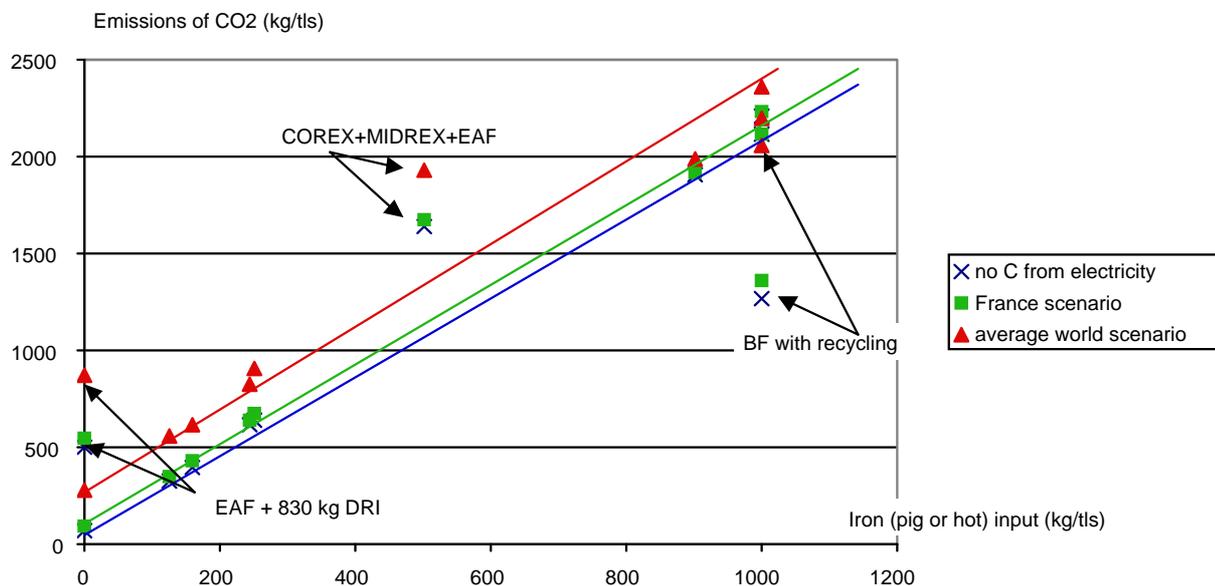


Figure 2: simulation results of CO₂ emissions as a function of iron (pig and hot metal) input

Process route	Input in blast furnace (kg)					In steelshop	CO ₂	Electricity	total CO ₂ (kg / t steel)	
	sinter	pellets	DRI	coke	coal	Iron (pig/hot)	(kg / t steel)	kWh / t steel	France	50% fossil
Ref. blast furnace	1357	103		331	153	1000	2111	187	2122	2198
BF 100 % sinter	1600			331	153	1000	2156	191	2167	2245
BF 200 kg PCI	1290	168		290	200	1000	2088	186	2099	2174
BF 250 kg PCI	1290	168		250	250	1000	2084	184	2095	2170
BF + pellets+DRI	1217	112	94	269	189	1000	2052	185	2063	2139
BF 900 kg hm/tls	1357	103		331	153	900	1904	174	1914	1985
BF gas recycling	1357	103		224	0	1000	1264	1696	1366	2055
CCF S-Reduction						1000	2212	319	2231	2361
EAF 125 kg pig iron	1357	103		331	153	125	323	499	353	556
EAF 160 kg pig iron	1357	103		331	153	160	396	478	425	619
Redsmelt 250 kg hm/tlst						250	639	574	674	907
EAF 830 kg DRI							500	798	548	872
EAF 244 kg hm/tls kg pig iron	1357	103		331	153	244	611	468	639	829
Corex +Midrex+EAF						500	1639	632	1677	1934
EAF 100 % scrap						0	68	458	96	282

Table 2: simulations of CO₂ emission in the various model Steel Mills studied in this work

The 100 % scrap EAF is the leaner route in terms of CO₂ emissions (280 kg CO₂/tIs - electric power average world scenario), but is a rare case in practice, as pig iron is routinely added to the charge to provide cheap and process effective carbon; as a matter of fact, our simulations show that this practice doubles CO₂ emissions. The leaner route is about 6 times less CO₂-intensive than the blast furnace route (2,198 kg CO₂/tIs).

The blast furnace itself is discussed in

Figure 3. The reference blast furnace exhibits a 2,198 kg CO₂/tIs consumption level and all the variants lie within a range of 260 kg of carbon dioxide. The lower range is occupied by the two variants that use an input of reduced iron, either as DRI (2,139 kg CO₂/tIs) in the BF or as scrap in the BOF (1,985 kg CO₂/tIs), the difference stemming from the gangue of the DRI and from the fact that DRI is added to the blast furnace rather than to the converter. CO₂ emissions are insensitive to the level of PCI. There is a slight positive influence of using green pellets instead of sinter, at the level of 48 kg CO₂/tIs per 100 kg of pellets.

The gas recycling blast furnace certainly provides the lowest operating point in terms of direct carbon consumption (1,264 kg CO₂/tIs), but its extra energy requirements, which are filled by electricity, bring it up to 2,055 kg for the world scenario, close to the performance of the reference blast furnace (vs. 1,366 for the French scenario). This means that carbon has a better yield in the blast furnace than in an electrical power plant, hic et nunc. On the other hand, the more carbon-free electricity there is available, the more attractive would this route seem to be. Today, it is still too expensive, with the present price structure of kWh vs. coking coal (in France).

Smelting reduction routes cannot be clearly distinguished from the blast furnace route, a point which was not true in 1993 [1] and is a tribute to the progress made by these new processes since then. The addition of a Midrex plant beside the Corex furnace, in particular, has brought what was in effect a gas generating process back into the flock of ironmaking processes at the honorable level of 1,934 kg CO₂/tIs. The CCF process, which is still pre-emergent, lies at a high 2,361 kg C due to its lack of sophistication at making use of carbon compared to the 100-year old blast furnace technology. SR does not provide original answers to the problem of CO₂ emissions.

The EAF's that make use of large amounts of virgin iron units arrive at the levels of 872, 907 and 829 kg CO₂/tIs respectively for the DRI EAF (650 kg of DRI /tIs), the hot metal EAF in a Redsmelt scheme (250 kg of hot metal /tIs) and the hot metal EAF fed by a blast furnace (244 kg of hot metal /tIs). The DRI furnace is comparatively the least carbon-intensive, because the prerduced iron is produced from natural gas in a Midrex unit, where carbon is partially replaced by hydrogen as a reducing agent. The blast furnace vs. Redsmelt Derby seems to come out in favor of the blast furnace, but, here again, we are comparing an established technology with an emerging one and the conclusion ought to be put on hold for a while.

2.3. Provisory conclusions

In conclusion, the Steel Industry has one strong control parameter at its disposal today, which is recycling, i.e. scrap utilization. Electricity can also replace carbon as an energy source, but this is a weaker control parameter in two aspects: the energy role of carbon is much less than its chemical reducing role and carbon energy yield is better in Steel producing reactors than in an electrical power plant. Of course, carbon-free electricity is always good to have. Once the process is chosen, there is little leeway for adjusting carbon emissions, which only demonstrates that the processes have been brought to a high level of efficiency already. The highest

potential lies with the recycling of off-gas in the blast furnace and the utilization of natural gas as a reducing agent in a prereduction process .

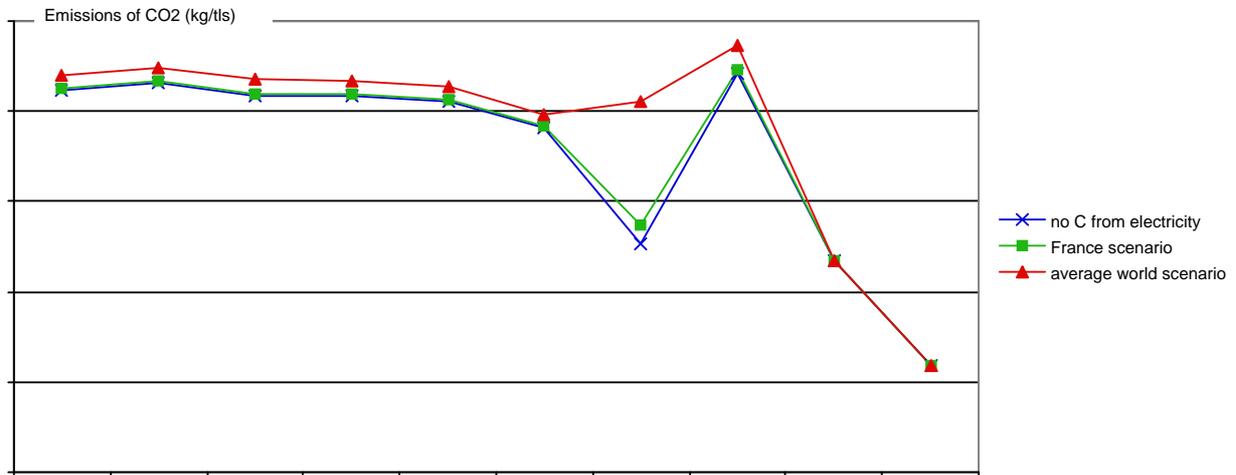


Figure 3: simulation of CO₂ emissions per ton of liquid steel of various model Steel Mills

2. THE STEEL INDUSTRY HAS BEEN REDUCING ITS CO₂ EMISSIONS SINCE THE FIRST ENERGY CRISIS

Energy conservation has been a strong driver of cost reduction in the Steel industry since before the first Energy Crisis. In the case of the French Steel Industry, energy intensity has been divided by 1.9 over the last 40 years.

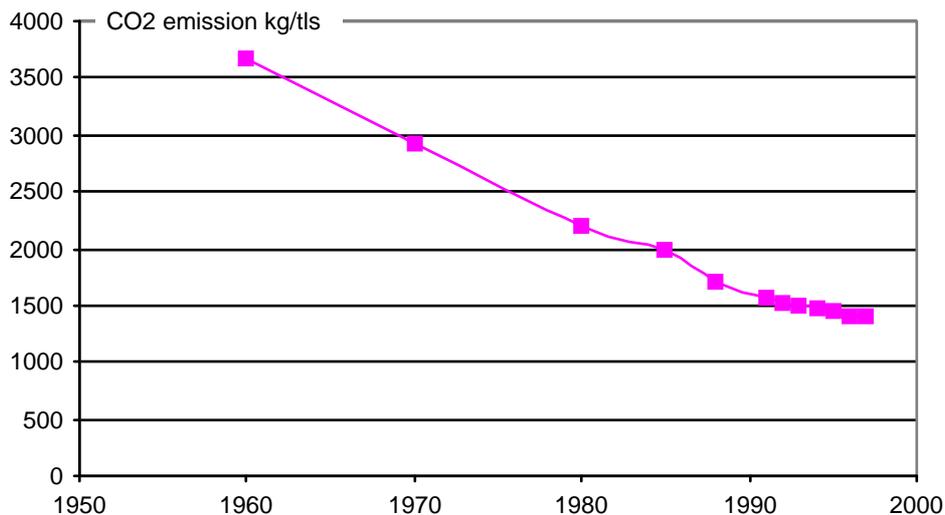


Figure 4: evolution of CO₂ emissions in the French Steel Industry over the last 40 years

This has resulted in a parallel decrease in carbon intensity, which is shown in Figure 6. The effect, however, is even stronger, with a drop by a factor of 2.6 over the same period of time. This excellent performance explains why the potential for further decrease is rather limited, as was pointed out in the previous section.

This situation is representative of the Steel industry of most modern countries, but not of that of less favored world regions, like Eastern Europe or the former USSR, where much of this progress remains to be carried out.

3. A PERSPECTIVE ON FUTURE DEVELOPMENTS IN THE STEEL INDUSTRY

A candid presentation of what leeway the Steel Industry has available in terms of managing its CO₂ emissions has been given in section 2. Since Global Warming is a long term phenomenon, it might be tempting to look also at technologies which are still immature - with the implied rationale that they could be developed in the meantime, a scientific presupposition that may be inconsistent with the whole issue!

3.1. Carbon-free energy

The quest for carbon-free energy duplicates that of **renewable energies** and plays with the myth of **free energy**.

The French language has poetic words to talk about renewable energies: **houille³ blanche⁴**, **houille rouge⁵**, **houille bleue⁶**, **houille d'or⁷**. Except for hydroelectric power, which is close to saturation, all of these, complemented by **wind and biomass power**, are developing at their own pace, but are still far from replacing fossil fuel or nuclear energy at a significant level. Cost remains a major limiting factor: wind power has been brought down to 4-6 US¢/kWh, but solar energy is still 17¢/kWh for photovoltaic and 8-13 ¢/kWh for thermal solutions, with biomass electricity at 6¢/kWh (classical electricity cost varies from 1.5 to 4 ¢/kWh).

The issue of the storage of nuclear waste has brought **fission nuclear power** to a standstill. **Fusion power** is locked in a permanent 50 year future and the recent uncertainties about the ITER project do not augur well of its future. **Orbital solar power plants** that would beam down energy in microwave form still belong to science fiction-like technology, almost at the same level as the Dyson spheres!

A public and worldwide debate on renewable and nuclear energies has still to be conducted before any clear picture of their future can be outlined and policies for energy intensive industries derived from it.

3.2. Carbon-free reducing agents

Natural gas is the only alternative to carbon as a reducing agent that has any realistic existence today. It has been used in the most common prereluction processes.

³ *houille* is an old word for coal

⁴ *houille blanche*, literally white coal, is hydroelectric power

⁵ *houille rouge*, or red coal, is geothermal power

⁶ *houille bleue*, or blue coal, is tidal power

⁷ *houille d'or*, or golden coal, is solar energy

Hydrogen would have interesting advantages, but it is not available as a raw material today. It can be produced from natural gas (NG), for example by reforming, but as such it is not different from NG, as it is "hidden" in the process of the user. This is already the case in the Circored or in the Iron Carbide processes in the Steel Industry. Hydrogen can also be produced by electrolysis of sea water, and as such is actually an energy vector substituting for nuclear power or renewable energies, which cannot be stored as electricity. Its future is entirely linked to that of these new energies.

One may recall that **hydrogen-based prereduction** was developed [7] 40 years ago at the scale of a credible pilot plant that carried out the reduction of fine ores in a fluidized bed. The H-Iron process never became commercial due to the absence of large quantities of cheap hydrogen on the market.

Electrolysis is widely used in the metal industry to produce aluminum, copper or zinc. It is in effect using electrons to reduce metal cations into the zero valence element. Although not used in the Steel Industry, electrolysis could in principle be applied in different ways to Steel production:

- 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 at CRM under the name of Electrofoil process, with an output of 4.5 t/h and a drawing speed of 31 m/min for the 0.15 mm thickness [8]. The solution was either replenished with scrap or with sulphide ore.
- a soda solution, where iron ore pulp was dispersed, was also experimented upon at IRSID [9]. 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, cast, rolled and finished..
- iron ore can also be dissolved into liquid salts (e.g. $\text{Na}_2\text{CO}_3 + \text{B}_2\text{O}_3$) 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 aluminum production. These routes have been studied at MIT [10].

The energy requirements for the first process was 6 400 kWh/t or 23 GJ/t (electrolysis + annealing), while the second one used up 3800 kWh/t or 13.7 GJ/t., for the electrolysis and 1300 kWh/t or 4.7 GJ/t for the subsequent production. Electrolysis, which leads directly to final products, is to be compared to a whole conventional mill, which has an energy consumption of 15 to 20 GJ/tls, a similar order of magnitude. The technology might be attractive in terms of CO emissions, if the carbon content of electricity is sufficiently low. Electrolysis, however, needs to be better understood, before its significance for the future can be assessed.

Biological treatment of ores by bacteria is practiced in the precious metals industries, but not in the Steel Industry. Bacteria that transform Fe^{+++} into Fe^{++} have been identified [11], but none are known today that would completely reduce Fe cations into metallic Fe.

3.3. Carbon dioxide sequestration

A potentially attractive solution for carbon-intensive activities is CO_2 sequestration. It can be carried out, in principle, in a variety of ways, although all remain speculative, as no large scale experienced has been acquired yet. Chemical, physical or biological sequestration has been proposed [12].

Chemical sequestration consists in storing CO₂ as a chemical compound. This can be done, for example, by adding a -C-O-O- chain in an amine molecule (MEA, MDEA or AMP). Industrial systems exist at the scale of several hundreds of tons of CO₂ per day, which is an order of magnitude less than what would be needed for treating the emission of one blast furnace. The cost is estimated at 40 US\$/t of CO₂.

Physical sequestration means either trapping CO₂ in underground reservoirs, such as aquifers or empty gas or oil deposits, or injecting it to the bottom of oceans, where the pressure beyond a depth of 500 m liquefies CO₂⁸. The storage capacity available worldwide is estimated at 63 Gt of CO₂, or roughly 10 % of the anthropogenic emissions per year. A technology for injecting CO₂ into oil reservoir already exists, as it is being used by the oil industry to improve the recovery of oil. Sea sequestration has in principle a potential several orders of magnitude larger than underground reservoirs and is expected to be effective for at least one century. The Norwegian power industry has shown that one third of the power of a fossil fuel power plant would be used up by the injection [13].

Biological sequestration means that C or CO₂ are accumulated in living organisms, the energy necessary for the process being derived from solar energy by natural photosynthesis. It is interesting to recall that the reduction in CO₂ levels of the primordial atmosphere of the Cambrian and Carboniferous eras was carried out by blue algae and gigantic trees by applying just these methods and that this had led to the thriving of life as we know it today...

The compensation of emissions by planting trees has been put forward as a realistic solution for carrying out biological sequestration [14]. This requires that the wood itself be sequestered after the death of the tree. Furthermore, the area necessary to absorb the emission of one blast furnace has the size of a French *département*. Car companies such as Toyota [15] or Peugeot [16] have started actually planting trees, probably as token of their concern over the issue, since 10 million trees fall far short of what would be necessary to absorb the emissions of the cars they manufacture.

The concept of using the wood to make iron in a charcoal blast furnace is presently being applied in Brazil, with the provision of husbanding fast growing species to provide the necessary wood in a self sustaining manner [17]. Microalgae bred in biological reactors exhibit a more efficient photosynthesis than trees and experiments have been carried out in France and in Japan to produce rare pharmaceutical molecules [18]. The size of the reactor that could serve one blast furnace is however prohibitive.

Sequestration of CO₂ by living animals such as corals, which would produce carbonates from solar power, is another possibility, put forward by utopist architects and biologists [19]. They would use the material as building blocks for artificial islands. An experiment is in progress.

All of these concepts are studied in details by the power industry and can also provide a solution for the production of Steel from virgin iron. This would be a long term endeavor, as a complex technology would have to be designed to concentrate CO₂ on the basis of membrane solutions or on special thermodynamic cycles, which would avoid the dilution of CO₂ by nitrogen from the air and thus make separation easier (IGCC⁹). **Anyway, the solutions outlined here need to be explored further by the Steel Industry.**

⁸ CO₂ would then either accumulate at the bottom of the ocean, or sink further down and then dissolve into sea water, or form hydrates known as clathrates.

⁹ Integrated Gasification Combined Cycle

4. THE ISSUE OF CARBON CONSUMPTION SHOULD NOT BE VIEWED FROM THE NARROW STANDPOINT OF MATERIALS PRODUCTION

The real societal issue in the present matter is **to minimize the emissions of CO₂ for performing some global functions**, such as transportation, food production, housing, etc. Each of these functions will lead to emissions, part of which stem from the materials used to accomplish them. This materials part of the emission is only of interest within the framework of the comparison between competing solutions. For example, if a tool made of steel necessitates 4 times as much carbon to make as one made of wood, it will still be more carbon efficient than wood whenever its time of utilization becomes 4 times longer than that of wood.

This type of analysis, where various kinds of material or energy "consumption" have to be evaluated with regards to the accomplishment of one practical function, is carried out under the name of **Life Cycle Analysis (LCA)**. One can do an LCA on a food can, or on an automobile and in the process compare two different materials. On the other hand, it would be meaningless to do an LCA on Steel and one on Plastics and to compare them directly. The methodology of LCAs has been embodied in an ISO standard [20]. But the methodology is complex and several more years will come to pass, while the data necessary are carefully collected to feed the databank that is needed to analysis the main goods of modern life in terms of LCA.

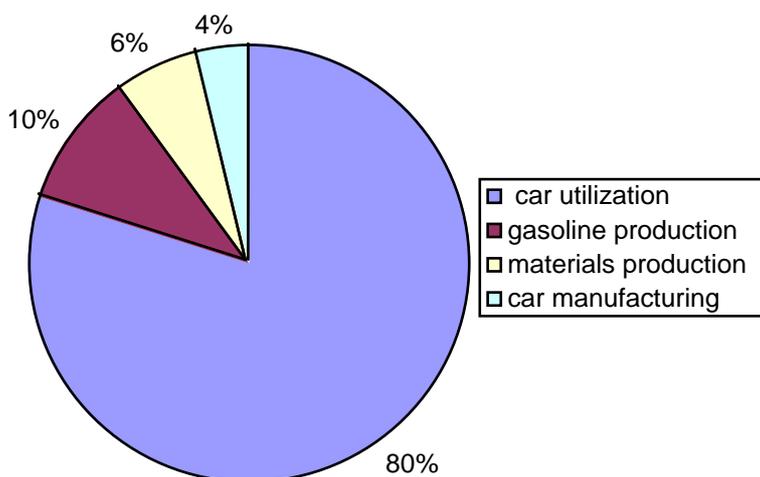


Figure 5: LCA of a passenger car: energy consumption for 10 years of utilization

An example can help stress the point. Figure 5 shows the results of an LCA type of analysis carried out on a passenger car, that has covered 150 000 km in 10 years, with a gasoline consumption of 8l/100 km (MVEG-A cycle). It gives the total energy necessary for producing the car and its fuel and for using it for 10 years, which altogether amounts to 540 GJ. The materials part of this energy consumption, all materials put together, is 32 GJ, i.e. 6 % of the total. The act of transportation itself is responsible for 80 % of the CO₂ emissions, which means that the influence of materials on fuel efficiency will be much more important than the direct emissions due to their own manufacturing.

The **ULSAB¹⁰ project** [21] has produced relevant information on the issue, by showing that a weight reduction of 20 % as compared to current industry standards could be brought about by making a more sophisticated use of the variety of available steels. A 25% reduction on the

¹⁰ Ultra-Light Steel Automotive Body

271 kg body-in-white of a 900 kg car would thus mean a reduction of 5 to 11 g of CO₂ emission per kilometer. This would help meet the voluntary commitment of 140 g of CO₂ per kilometer signed by European Automotive Manufacturers for all cars by 2008.

Reducing emission due to transportation is obviously not only a matter of materials optimization or of engineering design. Societal, cultural and political issues are also essential: for example stressing public transportation instead of individual transportation or fostering the use of bicycles in cities would have consequences on emissions reaching far beyond the reach of solutions proposed by engineers.

5. RECYCLING IS PROBABLY THE MOST POWERFUL METHOD FOR REDUCING CO₂ EMISSIONS IN THE WHOLE MATERIALS COMMUNITY

Recycling is a more powerful tool for reducing the CO₂ emissions caused by materials production than is commonly recognized.

In the case of Steel, recycling means using an EAF-based manufacturing route rather than an integrated route. This amounts to a reduction in CO₂ emissions of 556 - 2198 = - 1642 kg CO₂/t of Steel, when 1 ton of virgin iron is replaced by 1 ton of Steel produced from scrap. These are average conservative figures based on good practices for both routes actually experienced today.

Now, in a sustainable economy recycling should itself be sustainable, which means that it should be able to take place any number of times, without any limitations on the number of recycling cycles. We have already shown elsewhere that such an ambition is not idealistic, at least for Steel. This requires:

- that the scrap recycling industries keep the pollution from certain non-ferrous metals (Cu, Sn, Mo, Cr & Ni, mainly) within limits, such as the ones set by the European Scrap Grading System,
- and that the purity requirements on Steel grades expressed in materials specifications be maintained at the exact level required by the necessary usage properties, within any excess quality [22].

In such a situation, each extra recycling cycle brings about the same reduction in CO₂ emissions as the first cycle. This is cumulating indefinitely, as shown in Figure 6. The more sustainable recycling is, the more powerful it becomes at reducing CO₂ emissions. This is an important point that is still not properly taken into account in LCA studies.

Scrap generated from integrated mill Steel could therefore be attributed a credit in CO₂ emissions, all the bigger as the number of recycling cycles is large. In order to calculate such a credit, a slightly more elaborate model should be used. Figure 7 thus shows the reduction in CO₂ emissions that could be cumulatively attributed to 1 original ton of integrated Steel, when one takes into account a recycling rate necessarily smaller than 1¹¹ [23, 24]. Because the quantity of initial Steel actually recycled at each step decreases, the extra credit for each step

¹¹ the value of the recycling rate in developed countries is comprised between 0.7 and 0.85 [11]

The concept of recycling rate, which has also been called a recovery rate, is discussed in [23, 24]. It represents the proportion of scrap becoming available by the arrival of investment or consumer goods at the end of their life that are actually recovered *in the year of their generation*. It is a rather elaborate concept and, therefore, the corresponding index is only available from econometric simulations of the discarding of goods.

decreases and reaches an asymptotic value for the case of an infinite number of cycles. The asymptotic value depends on the recycling ratio: it is 3,827 kg CO₂/t Steel for a ratio of 0.70, 6,473 for 0.80 and 8,880 for 0.95. The value tends towards infinity, when the recycling ratio tends towards 1.

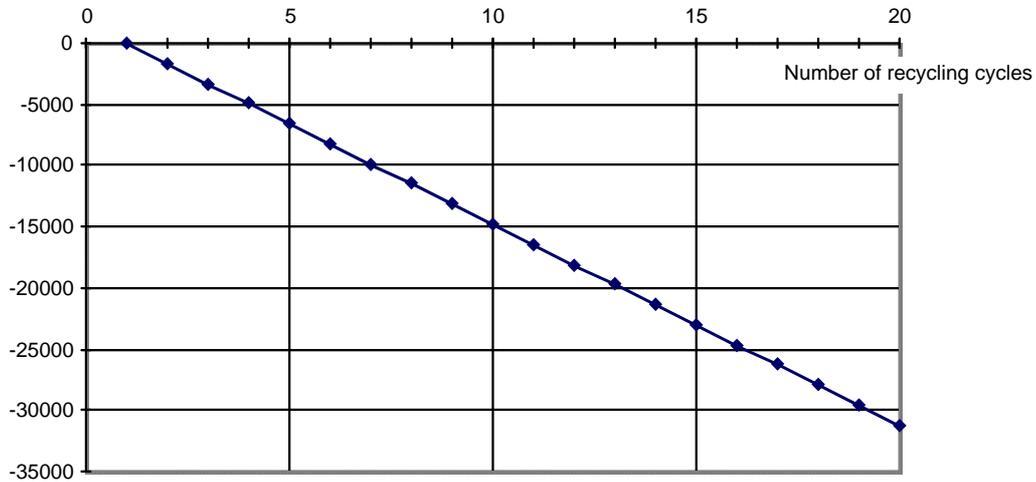


Figure 6: reduction in CO₂ emissions as a function of the number of recycling cycles (recycling rate = 1)

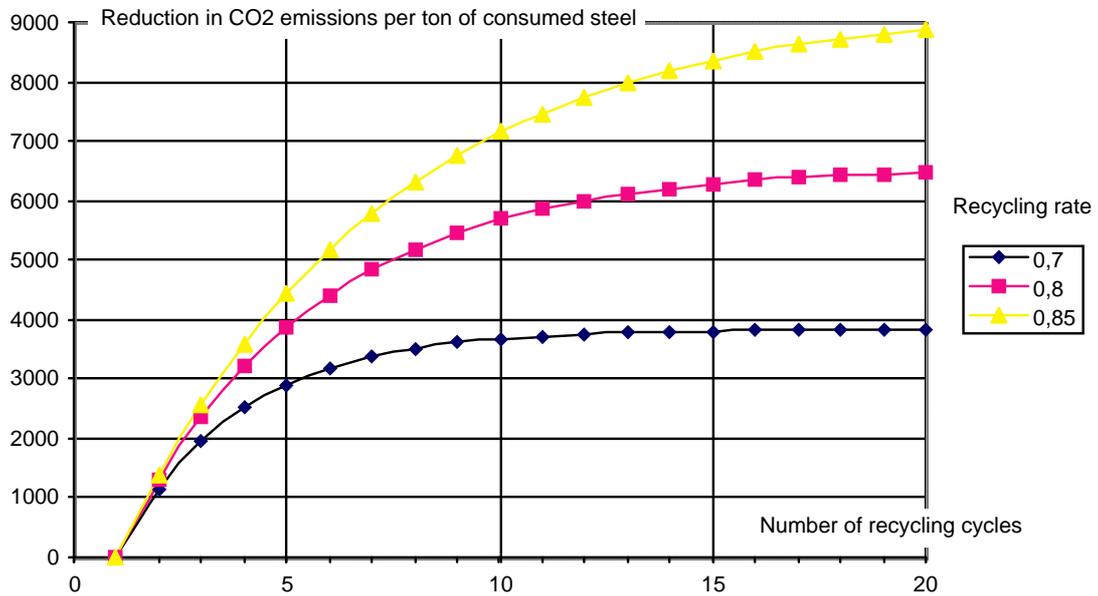


Figure 7: cumulated CO₂ emissions due to 1 ton of virgin steel vs. number of recycling cycles with the recycling rate as a parameter

The Steel Industry behaves as a true global system, where each type of mill plays a complementary role in the recycling business. **Integrated mills ensure the continuous creation of scrap, which would disappear if virgin material were not compensating for the losses in the**

recycling cycle - expressed by the recycling rate. The credit system would ensure that this symbiotic cooperation between integrated and electric mills be properly recognized.

The previous development was strongly aimed at showing the importance of recycling, i.e. of utilizing renewable scrap instead of non-renewable iron ore. A slightly different viewpoint is necessary to project a geopolitical image of a likely future in this matter.

Indeed, virgin iron cannot be replaced by recycled iron in any proportion for any period of time. This point has been made quite often by the supporters of the scrap rarefaction theory. Our argument here, however, is different: because scrap recovery necessarily lags behind steel production in a growing world economy, due to the time lag between first use and end of life and to the impossibility of recovering 100 % of used steel. The apparent recycling rate today is the ratio of scrap over Iron ore, which was equal to 40 % in 1997. Theoretically it might be brought up to the level of the present true recycling ratio estimated at 70 to 85 %: this is however too high a figure for a variety of reasons and most experts would agree that, for a foreseeable future, a 60 % ratio is more likely. In such a context, the production of CO₂ would decrease by 24 % from 1540 to 1210 kg of CO₂ per ton of liquid steel.

This analysis, which has been developed here for Steel, can be applied to the recycling of any material.

6. CONCLUSIONS

Global Warming results primarily from the growth of the world population and the improvement of its quality of life. For the first time maybe in human history, Man has a global influence on the physico-chemical balance of the whole ecosphere. The issues are complex and challenge the imagination of politicians, industrialists and citizens.

The main task facing policy makers is to find solutions that would improve and not worsen the situation. Curbing emissions while allowing the South to reach a higher standard of living is one aspect of this delicate balance. Sharing targets of emissions between industrial and social actors, in such a way that some global social function is optimized, is another difficult task, that may be fulfilled by the extension of LCA.

The Steel Industry best response to Global Warming is to provide society and its customers with products that are innovative and perform their function better, in terms of greenhouse gases emissions, of service and economical performance.

The Steel Industry should also set its house in order. It is not enough to recall that reductions in emissions have been accomplished for the last 40 years, under the strong competitive pressure to reduce cost and energy consumption. More progress is possible, through the extended use of scrap and the fostering of recycling, even though steel may rightly claim to be the most recycled material in the world. On the other hand, one should be conscious of the fact that recycling will also saturate at some point.

In the longer term, some original solutions might become attractive. However, much R&D will be needed, probably at an International level, to advance in these fields. Recycling the top gas of the blast furnace, electrolysis and carbon sequestration are the major open issues. Should cheap hydrogen somehow become available, it would also turn into a raw material of choice for the Steel Industry.

Last, one should be wary of solutions, which look too obvious. For example, it was shown earlier that carbon is better utilized in a blast furnace than in a power plant, a result that it per-

haps not completely obvious. There is, therefore, a trade-off to make between the Steel Industry and the power industry in this matter.

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Appendix 1: carbon and energy balance calculations for the reference Blast Furnace

Basic data : 103-kg pellets / thm - 103-kg pellets /-thm - 331-kg coke / thm - 153-kg coal / thm - PCI gas BF-3340 1357-kg sinter / thm - 0,248-kg C / m3 BF gas - (kJ/m3)- 1000-kg hot metal / t/s - 1486-m3 BF gas / thm - 50-kg lime / t t/s

SINTERPLANT	per t sinter	per t/s	C coefficient	kg C/t/s
coke	32,7	44,4 kg	0,8724	38,71
coal	13,7	18,6 kg	0,7943	14,77
coke oven gas	2,5	3,4 m3	0,230	0,78
CaO	127	172,3 kg	0,214	36,93
total input				91,19
total output	(fumes)			91,19
PELLET PLANT	per t pellets	per t/s	C coefficient	kg C/t/s
treated gas	876	90,2 MJ	0,0555	5,01
fumes				5,01
COKE OVENS	per t coke	per t/s	C coefficient	kg C/t/s
coal	1268,2	476,0 kg	0,7943	378,13
CKO preheating gas	8,1	3,0 m3	0,230	0,70
BF preheating gas	984,8	369,7 m3	0,248	91,68
light fuel oil	0,052	0,020 hl	262,000	5,11
total input				474,92
coke	1000	375,4 kg	0,8724	327,48
COK gas for sinter	11,3	4,2 m3	0,230	0,98
COK gas for BF	71,5	26,8 m3	0,230	6,17
COK gas for steelshop	5,8	2,2 m3	0,230	0,50
output COK gas	351,3	131,9 m3	0,230	30,33
tar	38,2	14,3 kg	0,913	13,09
fumes				97,49
total output				476,04
BLAST FURNACE	per t hot metal	per t/s	C coefficient	kg C/t/s
coal	153	153 kg	0,7943	121,53
coke	331	331 kg	0,8724	288,76
BF gas for hot stoves	515	515 m3	0,248	127,72
COK gas for hot stoves	23,4	23,4 m3	0,230	5,38
steelshop gas	50,0	50,0 m3	0,445	22,25
treated gas	5,31	5,31 kWh	0,184	0,98
heavy fuel oil	0,334	0,334 kg	3,169	1,06
total input				439,96
BF gas for COK		369,7 m3	0,248	91,68
output BF gas		601,3 m3	0,248	149,13
fumes				157,39
hot metal	1000	1000 kg	0,047	47,00
total output				445,20
LIME PLANT	per t lime	per t/s	C coefficient	kg C/t/s
castine	1786	89,3 kg	0,12	10,72
CO2	785,8	39,29 kg	0,273	10,72
BOF SHOP		per t/s	C coefficient	kg C/t/s
hot metal		1000 kg	0,047	47,00
COK gas		2,2 m3	0,230	0,50
total input				48,86
BOF gas before BF		50,0 m3	0,445	22,25
output BOF gas		50,6 m3	0,445	22,52
fumes				4,09
total output				48,86

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