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Global Technology Roadmap for CCS in Industry

Steel Sectoral Report

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Contribution to the UNIDO roadmap on CCS[1] - fifth draft

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Abstract

What is the status of CCS today in the Steel sector as a tool for mitigation CO_2 emissions? How mature is CCS as a solution against other approaches? What is the level of emissions to be handled, today and in the temporality of climate Change, i.e. 2050 at least? Are there gaps in the technology and barriers to its implementation in the sector? Does the level of development of a country have any incidence on the issue? These are the main questions tackled in this sectoral report for Steel.

Today, CCS has not quite reached the level of being a technology in the Steel sector, as it is still a concept that needs to be fleshed out and validated at a credible scale. Open questions are related to the kind of capture that can be applied in the sector as the players speak of CCS in roadmaps but are still working out how this general concept can be turned into a practical technology. The main trend is to develop a sector-specific concept called "in-process" capture that can be applied to the mainstream process routes (blast furnace or direct reduction, for example) with the expected benefit of improving energy needs and productivity of equipment compared to the benchmark best practice of today.

The first gap and barrier is therefore to make this technology available, which requires an enduring research and development effort, as a breakthrough technology has to be invented (the merger of iron making and capture technology referred to as in-process capture) – this calls for a careful scale-up through larger and larger scales, called laboratory, pilot and demonstrator: altogether, 10 to 20 years of development with a budget in excess of one billion Euros. Risks are technical but also financial due to the size of this budget. Until these steps are successfully concluded, the sector is reluctant to provide cost values for CCS as the estimates may be off scale by more than 100%. When and if the technology is successfully developed, its commercial deployment is also an issue as a CCS iron or steelmaking process technology is a regret solution, that can only be profitable if a value, probably quite high, is attached to carbon.

The key issue beyond fleshing out a successful technology that can be deployed is thus to provide financing solutions for the research and demonstrator step, for investments in the technology and for balancing its regret cost: this will probably end up being a mix of subsidies and mechanisms for setting up a carbon price that is fair enough to avoid massive rebound effects.

Another major barrier in the Steel sector is related to storage, which requires large reservoirs (10 to 20 Mt/yr) available for long periods of time (50 years or more). The uncertainty related to the existence of such reservoirs is very high, due to contradictory statements between theoretical ("1000 years of storage is available" [1]) and applied geologists, who find fragmented storage sites, the closure, permeability and injectability of which needs in situ measurements. The social status of storage is also an open question in terms of acceptance by local populations, which translates into long delays for obtaining the various permits needed for practically implementing CCS.

[1] Prepared for the UNIDO Global Technology Roadmap for CCS in Industry - Sectoral Experts Meeting, in Amsterdam, 24 September 2010

Still another barrier is related to legislation and regulation regarding CCS. Europe may be rather advanced in the area at EU level, but this is not the case everywhere the world. Due to the scale and to the temporality of implementation CCS, this is a major matter.

In the Steel sector, major R&D programs are under way in the world to develop the sector-specific technologies that are needed. The ULCOS program, in the EU, supported globally by the Steel sector there, is the most advanced one of them. It has come up with a series of carbon-lean, breakthrough iron and steelmaking process routes, based on CCS for 3 of them but offering a broader range of solutions based on the direct use of electricity, of hydrogen or of biomass (mainly sustainable charcoal). This is unique compared to other industrial sectors, which are still at the level of declaratory roadmaps and of a concept-level definition of CCS.

This may be why the Steel sector can demonstration rather impressive progress on the road to carbon-lean technologies and CCS in particular, while, at the same time, conduct a detailed criticism of CCS and lay down a long list of barriers and risks, which stems from practical experience in the sector.

If all technical, financial and cost barriers are overcome, then CCS could be deployed from 2020 to 2050 through the Steel sector, worldwide. If they are not, a number of scenarios are possible: either CCS cannot be applied and the production of carbon-lean steel becomes problematic; or the change of technology may induce massive relocations of the steel industry, if geopolitical gradients in the value of carbon are observed, what is sometimes called carbon leakage.

In terms of sector-specific figures, the stakes are a generation of 2.3 Gt/yr of CO_2 *today (scope I + II) and either 2.6 or 0.58 Gt/yr in 2050, depending on the kind of scenario that is implemented by then. The reduction would be due in part to the use of CCS, probably to a large extent in 2050 and a lesser one later, when post-carbon technologies come on stream.*

These figures are scope I and II. They fail to capture the value chain in which a material like steel is embedded: thus avoided emissions due to the use of steel are not included. They are certainly of a different nature, more scenario-based that physical, but they reflect an important contribution of steel to society [2].

The challenge for the whole roadmap is to patch together sectoral views built with different perspectives, i.e. normative views developed without regard to what can practically be done in a limited period of time, lobbying statements ranging from negative to overly positive ones, and practical results available from on-going research, development and experience that are often pioneering. Figures of production and emissions are uncertain and fuzzy, and what they will be in 2050 is even more uncertain. This uncertainty about data is the main issue that a roadmap should face: this includes data on the cost of CCS, which either do not exist or have been published without being acknowledged as realistic by the main stakeholders.

This does not deny the value of a roadmap, just calls on it to organize its argument in a slightly different way from what has mostly been done until now.

1. Introduction

In the scientific, political and societal context of Climate Change, the exercise of building a roadmap focused on CCS for industrial sectors and paying a particular attention to emerging and developing technologies is original and challenging. Indeed, very many roadmaps have been published and a non exhaustive list of recent ones is given in references [3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18, 19,20,21,22, 23,24,25,26,27,28,29,3031,32, 33,34], but they were addressing a more general context

What is particular to the industrial sector, and more particularly here, to the Steel sector as far as a CCS roadmap might be concerned?

The first obvious point is that CCS is not used today in the Steel sector by any of its players, an echo of the status of this "technology" in general, which can only exhibit a few demonstrators and a larger number of smaller-scale projects.

The second point is that giving to CCS the status of a technology is in itself controversial. Indeed, CCS is more often than not discussed in the context of energy generation based on fossil fuel, coal and oil mainly and to a lesser extend natural gas. There, experts have become familiar with the distinction between pre-, post-combustion and oxycombustion capture on the one hand and with EOR and geological storage on the other.

The Steel sector has been engaged in developing carbon-lean technologies, among which CCS plays a key role, and has published roadmaps of its own on the matter.

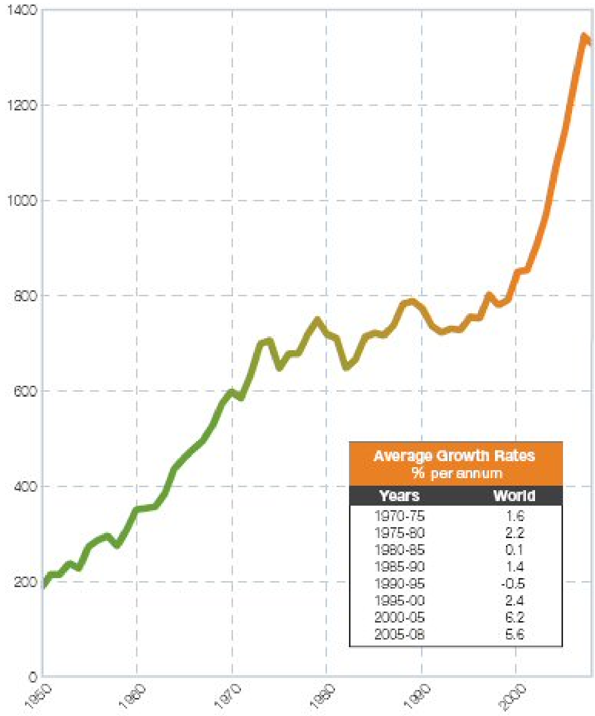
In this particular context, the challenge for a roadmap is to take on board the true circumstances that prevail today and are likely to prevail in the distant foresight horizon of 2050. This is far from simple and some general comments regarding existing roadmaps are made in appendix 1.

The status of CCS, as a solution to mitigating Climate Change, is also a broad matter of argument. One of them is the bridging status – or not – of the technology. We will discuss it later in this document, but our point is that CCS cannot be seen as a bridging technology for the Steel sector at any reasonable time horizon: it ought to be here to stay until the end of the century at least.

A further point is related to the public acceptance of CCS. Although this matter is presently very much debated based on risk analysis (based on fear, really!) rather than on any actual facts, it is probably an essential issue that needs to be addressed in any serious discussion of CCS applications.

2. Current and projected emissions

What is the amount of emissions in the sector at present and what are the projections (and assumptions for growth/decline) for the future? What are the most important regions and countries in terms of value added in the sector, currently and in the future, as well as for energy use and emissions?[2]



The Steel sector operates in a global, worldwide market (40% of production is traded internationally), the size of which has been recently affected by the economic crisis, but has been increasing sharply since the onset of this century due the growth of BRICS countries. It peaked in 2007 at 1.351 Gt/yr and dropped to 1.327 in 2008 and to 1.220 in 2009 (crude steel figures). The drop affected most countries in 2009, except China, the production of which amounted to 568 Mt in 2009, i.e. 46% of the world output, and thus has been the most important country in terms of production since the early 2000s; BRICS countries accounted for 53.3% of world production in 2009.

The largest operator in the sector is ArcelorMittal of Luxembourg, 73.2 Mt/yr in 2009 (peak at 116.4 Mt in 2007), which is twice larger than its followers, Hebei I&S, the Baosteel group and POSCO. Nippon Steel, which was #2 in 2008, is now #8 in 2009. The figures are from [35].

Note that steel is either mentioned as crude steel (i.e. liquid steel, an intermediate product in a steel mill, which is (almost) never sold on the market) or finished steel (rolled products sold on the market). The corresponding figures in 2008 were 1,327 and 1,198 Gt[3], i.e. a yield ratio of 90.3%. We will be using this figure in this report, even though it changes with time and the sophistication of the technology used for producing steel, but rather slowly.

Steel is produced mainly by two major routes (see also box p. 17):

- the Integrated Route based on Blast Furnace and BOF and using mainly iron ore as iron units and coal/coke as reducing agent/energy source and is therefore a primary, virgin iron route,
- and the Electric Arc Furnace (EAF) route, which uses scrap, i.e. recycled steel, as iron units and electricity (plus some coal and oxygen) as energy source and is therefore a secondary route.

According to worldsteel the proportion of each route [35,36] was at 70% and 30%, respectively, in 2007 and 2008. The amount of scrap consumed in 2008 was 475.5 Mt, which roughly checks with these route proportions.

Note that these 30% represent an average *recycled content* in the steel produced in the world, not a direct measure of the *recycling rate* of steel, which is estimated at 85%: the gap between the two figures is due to the fat that steel is maintained in use for a long period of time (between 15 and 20 years, on the average). Put differently, out of the 1,220 Mt of steel produced in 2009, at least 85% or 1,040 Mt will eventually be recycled when steel products reach the end of the use life[4]. Note, moreover, that recycling takes place over and over, actually indefinitely.

[2] The texts in italics at the beginning of each section are from the terms of reference for this work
[3] Gt: gigatons or billions of tons
[4] Assuming that the present recycling rate is maintained over a long period, which is a very likely assumption. In an LCA context, this would be considered as an LCA approach.

Integrated and electric routes do not cover the whole spectrum of steel production routes. There is a lively route based on the direct reduction of iron ore, most of which is based on the use of natural gas as a reducing agent, but some is still accomplished with coal, and the intermediate product, direct reduced iron, is melted in a EAF. It accounts for 4 to 5% of world production and is included in EAF production in worldsteel statistics. About 2% of the production is made by outdated processes, like the Open Hearth Furnace. Last, steel is produced in many shades while the discussion above has been centered on carbon steels: they are overwhelmingly the largest category in volume, but important alloyed steel, such as stainless steel ought also to be mentioned, because of their importance, technically and economically: alloyed steels have higher energy requirements and generate larger amounts of CO_2, in all 3 scopes.

Methodological issues

A layer of methodological issues needs to be addressed prior to reviewing figures and data. Many of them have already been outlined in a previous note [37].

Among the methodological issues that are not often discussed is the fact that CO_2 emissions are more or less always attributed to the smoke stacks which spout them into the atmosphere. This is however somehow arbitrary and very much related to the idea that emissions carry a responsibility, which is easy to put on the shoulders of the "emitter", in a kind of variant of the polluter-payer principle; it is also very similar to the value-added tax concept and to the *rucksack* approach to pollution issues. However, Aristotle has developed a theory of causes [38], 20 centuries ago, which takes on board the fact that a statue is as much the consequence of the decision of the city council to erect it, of the talent of the artist who has been chosen to carry out the assignment of making the statue, as it is of the "existence" of the god, that the piece of art depicts, or of the marble that it is made of, etc. (*material, formal, efficient and final causes*). In more economic terms, CO_2 is emitted at the end of an economic value chain, that extends from the coal mine or the oil field to the process industry or the car that oxidizes it: why tack the emissions to the last users of carbon rather than to anyone else in the value chain? If a different analysis than the prevailing one was carried out, then "responsibilities" would be shifted upstream of the value chain and, more importantly, a whole new world of solutions would open up, which are not necessarily taken on board today. For example, CO_2 burned in market economies could be collected and sent back to oil fields where they could be stored, etc [39].

Last, but not least, GHG comprise CO_2 as the major gas in terms of climate action, but also minor gases. CCS deals only with CO_2[5], which sounds like a *lapalissade*; however, issues due to CH_4 or N_2O are also paramount and one should keep in mind that CCS is not dealing with them at all. On the contrary, if CCS were to help solve the CO_2 problem in a big way, then the other gases would become more important and the issues they raise move to the forefront.

The present work is not different from previous ones in as far as it is not based on any new data. Its originality, if it shows any, rests on the critical analysis which accompanies the data used here.

CO_2 emissions

There is no comprehensive global registry of GHG or CO_2 emissions published anywhere for the Steel sector.

All figures found in the literature are therefore estimates or are proprietary data of steel companies. Some are actually rather phantasmagoric, as the footprint of the sector on anthropogenic emissions is quoted between 3 and 9%! Some sectoral organizations have published interesting analyses, though [40].

Various efforts are under way to collect a comprehensive set of emissions data for the Steel sector, but they are still in the making at worldsteel and the Asia Pacific Partnership. They have developed methodologies for collecting data in a coherent way. The effort needed to duplicate or replace these initiatives is out of scope of the present study. Anyway, the publication of the data is expected soon from worldsteel and the APP, most probably in 2010 [41,42].

[5] there is some academic work going on the co-storage of different gases, like CO_2 and SO_x. We are not aware of anything that could be applicable to the Steel sector yet.

An example of the data which have been published based on information from Eurofer is shown in Table 1 [40]; they relate to on-going discussions about the benchmark of the EU ETS. They show plant by plant emissions calculated from scope I specific emissions (i.e. emission factors), which, calculated back from these data amount to 1.25 $t_{CO2}/t_{crude\ steel}$ for the years 2005-2009. As a matter of fact, this back calculation constitutes a kind of tautological use of sparse data!

Table 1 – CO_2 emissions by plant in a steel mill

Activity	Production vol. EU27 (Mt)	Approx. specfic emissions (kg CO_2/t product)	Approx. GHG emissions (Mt of CO_2-eq.)	Share in total sector emissions (%)
Coke[1]	46	500	23	9.1
Sinter	128	250	32	12.7
Hot metal	113	1550	175	69.3
EAF steel	81	102	8.3	3.3
of which				
(EAF- non-alloy steel)	(73)	(100)	(7.3)	(2.9)
(EAF – high-alloy and other alloy steel)	(8)	(120)	(1.0)	(0.4)
Hot rolled steel	62[2]	100[3]	6.2	2.5
Processed steel	90	?	4.5	1.8
of which				
(Cold rolled steel)[4,5]	(50[3])	(50)	(2.5)	(1.0)
(Coated steel)[3,4]	(40)	(50)	(2)	(0.8)
Foundry products	4	400 – 600[6]	3-4	1.4
Total			**252.5**	**100.0**

Of course, there are national registries published regularly to comply with international commitments of individual countries, to the Kyoto protocol for example, but they do not provide the details needed to access Steel sectoral data [43,44].

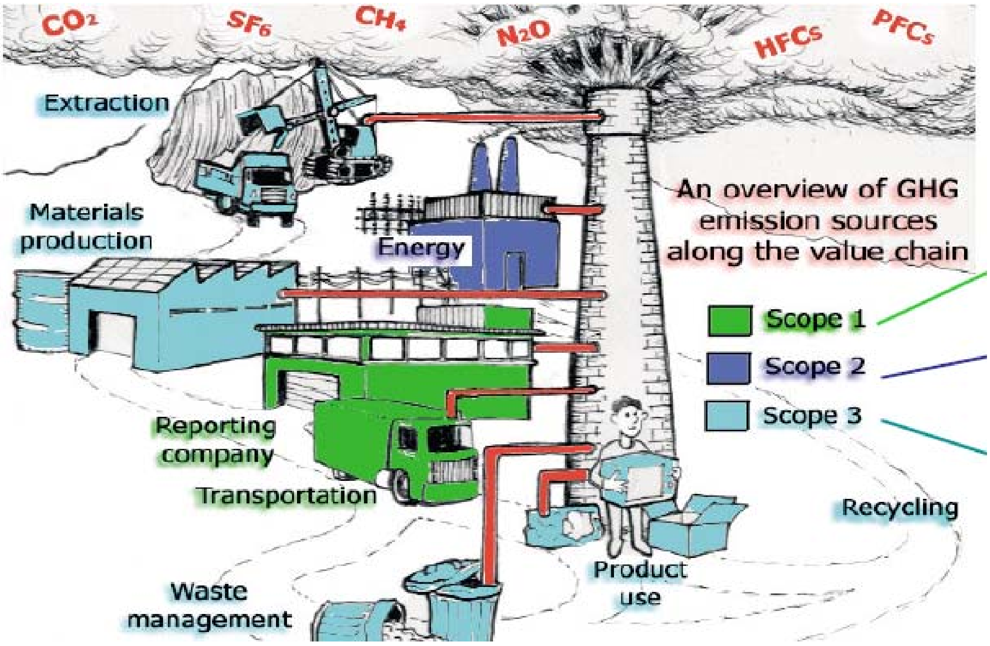


Figure 1 – definition of the boundaries of the systems defined around a plant by the Greenhouse Gas Protocol (scopes I, II and III)

Methodological issues ought now to be pointed out. Most of them relate to the boundaries of the system within which the CO_2 emissions are accounted.

The Greenhouse Gas Protocol [45] has carried out an analysis in terms of scopes, shown in Figure 1, that has become a standard [46] and can simply be referred to as direct emissions (scope I), emissions related to energy production (scope II) and upstream and downstream emissions, including credits for co/by-products, for example (scope III). Thus an LCA database will contain scope I + II + III emission data, while a registry for physical emissions from a production plant will contain scope I emissions; on the other hand, technologists interested in process engineering will be more interested in scope I + II data.

Another level of ambiguity is related to the kind of plants which are included in a steel mill, as some may have coke batteries or a lime kiln, or an oxygen plant, or a power plant to recover process gases and combust to generate electricity, and others not. There are no rules for these and therefore scope I data represent the actual direct emissions of the mills: it is hard to compare these individual data, unless the mill is fully described, but, on the other hand, this aggregation of emissions is representative of the emissions of a sector as a whole and they can readily be compared to other sectors, and the data aggregated with those of other sectors to build up a snapshot of world emissions.

Table 2 – examples of specific CO_2 emissions (emission factors) for steel production

source	Scope I	Scope II	Scope I+II
	$t_{CO2}/t_{crude\ steel}$		
Country A, global	1.67		
IPCC	1.9		
Country B	1.83	0.44	2.26
Source a Integrated route	2.0		
Source a EAF route	0.15		
Source a Steel sector	1.26		

Still another difficulty is related to specific emissions, i.e. emissions normalized by production volume. Usually, crude steel is used as the normalization factor, even though emissions for the whole steel mill are shown (thus emissions from gate to coil per ton of liquid steel).

Last, data may refer to a *sectoral average*, worldwide or regional, or to *best performers.* Some documents also refer to *Best Available Technologies* (BAT)[6], although there are difficulties in building coherent production routes based on BATs [37].

Raw data as published or communicated are shown in Table 2. The sources, most of them confidential, do not matter here. What is more important is that the data do not match, not necessarily because they are intrinsically different in terms of emission performance, but because they refer to systems which are most probably somewhat different, have slightly different boundaries and therefore cannot be readily compared with the information available. One major difficulty in a worldwide data collection exercise is that the data cannot be readily analyzed, and hence validated. In other words, for the purpose of our study here , they are not of much help.

To move forward and avoid the intricacies of actual data collection and of varying steel mill boundaries, we will provide emission factors based on estimates, but as much as possible on rigorous ones.

We will use the same methodology as in the ULCOS program, i.e. define a model steelmill, which includes coke ovens, adjusted to the capacity of the blast furnaces, a lime production kiln, an oxygen generation plant, a power plant to combust excess steelmill gases, etc. [see the details in reference 25 and Figure 5]: thus, scope I emissions also include emissions from these plants, as they are by definition an internal part of this model steelmill.

We will provide estimates of the emissions of a benchmark steel mill, both in its Integrated Mill and its EAF mill avatars, which will constitute a baseline against which future technologies can be benchmarked. However, estimates of present emissions will be made with some assumptions regarding the

[6] The EU publishes documents called BREFs (Best REFerences) which spell out in details what BATs are. http://eippcb.jrc.es/reference/

spread of emissions of actual steel mills, the world over. Because, this is a difficult exercise, in the absence of published detailed data, an uncertainty around these values will also be provided. Note that this is new, even if it seems like an obvious thing to do!

We will discuss scope I, II and III emissions. We should stress, though, that scope III emissions give a very special, Life Cycle centered, type of information, which is usually not reported by other sectors in the usual CO_2 accounting:

- the benchmark steelmill is an integrated steelmill (IM), which is a composite of best performers using a coherent set of plants from raw materials' gate to product's gate (hot rolled coils or bars, or others). Its scope I emissions are 1.81 t of CO_2 per ton of coil (not of crude steel); scope II, with a European electricity mix of 370 g of CO_2 per kWh, is 0.03 t_{CO2} and scopes I + II, add up to 1,84 – 1,66 t_{CO2}/t of crude steel.
- a benchmark steelmill based on an EAF, best performer level, has scope I emissions of 0.10 t/t of coil. Scope II emissions are 0.20 t, i.e. 0.30 in total – 0.27 t_{CO2}/t of crude steel.
- a world mix of 70/30% IM and EAF routes has an emission factor, scope I + II, of 1.38 t_{CO2} per ton of hot rolled product – 1,25 t_{CO2}/t of crude steel.
- estimating scope III emissions would require a detailed analysis, which is not readily available in the public domain and therefore would embody a consensus of the various stakeholders on the figures. The difficulty is related to the fact that scope III estimates are not exactly identical to a well defined part of an LCI[7] and that, moreover, LCA is a methodology defined by standards and not physics and therefore can be performed in umpteen different ways that yield very different values, adding another layer of fuzziness in the data [47]. An example of the LCI calculated for an actual steel mill is shown in Figure 2, Figure 3 and Figure 4 [48]: shown are emissions without any allocations, where scope I, II and III are more or less equivalent to the GHG definitions, then total emissions (scopes I to III) with allocations, which give credits for co-products, with some rather specific assumptions that are just given here for the benefit of showing a trend, and the last graph shows what allocations have been taken on board. Thus, depending on assumptions, scope III emissions *in this example* can range from 0,40 t_{CO2}/t_{HRC} to -0,41 t_{CO2}/t_{HRC}.

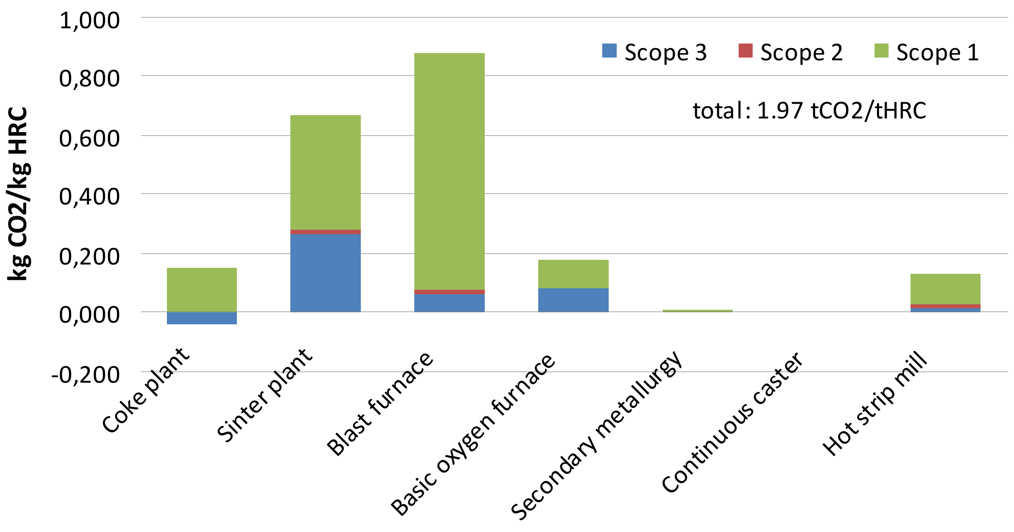


Figure 2 - LCI of an integrated steel mill, without any "allocation"

[7] Life Cycle Inventory

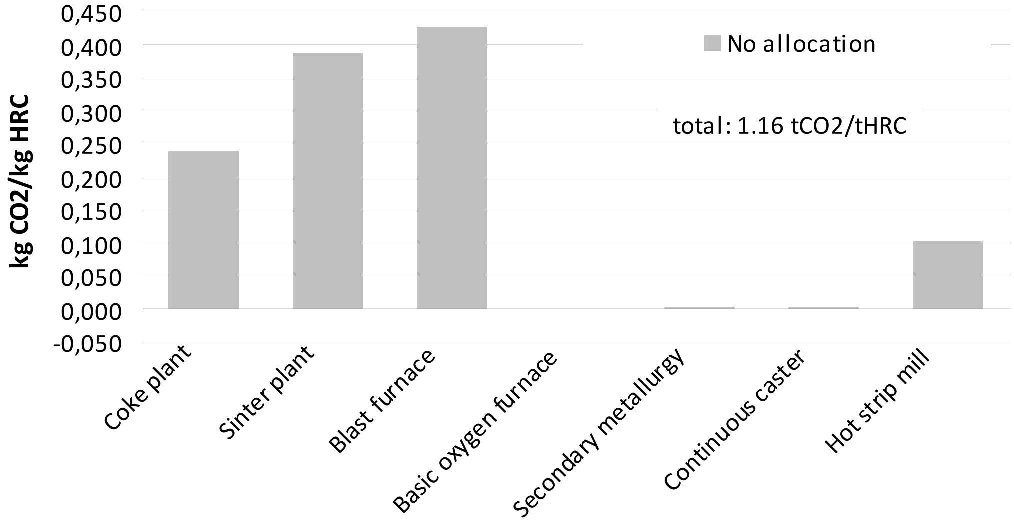


Figure 3 - LCI of the same integrated steel mill, with "allocations"

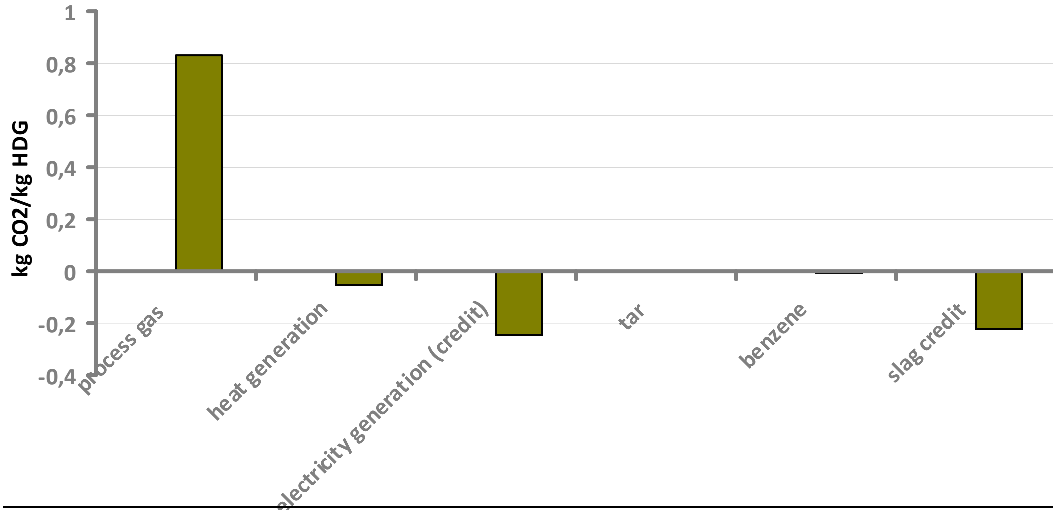


Figure 4 – amounts of allocations taken on board in the LCI for various co/by-products

- in order to use a figure for scope III, we arbitrarily estimated at 0.2 t for the integrated route and 0.1 t for the electric route, which bring IM, EM and world sector in scope III to 2.1, 0.4 and 2.0 t/t of coil.
- now, actual emissions are different from the ones of this model steel mill and, in Table 3, we have presented an estimate of best performers, worst performers[8] and average sectoral mills according to the typology presented before. The first column of data gives a scaling factor with respect to the Scope I+II emissions of the model steel mill. The second column gives the emission factor. This time the value are in emissions per ton of crude steel.
- the uncertainty of the values, given from "experience", is estimated at 20% in the 1st case and 30% in the second case, i.e. 2.3 ± 0,5 and 0,6 ± 0,2 t_{CO} /t of crude steel. The point about this uncertainty is not to stress that the emissions might be 25% higher than shown, but, rather, that they are rather uncertain.

[8] *Worst* is the contrary of *best*, not any kind of judgment on the quality of the operator

Table 3 – estimation of the uncertainty on scope I + II emissions due to the dispersion of level of CO_2 efficiency across the world

		scaling factor	$t_{CO2}/t_{crude\ steel}$
Inte-grated Mill	model mill	1,0	1,7
	best	1,0	1,6
	worst	3,0	5,0
	average	1,4	2,3
EAF C-Steels	model mill	1,0	0,3
	best	0,8	0,2
	worst	5,0	1,5
	average	1,9	0,6
sec-toral, world	model mill	1,0	1,3
	best	0,9	1,2
	worst	3,6	3,9
	average	1,6	1,8

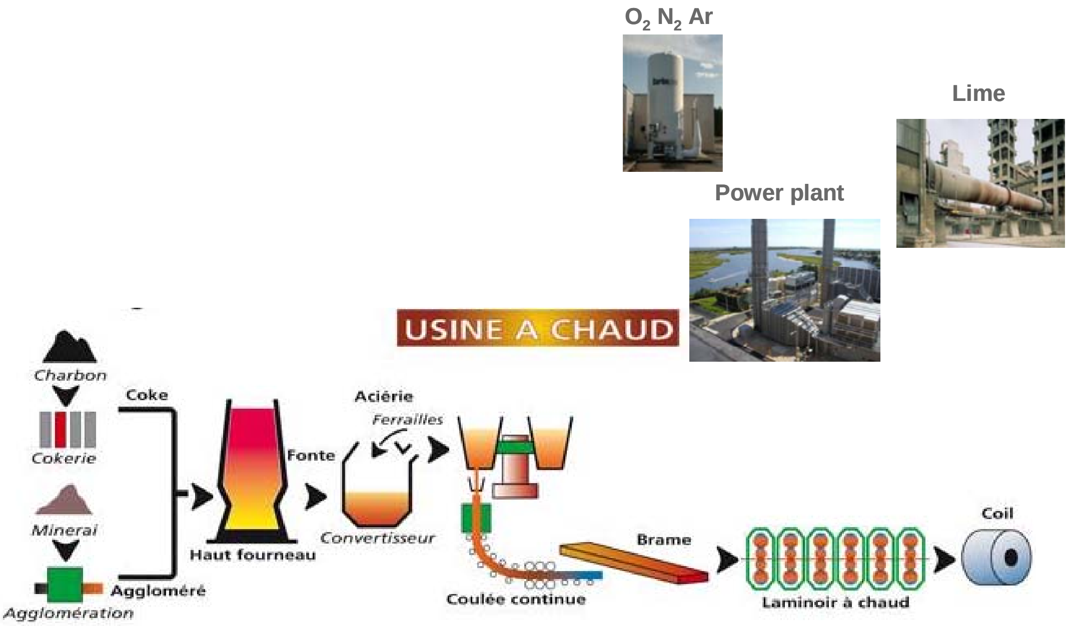


Figure 5 – schematics of the plants included in the model steel mill (oxygen, nitrogen and argon plant, lime kiln, power plant to combust process gases, coke ovens and sinter plant)

- total CO_2 generation can thus be estimated at 2.8 and 3.1 Gt in 2009 and 2007 with the same kind of uncertainty as above.

The reader will have noticed that one major reason, among many, for the discrepancy between scope I, scope II and real physical emissions is the fact that steel mills do not always include the same plants, foremost of which is the power plant, which, in regions like Europe or Japan, are systematically built to recover the energy of the process gases, not used inside the steel mill to reheat furnaces, ladles, etc., but may be part of the mill or constitute a separate activity contracted out to a utility company (cf. Figure 5). These details are business-based and not process-based and the aggregated emissions reflect this "biodiversity" of steel mills, not necessarily causes of emissions on which action can be taken to reduce them: divesting the power plant from the steel mill to a utility does not erase the corresponding emissions, it simply shifts them to a different business entity.

If this is taken on board, then average emissions can range from 1.3 to 2.3 $t_{CO2}/t_{crude\ steel}$ an even larger bracket than the one mentioned before as an uncertainty on the data. It is part of the fuzziness of the data that are circulated around and used by various stakeholders, as are the scope III estimates, which would compound this further.

Energy consumption

A detailed discussion on energy consumption, like the one conducted on CO_2 emissions, would be in order. The issue, however, is simpler as the ambiguities related to boundaries are not as large: indeed, while CO_2 is measured at the stack, thus at the exit of the industrial plants, energy is accounted at the gate, as an input.

According to the IEA, the steel industry's final energy use in 2005, for the world, was 560 Mtoe, or 21.3 GJ/t of crude steel [30, page 476], which represents a sectoral average.

The Integrated Model Steel Mill needs 18.5 GJ/t_{HRC}.

According to ESTEP and Eurofer [49], best performers in an integrated steel mill consume 17 GJ/t, 16 of which are related to coal and 0.9 GJ/t to electricity (250 kWh/t); in an EAF route, the best performers are at 3.5 GJ/t of hot rolled product, of which 1.6 GJ/t is related to electricity consumption in the EAF (450 kWh/t), 0.6 GJ/t of fossil energy (coal and natural gas) and 0.3 GJ/t (80 kWh/t) of energy for hot rolling plus 1 GJ/t natural gas for the reheating furnace. The sectoral EU 27 average for the EAF route is 4.5 GJ/t.

Mixing IM and EAF routes at world level, this means a best performer figure of 12.95 GJ/t, almost twice less than the IEA figure.

Thus the EAF, secondary route, uses about 20% of the energy of the integrated route.

Worst performers, according to the author's experience, are at the level of 50 GJ/t_{CS} and 30 GJ/t_{CS} for the IM and the EAF route; sectoral average are at 25 and 13 GJ/t_{CS}. The world sectoral average is thus at 21.4 GJ, almost exactly the IEA figure.

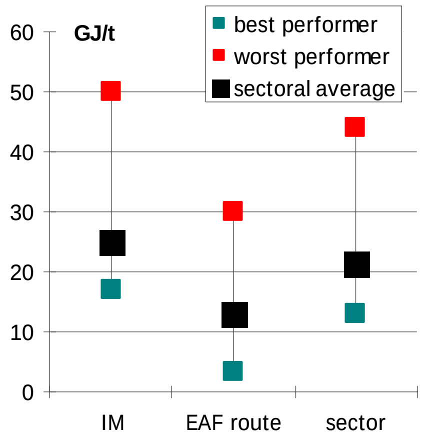


Figure 6 – energy data

Foresight projections

The previous sections dealt with present day emissions and energy needs of making steel. In the future, production amounts will increase and technology will change, marginally or drastically, depending on the level of carbon constraint that does materialize in the middle of the century.

Information is available from the literature regarding demand and production until 2050 of the main structural materials and of steel in particular.

The past level of production over the 20th century, which can serve as a background to analyze future projections, is shown in Figure 7 [50].

This present study is only focused on steel, but it is of interest to show all the structural materials together, as it gives information on the robustness of the projections, on the competition among these materials and on its evolution.[9]

[9] This is an important point, as far as the author of this memo is concerned: the value, or the credibility of foresight projections is related to the depth of their analysis. Comparing projections related to the major core struc-

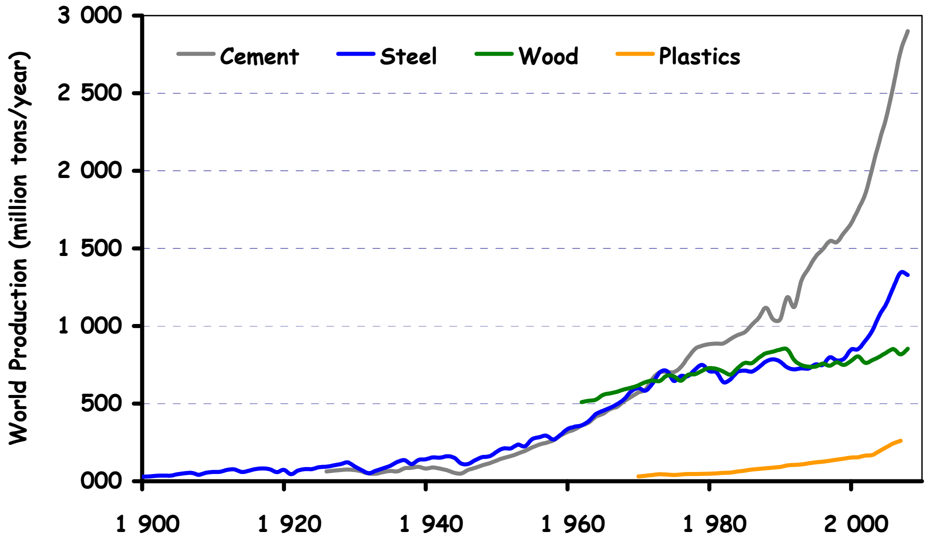


Figure 7 – evolution of the annual production of some structural material plus plastics over 100 years [50]

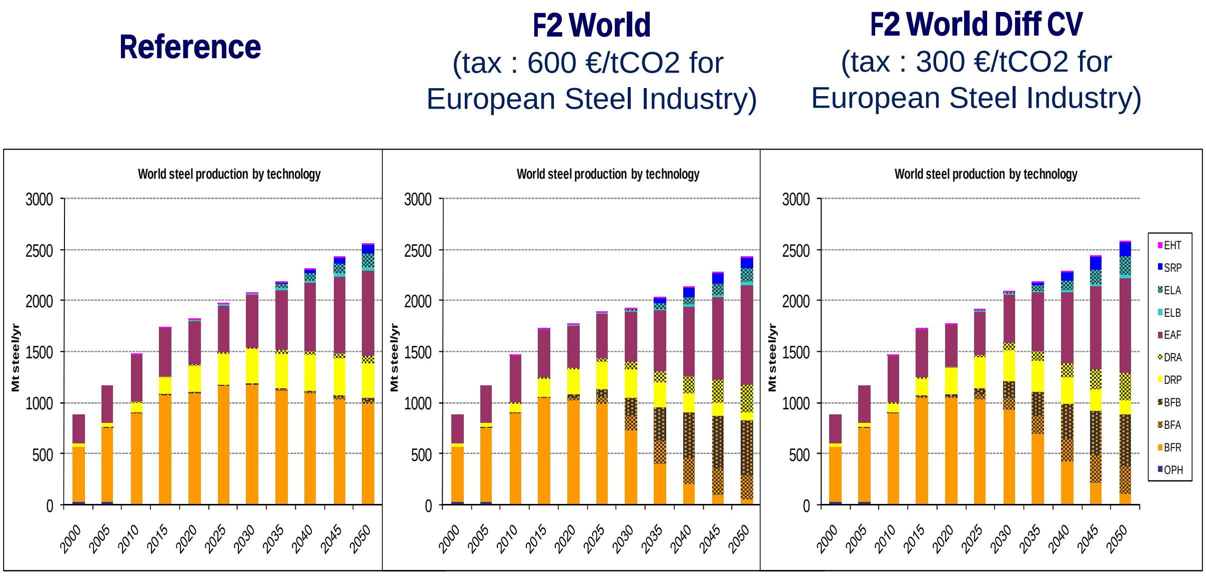


Figure 8 – evolution of steel production until 2050

The evolution until 2050 of the production of steel, cement, glass and aluminum, available from published foresight work with which we have been associated is shown in Figure 8 to Figure 12 [51], while the projections of the IEA are given in Figure 14 and Figure 15. The major materials in terms of volume, steel and cement, are covered in both sets of data, while others like wood, glass and aluminum are not. The time dependent projections for the future, shown in Figure *8,* which originate from LEPII, are shown according to various scenarios. As the long term (2050) would seem to be strongly determined by the strength of the carbon constraint, it is indeed the key parameter which was studied in the underlying studies. Reference scenarios are BAU kind of scenarios, while the F2 world and 450 scenarios are roughly identical, although not exactly formulated in the same way (F2 is a factor 2 scenario for the world and factor 4 for Europe, while 450 assumes a final level of CO_2 in the atmosphere of 450 ppm).

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tural materials and, as a matter of fact, reviewing a study that addresses them all at the same time, is a way to ensure the quality, depth and robustness of the data.

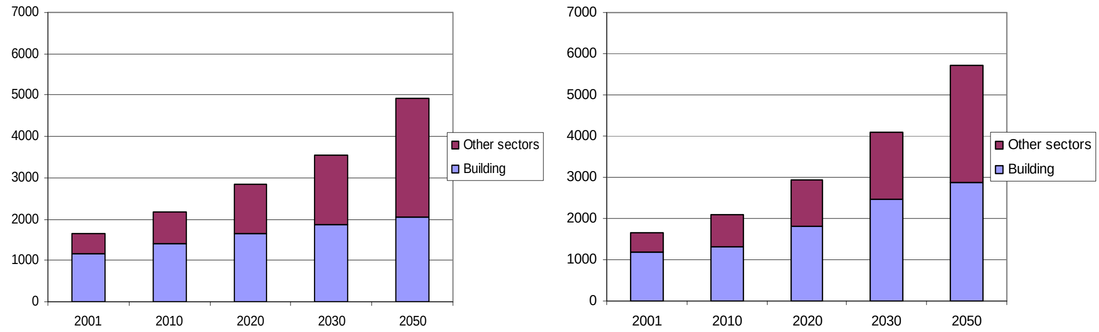


Figure 9 – evolution of cement production until 2050 (reference BAU and 450 scenarios). Production in kt/y.

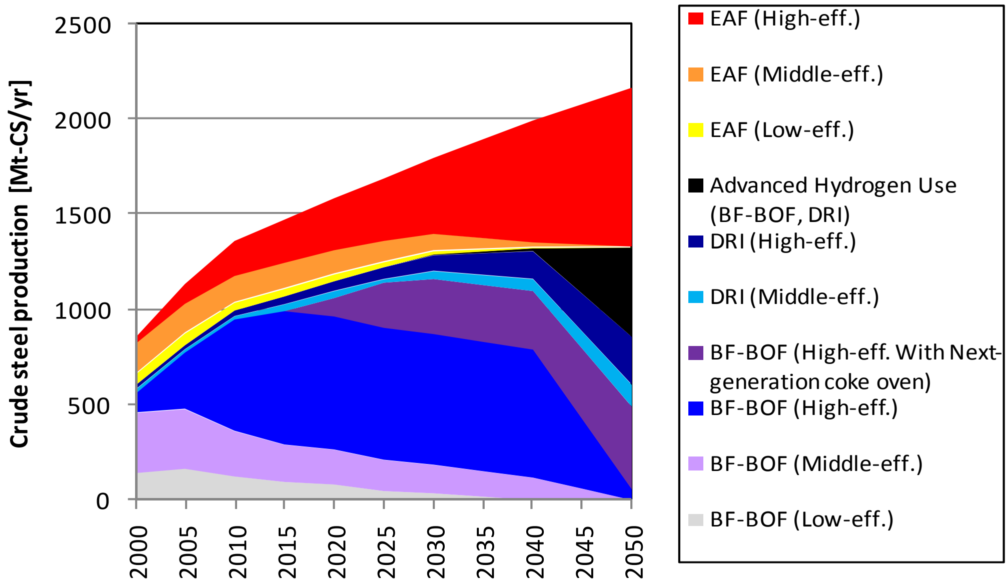


Figure 10 – World crude steel production projections (source: RITE)

Projections comparable in terms of volumes have been worked out by RITE in Japan [52] (cf. Figure 10) and worldsteel in Belgium [53], while lower estimates have been made, using different methodologies [54] (Figure 11); IEA projections are also somewhat different from LEPII's (cf. Figure 14).

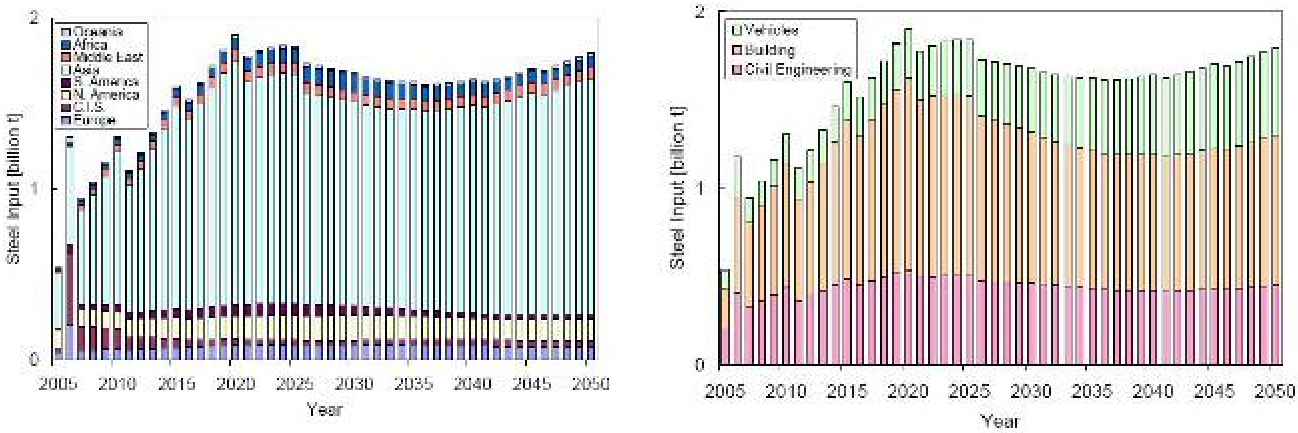


Figure 11 - Forecast of steel demand by 2050: (left) by region; (right) by end use (source: University of Tokyo)

Building and transport data are singled out in Figure 8 to Figure 12, where this reinforces the analysis. Figure *8*, on the other hand, singles out processes for making steel and introduces the portfolio of breakthrough technologies being developed by the ULCOS program [55]. Incidentally, this shows that some sectors have already developed an analysis to show how a decarbonization of their industry can take place to meet the kind of carbon-constrained scenario that are likely to be eventually adopted to fight Climate Change.

The 20th century past data show:

- a substantial increase in the production of all materials;
- a time kinetics that reflects history and economic history, as the wars, the great depression and the lesser ones are easily visible in the blimps of the curves;
- steel, cement and wood are running at the same level in terms of weight from the end of the 2nd world war until the 1st oil shock; plastics run parallel to them, with a historical start point in significant volumes at the beginning of the second half of the century;

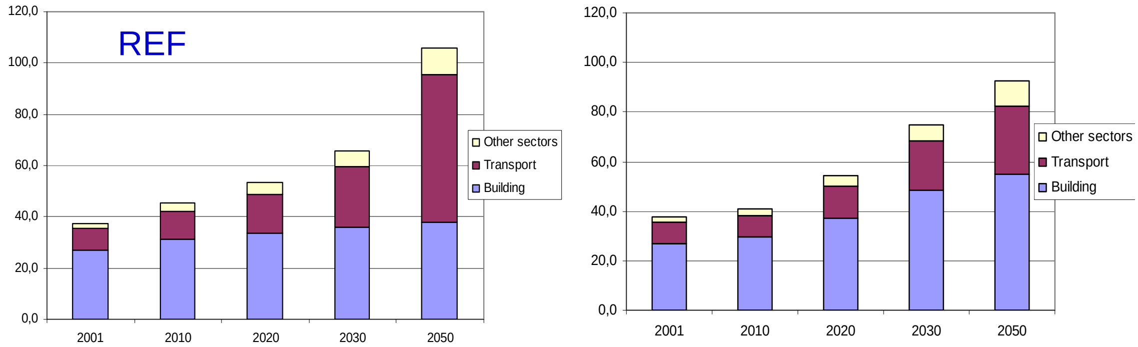


Figure 12– evolution of glass production until 2050 (reference BAU and 450 scenarios). Production in kt/y.

- then cement starts diverging: the other core materials slow down with the crisis of the 20 "piteous years" triggered by the so-called 1st oil crisis, while cement does not. It actually doubles its production compared to steel and wood during this period. This clearly means that while the former materials were connected to GDP evolution, the latter continued to increase in terms of intensity per unit of GDP. A clear analysis of why this was the case is lacking;
- finally, with the economic boom launched by China at the beginning of the 21st century and carried on by the other BRICS countries, an acceleration of growth takes place, which the 2008 crisis has slowed but not necessarily for a very long time, if present data are to be seen as a sustainable trend.

Figure 13– evolution of aluminum production until 2050 (reference BAU and 450 scenarios). Production in kt/y.

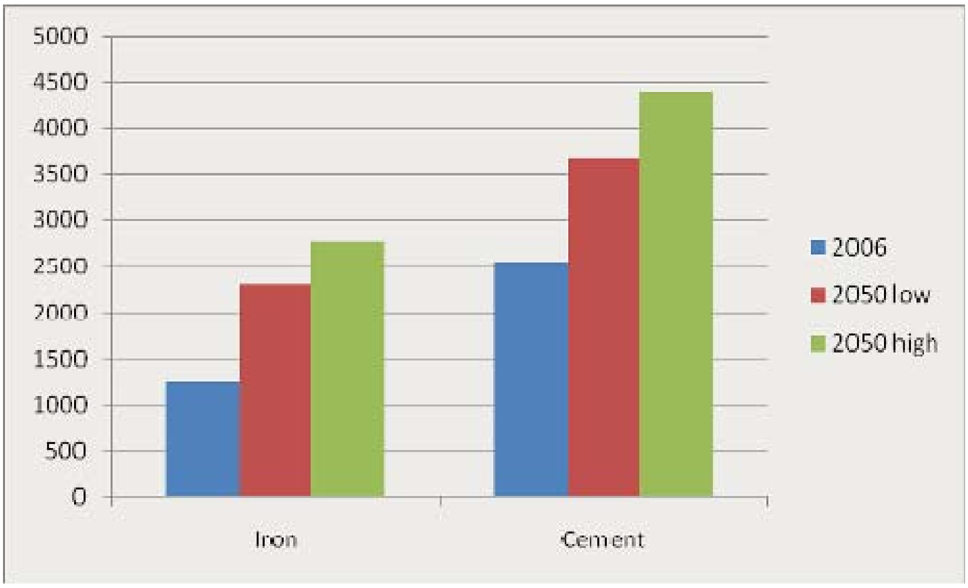


Figure 14– Production of steel and cement 2006 and 2050 according to IEA projections

The foresight data also exhibit some interesting features:

- the 2050 production of all materials shows a significant increase with respect to 2000, roughly a tripling in volumes (a 2.2% average growth rate along the period); this projects a strong increase in material intensity per capita, as the world population is to increase by roughly 30% "only" during the period. The intensity per unit of GNP exhibits an elasticity of roughly one with the increase in GDP.
- production level forecasts for 2050 are rather insensitive to the carbon constraint, like in the case of steel where slightly lower and slightly higher values are projected by 2 variants of an F2 scenarios: aluminum and glass projections are slightly lower (significantly?) and cement is slightly higher. Nothing like the uncoupling of cement from the other materials, shown in the historical data record, is exhibited here, which probably goes to say that the underlying behavior of the markets has not been modeled into the studies as the effect had probably not been identified by the researchers and is certainly not well understood.

Again, we have decided to show projections for the major structural materials together, not just those for steel, because they have been generated together by the researchers who have published them. The level of the estimates vary together, depending on their source and thus on the modeling methodology used to marshal the figures (e.g. a Markal model or the POLES model) and on the schematization of the long term scenarios under carbon constraints, etc.

Most of these models are technology optimistic and thus assume that the structural materials all have a key role to play, both to increase the world's standard of living and to solve the climate change challenge.

Moreover, quoting all the figures together shows which level of estimate for steel goes with which level of estimates for cement, for example.

Last, they also show that the competition among these materials is not going to be reshuffled dramatically, because of climate change, although this is a complex issue that would need more studies to be settled, beyond the kind of first order statement that the works quoted here make.

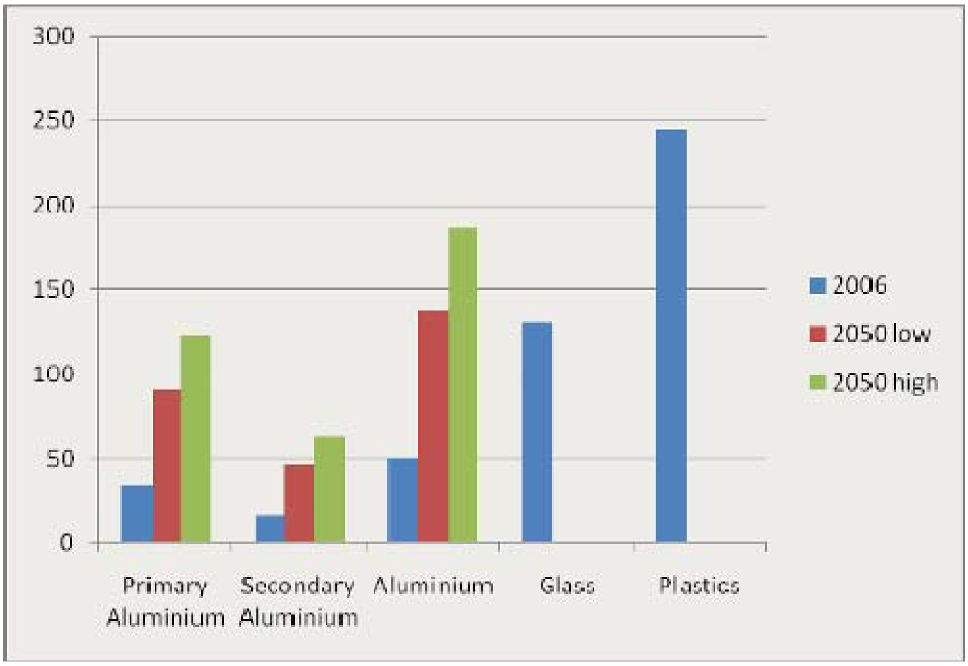


Figure 15 - Production of aluminum, glass and plastics 2050 according to IEA predictions.

Is it possible to go beyond these general and careful statements, for example by saying that the production of steel will double in 2050 compared to its present level of production? The various projections are compared in Table 4: they differ by almost 1 billion tons of steel and this figures is less than what would show if unpublished data had been taken on board. Clearly, foresight studies are not predictions and it is difficult and hazardous to take them out of the context for which they have been produced - what we have been doing to a limited extent here, though.

All these projections are based on rather different models originating from different schools of thought. POLES and Markal models, for example, are based on fairly different views of the way the economy works: refer to the original documents for an in-depth discussion of this point. One can't simply say that one is more or less true than the other, although one's school of thought would favor one over the other, POLES over Markal models for example in the case of the authors' preferences. What is interesting, for the kind of roadmap that UNIDO is planning to get at, is that in spite of their diversity they do project trends, which are coherent, if they are taken as trends, not as exact quantitative projections.

Table 4 – comparison between the projections for steel production in 2050

Source of estimates	**Annual production (Mt/yr)**	**comments**
ULCOS-LEPII	2,450 / 2,550	POLES estimates
RITE	2200	Markal model
Tokyo University	1800	MFA model
IEA Blue Maps (low/high)	2350 / 2700	

Thus a statement like: "in 2050, assuming that the economy continues on its present tack without a major paradigm shift such as negative growth, steel production will increase to a large extend compared to today, more or less doubling from the present level" can be made, with all the fuzziness of the words that have been carefully selected. That similar statements can be made for cement or aluminum or glass reinforces the statement for steel and puts it in the family of positive visions of the future.

How do these projections of production translate in terms of GHG projections?

LEPII and RITE projections are shown in Figure 16 and Figure 17. Whereas we could point out to similarity of the projections of both models, this is no longer true as far as CO2 emissions are concerned. LEPII's projections are scenario dependant, a fairly obvious consequence of the kind of modeling that have been performed (top down). Note that emissions peak in the reference scenario around 2030 and then decrease slightly, due to the market share that recycling and the EAF route grasps, as a mechanical consequence of the fact that past production generates scrap that is "integrally" recycled[10]. In the carbon constrained scenarios, CO_2 generation in 2050 drops, rather exactly by a factor 4 in the "F2 world" and by a factor 3 in the "F2 differentiated carbon value world". The differences may or may not be significant: the very least that can be concluded is that the *Differentiated Carbon Value* concept achieves a similar level of cuts as the usual *uniform Carbon Value* scheme. The results are due to the behavior of the overall economy, not just of the Steel sector, as shown in Figure 18: the two models at this global scale are also close in their prediction, but they also do not achieve exactly the same level of cuts, because the set of values selected for the DCV model have not been fine tuned in order to show this exact balanced outcome.

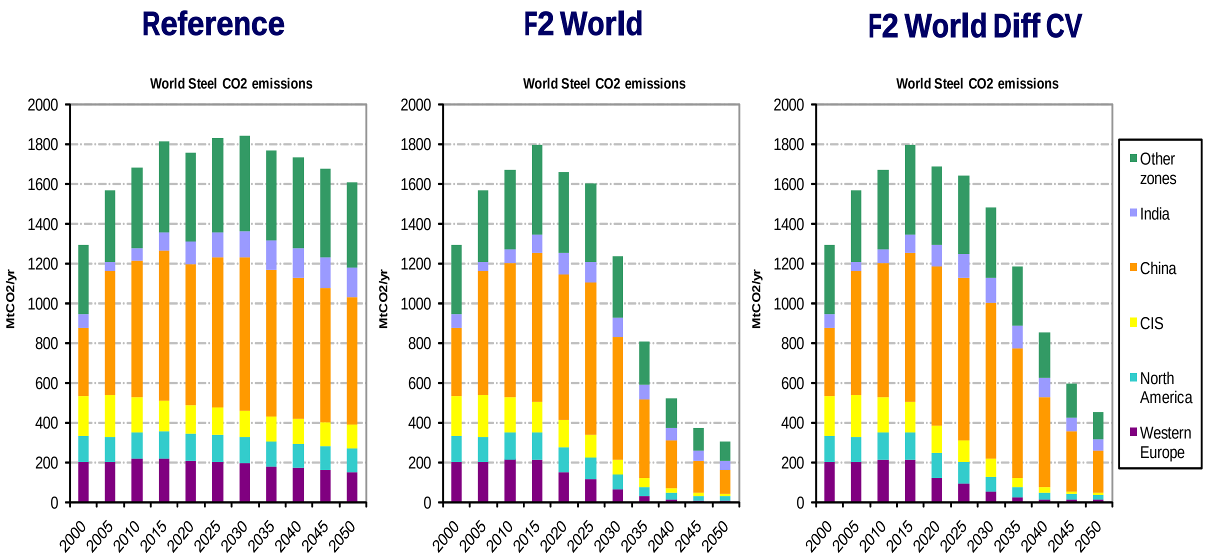


Figure 16 - CO_2 generation by the world steel industry until 2050 (source: LEPII)

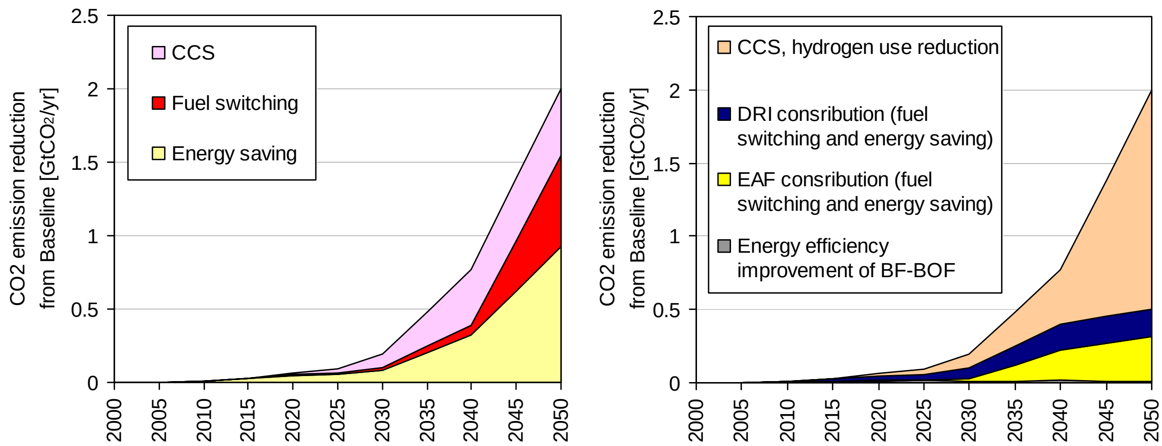


Figure 17 – reduction of CO_2 generation by the world steel industry until 2050 (source: RITE)

RITE projections only show a carbon constrained world. The reduction posted are then of a similar order of magnitude as those of LEPII. The way the cuts are achieved, however, is not explained in detail in the publications and this author is puzzled y the fact that energy savings would bring a larger proportion of the reduction, followed by fuel switching and CCS, which is different form his own understanding of the sector.

These results show what a top down modeling can produce: the level of cuts achieved are at the level of the pressure that is applied on the economy. In other words, since the value of carbon, in the

[10] All scrap that can be collected is actually collected, thus ensuring a high, but lesser than 1, recycling rate.

POLES model for example, is calculated to produce a F2 world, this is indeed what happens: the model shows that it is possible, that there is a solution in the economic space, by implementing the kind of breakthrough technologies that the models posit in their technology database.

Whether this can be done in a practical and realistic way is altogether different matter…! That some of modeling, IEA's for example, acknowledges very explicitely.

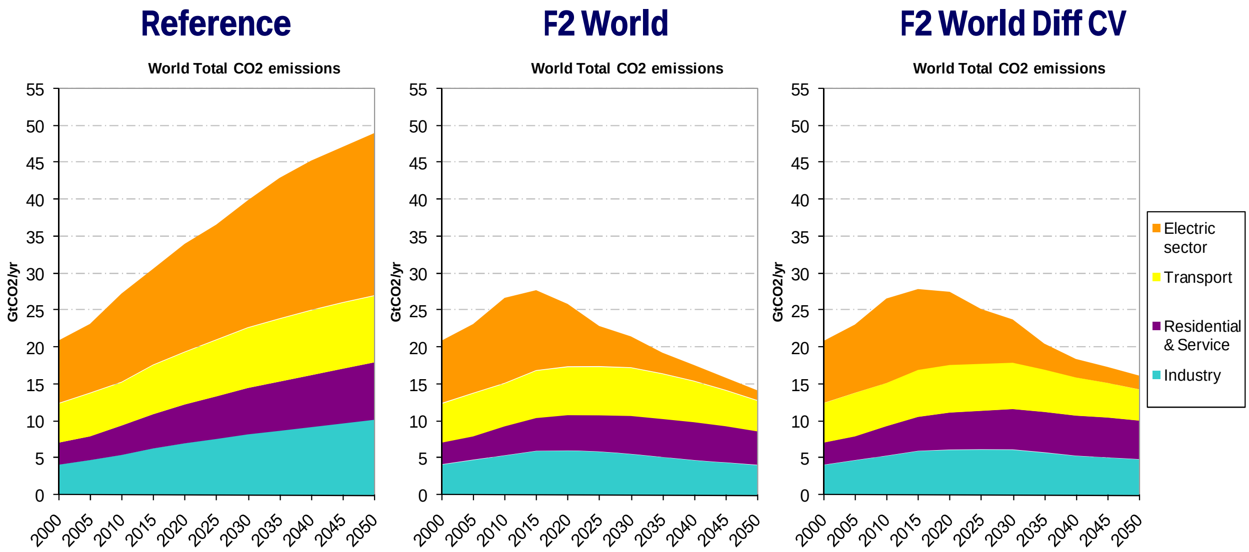


Figure 18 – world global CO_2 generation until 2050 (source: LEPII)

There are similar projections for the other materials, but it is irrelevant to this review to present them. The discussion indeed becomes technology focused and thus clearly out of scope.

IEA projections are shown in Figure 19. The wedge diagram that is shown can be compared directly to RITE's. Again, the overall level of cuts is roughly similar, but the levers for achieving the reduction are different: CCS, biomass use, switch to natural gas (DRI), recycling and energy efficiency, listing them in a decreasing order of influence. This is more or less the reverse order of RITE's. Moreover, if one goes deeper into the analysis that is carried out by the IEA, one sees that both the use of natural gas and of scrap is allowed to increase fairly arbitrarily without the kind of restraints that are embedded in the economy: the amount of recycling is completely bound by past production and the amount of natural gas that can be used for producing steel is bound by costs and thus gas prices: these shortcomings are acknowledged in the IEA report.

Note that these constraints have been built into the POLES model, because the model has the kind of high level description of the economy that makes it possible to take on board this level of complexity and because it has been developed by a collaboration between economists and steel experts. This kind of "detail" is not completely explicit in the publications and there is a danger of accepting them all at the same level, even though they deal with a similar problems with quite different tools. This flattening of scientific results is akin to relativism and is due to the fact that very many stakeholders express opinions and make decisions based on a shallow reading of existing results.

The technology options quoted in [31] by IEA meet the expectations of this author, but this is due to the fact that the data come from worldsteel and thus from ULCOS and other advanced CO_2 mitigation steel technology programs. This however is rather unrelated with IEA's modeling: it is presented as "options" that the user can shop from. It is also meant, explicitely or not, to show that there are many solutions around and that technology will always have the last word in solving this kind of problems. Again, this is a technology optimistic view, that is probably true at a vague and global scale, but does not necessarily apply to a narrow and focused problem.

Note also that in previous editions of the IEA report [29], the options were quite different and rather ill informed: in addition to the statements on using more scrap and more direct reduction, which we have already criticized, they singled out technologies which have not been particularly successful in terms of industrial implementation – probably based on available information, published with marketing and lobbying targets in mind. The conclusions at the time were the same, though, which is technology optimism again! This is a bit worrying concerning the robustness of the policy proposals that are put forward!

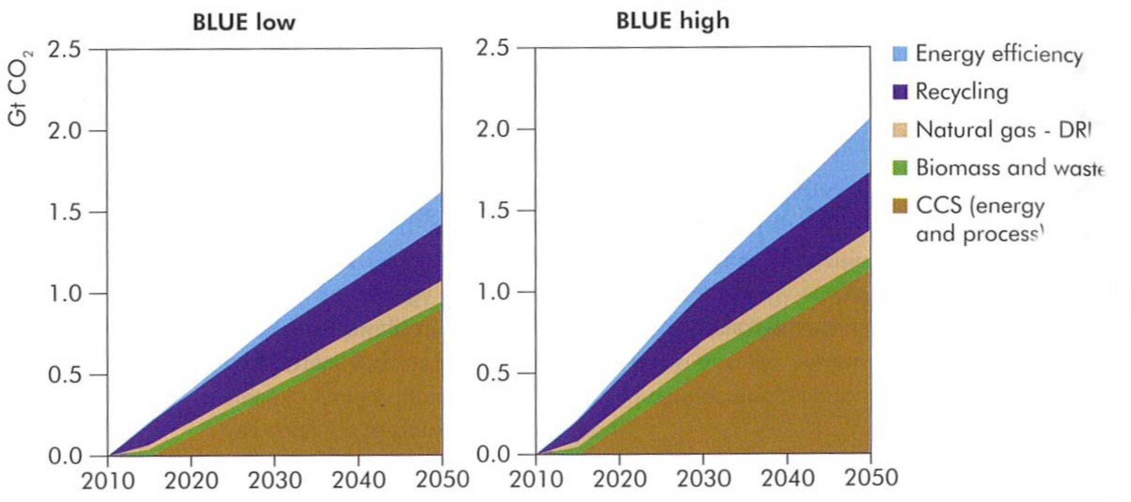


Figure 19 – Direct reduction by technology options as reported by the IEA (low and high blue scenarios) [31]

As a summary of this section and to shed some simple light in the complex storyline that has been told, a simple model updated from [56] has been worked out. It is based on the following assumptions, which mirror the content of this chapter but oversimplify it for the benefit of making some important points (cf. Figure 20):

- steel production in 2010 is assumed to be 1,300 Mt of crude steel, 30% produced by the EAF and 70% by the integrated route. Average emissions are 1.8 $t_{CO2}/t_{crude\ steel}$ and 0.6 and 2.3 respectively for each route.
- in 2050, steel production is supposed to have doubled, i.e. reach 2,600 Mt, with 60% produced by the EAF and 40% by the integrated route. Average emissions depend on scenarios:
  - a trend scenario assumes that emissions are cut by 15%, based mainly on more adoption of advanced technologies (like BAT) and some more energy savings (1.1/0.5/1.9 $t_{CO2}/t_{crude\ steel}$).
  - a factor 4 scenario, called "Low Carbon" (LC) assumes that technologies are available and policies have been designed to have to be applied in such a way that global emissions are cut by a factor 4 as compared to 2010 (0.2/0.1/0.4 $t_{CO2}/t_{crude\ steel}$). This is a prescriptive scenario. It cannot be achieved with the CCS based ULCOS technologies alone and needs either the use of biomass in large quantities (like in [88]) or new technologies not yet described nor, maybe, yet invented.

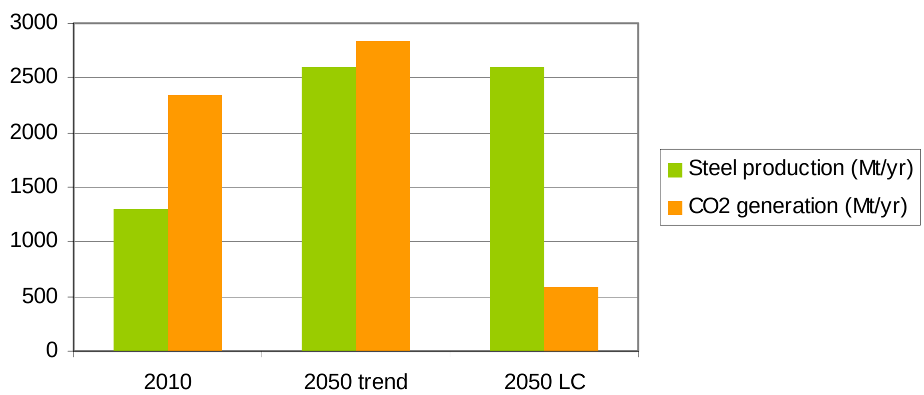


Figure 20 – simplified projections of CO_2 emission sin the Steel sector

Most of the complexity of the previous review has been erased, but two important conclusions stand out: an increase of production will lead either to a small increase in absolute emissions and not to a doubling - mainly because recycling keep the phenomenon under control, or to a sharp cut in emissions if the proper steps are taken to develop breakthrough technologies and implement normative and effective policies to implement them.

3. Technical overview of capture options[11] [20]

This is the first section going into the CCS aspects of industry. What are the mitigation options in general and the CO_2 capture options specifically in the sector (including integration into current and new processes)?

Why does the Steel Industry generate CO_2?

How steel is made

An Integrated Steel Mill, located close to a large river or a deep sea harbor, typically receives coal and iron ore (oxide, either hematite or magnetite) by ship, usually from far abroad, Brazil, Australia or South Africa, for example. The raw materials are blended and prepared to the specification of steel production in large plants, where the ore is sintered (sinter plant) or pelletized and the coal pyrolyzed into metallurgical coke (coke oven batteries) or ground into pulverized coal (PC grinders). Coke, PC and sinter, plus some bulk ore and sometimes pellets are fed to a very large, circular and vertical reactor called a blast furnace through which a counter flow of hot air is blown through a series of tuyeres located at the bottom third of the height – between bosh and hearth (cf. Figure 22). A blast furnace has a diameter of 6 to 15m, a height of 35 m, a working volume of 800 to 4800 m^3, a production of pig iron (hot metal) of 1,000 to 15,000 t/day and a power of 1 GW – it thus stands among the largest engineering reactors in all industrial sectors. The blast furnace taps hot metal, a saturated iron-carbon melt, at 1500°C, liquid slag (later commonly used as a raw material for the cement industry) and gases, since the high temperature chemistry in the reactor (Boudouard equilibrium) produce a gas that contains similar amounts of CO and CO_2. This gas is carefully collected, mixed with coke oven and steelmaking gases, and sent through an internal grid to reheating furnaces and a power plant to combust it fully into CO_2. The blast furnace may operate continuously (with rare shutdowns) for more than 25 years.

To make steel, it is necessary to oxidize the carbon out of the melt (and other elements like silicon and manganese as well). This is done in a further steelmaking plant, where pure oxygen is blown into the hot metal through a top lance or bottom tuyeres. The reactor is called a converter or BOF (Basic Oxygen Converter). It is a batch process, tapping regularly twice every hour, up to 400 t of liquid steel around 1600°C at each cycle.

There many more plants in the Steel mill, to customize the composition to produce hundreds of different steel chemistries (secondary metallurgy), solidify steel in a continuous caster and then roll it down to the desired shape and dimensions in the hot and sometimes cold stage. Metallurgical properties are met by various heat treatments carried out on-line or off-line, continuously or in batch. Most of energy intensive part of the Mill is in the blast furnace area and CO_2 is generated there and also at every downstream plant where some combustion takes place: hence the complexity of the CO_2 sources showed in Figure 23.

The DR route uses natural gas a reducing agent and fuel and therefore a different kind of shaft reactor called a prereduction furnace. Production is less, between 1 or 2 Mt annually. Steelmaking and downstream plants are the same as in the Integrated Steel Mill.

The EAF route is rather different in as far as recycled steel, scrap, is the source of iron. The physical requirement of the Mill is thus to melt the scrap, without the heavy needs of oxide reduction, and, as soon as liquid steel is available to move on into chartered territory with the same casting and rolling techniques as before.

There are two main reasons: on the one hand, energy is needed to produce steel, more often than not generated from fossil fuels, and, on the other hand, reducing agents are necessary to produce

[11] Reprinted from a chapter written by the author in reference [18]

steel from iron ores, the cheapest, most easily available reductant being the carbon of coal. Economist do not distinguish between these two uses of carbon and bundle everything together as energy.

Figure 21 shows the various production routes used today to make steel and their share in the world and in France. The Blast Furnace route produces steel from primary raw materials, i.e. iron ore, and requires both energy and reducing agents in the form of coke and pulverized coal; it is called an Integrated Steel Mill. The Electric Arc Furnace (EAF) route produces steel from secondary raw materials, i.e. iron scrap, and needs mainly energy, in the form of electricity, coal and oxygen. The Direct Reduction (DR) route is based on ore and uses natural gas as the reducing agent and fuel, along with electricity for the EAF. The carbon dioxide intensity of the three routes is respectively 1.97, 1.10 and 0.45 $t_{CO2}/t_{crude\ steel}$. [57].

An Integrated Steel Mill (ISM) is a complex series of interconnected plants, where CO_2 comes out from many stacks (10 or more). Figure 23 gives a simplified carbon balance, showing the major entry sources (coal and limestone) and the stack emissions, in volume (kg/t of hot rolled coil) and concentration of CO_2 (volume %). The major CO_2 stream comes out of the blast furnace and accounts for 69% of all Steel Mill emissions to the atmosphere. This is indeed where most of the reduction takes place and where most of the energy is needed. This is also the preferred place for dealing with CO_2, in a Pareto-type of approach[12]. The top gas of the blast furnace is composed of roughly 25% of CO_2, the rest being CO at a similar concentration with a complement of nitrogen. The other stacks all together account for 31% of the emissions: they exhibit rather low CO_2 concentration, typical of the flue gas a combustion chamber. Of course, the BF top gas never ends up directly in a stack, as the embedded energy is recovered in a power plant, which is part of the Mill complex.

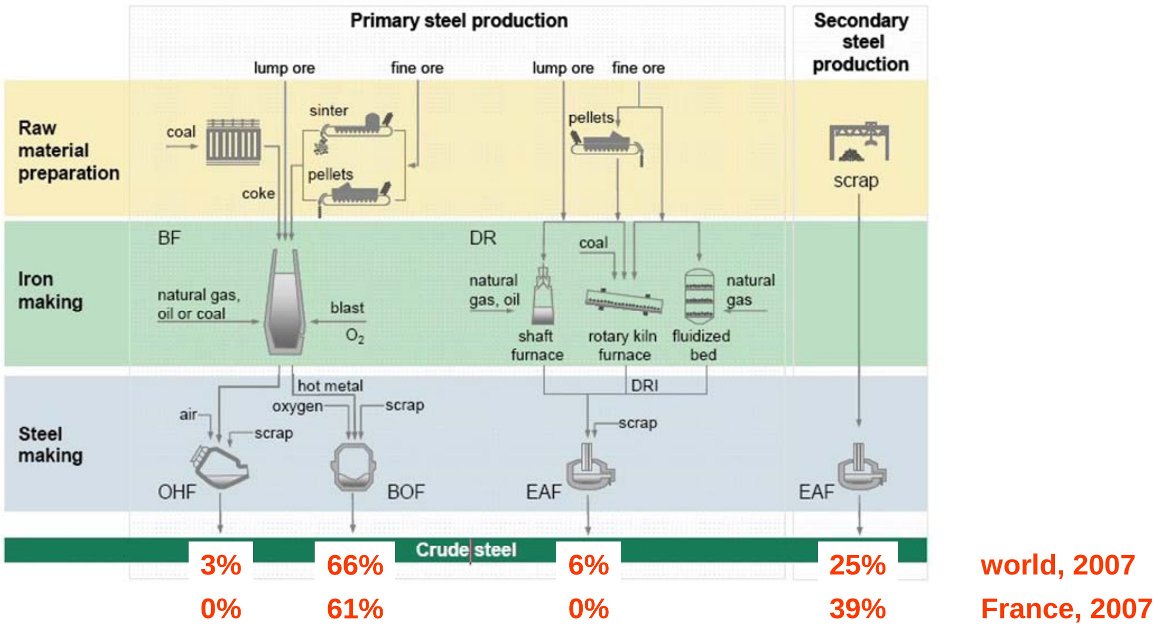


Figure 21 – production routes to make steel today, with production shares in the world and in France, an example chosen to show that the world data average scattered country ones (BF: Blast Furnace; OHF: Open Hearth Furnace; BOF: Basic Oxygen Furnace; EAF: Electric Arc Furnace; DR: Direct Reduction)

[12] It is possible in theory to apply CCS to every smokestack of the integrated Steel Mill, which would cut CO_2 emissions by 100%. The BF however is the largest source of CO_2 and the CO_2 stream it generates is quite concentrated (see further in the chapter). Most of the effort to develop CCS for the Integrated Steel Mill therefore concentrates on applying CCS to the BF, which moreover requires an industry-specific approach. Further reductions would mean applying standard technologies to other smokestack, similar to those used in power plants for example, starting at the coke ovens and sinter plant

Figure 22 – ArcelorMittal Florange's blast furnace skyline, in France

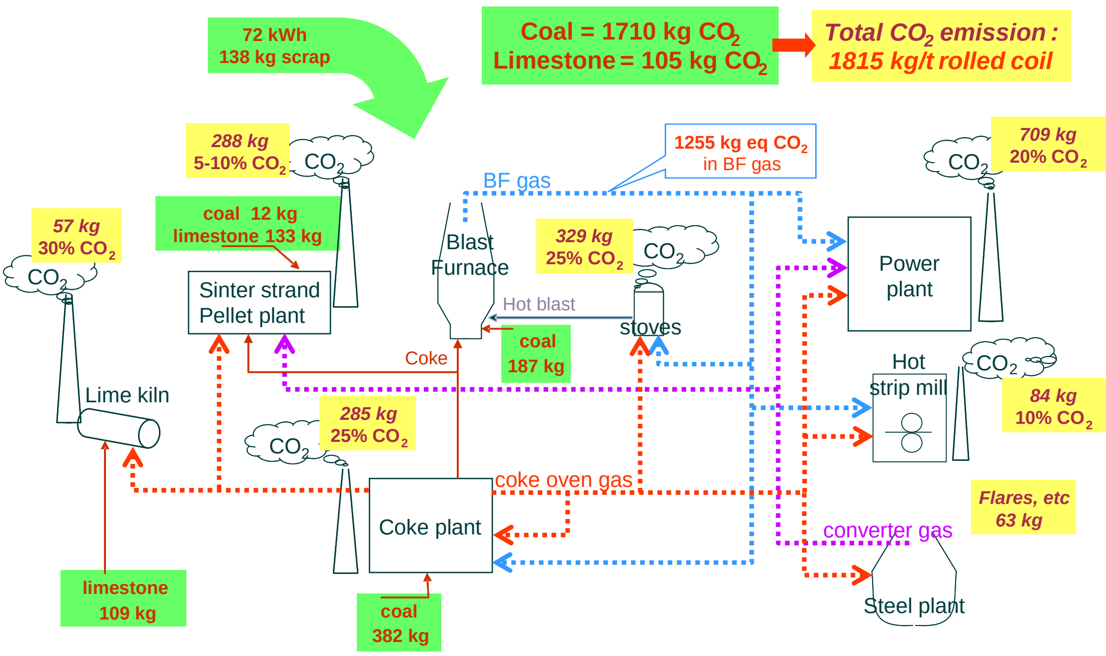


Figure 23 – simplified flow sheet of an Integrated Steel Mill, showing carbon-bearing material input (green boxes), CO2 emissions, expressed in volume (kg/t of hot rolled coil) and concentration in the flue gas (volume %).

A Direct Reduction steel mill generates CO_2 in lesser quantities at the stack of the DR plant - as well as downstream at the steel shop and rolling mills, like in the ISM. An EAF mill generates even smaller amount of CO_2, from the steelshop on: most of its emissions are actually due to electricity production needed to power the EAF.

Strategies to control CO_2 emissions from the Steel sector

A state-of-the-art Steel Mill is a much optimized system in terms of consumption of fuels and reducing agents. The Blast Furnace itself operates 5% away from thermodynamics and the whole mill has a potential of energy savings of roughly 10% only. This is due to several decades of cost management, as high energy prices have driven the industry to optimize its processes as close as possible to physical limits. The Industry rightfully claims energy savings and, correspondingly, CO_2 cuts which range between 50 and 60% over the last 40 years, depending on the local conditions: this is the highest level of energy conservation achieved by any industrial sector.

Cutting CO_2 emissions further, to the level that post-Kyoto policies require, raises therefore specific challenges: it is indeed necessary to uncouple energy savings and CO_2 reduction in the Steel sector – an original feature compared to other sectors.

First, a more or less obvious fact that ought to be stated, anyway, is that the usage of steel scrap should be kept at the high level that it has reached today. It is estimated that the collecting rate of obsolete scrap is around 85% today, which forms the basis of a strong recycling economy, complete with scrap dealerships and a specific steel production route based on the EAF. In simple words, value is created by the recycling of virtually all available scrap. In the long term, this situation will continue.

It should also be pointed out that the indirect emissions related to electricity production will evolve with time. For example, ULCOS has shown that, under a strong carbon constraint, the carbon intensity of the European electricity grid will drop form 370 g_{CO2}/kWh in 2006, to 144 g in 2050, a specific drop of 55%, which will be translated at the same level in indirect emissions [58].

The major source of CO_2 emissions from steel mills still remains the ore-based route, which will retain an important role in the long term, at least until a recycling society can replace the 20th and 21st century economy of production growth that is mainly driven by population growth – probably some time in the next century or at the very end of the present one [59].

Solutions to curtail emissions from the ore-based route have to be exhibited and it is clear from the previous sections that there is no simple process, available from the shelf, that can accomplish this. Deep paradigm shifts in the way steel is produced have to be imagined and the corresponding breakthrough technologies designed and developed, by strong R&D programs.

The largest such program called ULCOS, for Ultra Low CO_2 Steelmaking, has been running in the EU since 2004 to progress in this direction [55 ,60, 61,59].

The analysis that ULCOS has proposed in terms of Breakthrough Technologies is shown in Figure 24, which explains how reducing agents and fuels have to be selected from three possibilities, carbon, hydrogen and electrons, mostly in the form of electricity[13]. The mock ternary diagram of the figure is meant for didactic clarity: all existing energy sources can be represented on the triangle sides (e.g. coal is close to carbon on the carbon-hydrogen line, natural gas is closer to hydrogen, hydrogen from water electrolysis is on the hydrogen-electricity line, etc.).

The present steel production technology is based on coal, i.e. mostly on carbon, on natural gas, a mix of carbon and hydrogen and on electric arc furnaces. They are shown in red boxes in the figure.

To identify CO_2-lean process routes, 3 major solution paths stand out and three only: either a shift away from coal, called decarbonizing, whereby carbon would be replaced by hydrogen or electricity, in processes such as hydrogen reduction or electrolysis of iron ore, or the introduction of CCS technology, or the use of sustainable biomass. They are shown in yellow boxes in the diagram.

ULCOS has investigated about 80 different variants of these concept routes in the initial phase of its research program, using modeling and laboratory approaches to evaluate their potential, in terms of CO_2 emissions, energy consumption, operating cost of making steel and sustainability [25].

[13] Bacteria would also sit on the electron apex, if microbiological metallurgy was considered

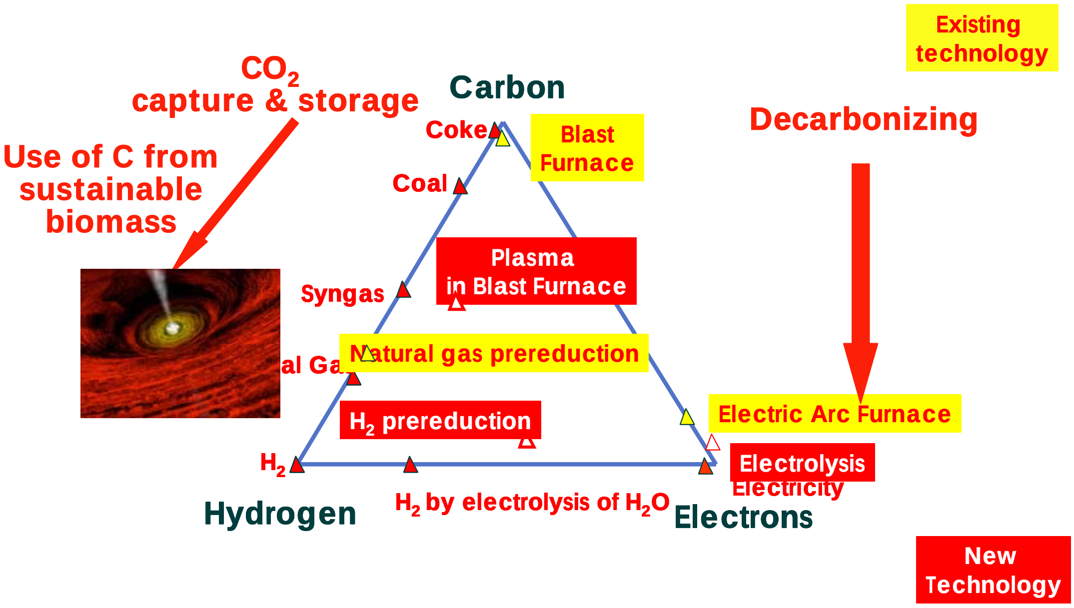


Figure 24 – pathways to breakthrough technologies for cutting CO2 emissions from the ore-based steel production routes

Among all of these, 6 families of process routes have been selected within the ULCOS program for further investigation and eventual scale up to a size where commercial implementation can take over:

- a blast furnace variant, where the top gas of the Blast Furnace goes through CO_2 capture, but the remaining reducing gas is reinjected at the base of the reactor, which is moreover operated with pure oxygen rather than hot blast (air). This has been called the Top Gas Recycling Blast Furnace (TGR-BF) or ULCOS-BF. The CO_2-rich stream is sent to storage (cf. Figure 25).
- a smelting reduction process based on the combination of a hot cyclone and of a bath smelter called HIsarna and incorporating some of the technology of the HIsmelt process [62]. The process also uses pure oxygen and generates off-gas which is almost ready for storage (cf. Figure 26).
- a direct reduction process, called ULCORED, which produces DRI in a shaft furnace, either from natural gas or from coal gasification. Off-gas from the shaft is recycled into the process after CO_2 has been captured, which leaves the DR plant in a concentrated stream and goes to storage cf. Figure 27).
- two electrolysis variants, ULCOWIN and ULCOLYSIS, which respectively operate slightly above 100°C in a water alkaline solution populated by small grains of ore (electrowinning process), or at steelmaking temperature with a molten salt electrolyte made of a slag (pyroelectrolysis).
- two more options are available: one consists in using hydrogen for direct reduction, when and if it is available without any carbon footprint; the other is based on the use of sustainable biomass, the first embodiment of which is charcoal produced from eucalyptus sustainable plantations grown in tropical countries.

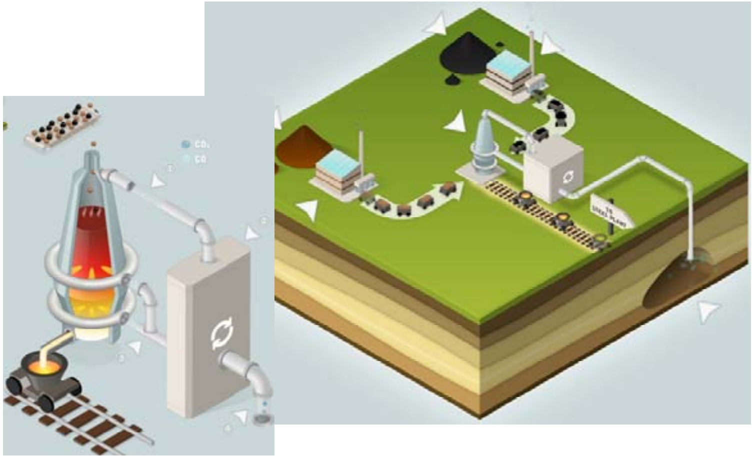


Figure 25 – schematics of the TGR-BF process; the furnace is in the center and is shown in a separate window, where the CO2 separation unit and gas reheater are shown feeding two rows of tuyeres; ; the cones show iron ore (brown) and coal (black); CO2 is sent to underground storage through a pipeline (from www.ulcos.org).

In the nearer term, the TGR-BF seems the most promising solution, as existing Blast Furnaces can be retrofitted to the new technology and thus extensive capital expenditures that would be necessary to switch over to the Breakthrough Technologies is maintained under some control. Moreover, the very principle of the process delivers energy savings because the capture of CO_2 and the recycling of the purified gas displaces high temperature chemical equilibria (Boudouard reaction) and uses coke and coal with a higher efficiency inside the BF than is possible with conventional operation. This balances the extra costs incurred by the capture and storage, to some extent. The concept has in addition been tested on a large scale laboratory blast furnace in Luleå, with positive outcome [63].

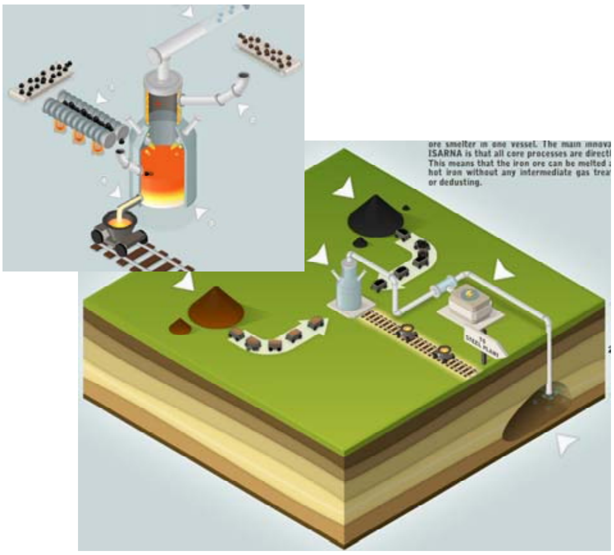


Figure 26 – schematics of the HIsarna process; the reactor, in the center, is also shown in a more detailed window, where the cyclone sits on top of the bath smelter and char from a screw reactor feeds carbon into the furnace; the cones show iron ore (brown) and coal (black); CO2 is sent to underground storage through a pipeline (from www.ulcos.org).

Where natural gas is available, ULCORED is an attractive option. A 1 t/h pilot is planned to be erected in Luleå in the next few years by LKAB, an ULCOS partner, to fully validate the concept.

Somewhat later and probably for greenfield steel mills, the HIsarna process will also be an option. An 8t/h pilot is to be erected and tested in the course of the ULCOS program.

The electrolysis processes have been developed from scratch within the ULCOS program and therefore are still at operating at laboratory scale. Although they hold the promise of zero emissions, if they have access to green electricity, time is required to scale them up to a commercial size (10 to 20 years).

Hydrogen steelmaking will depend heavily on the availability of "green hydrogen", while the use of charcoal, far way from growing countries, would require the set up of complex logistics, including heavy infrastructure across several continents.

The discussions have been centered until now on the major sources of CO_2, which allows cutting emissions for the whole steel mill by more than 50%. It is possible to cut emissions further, by treating the other stacks of the steel mill: the cost of abatement would of course be higher. With this rationale, though, zero emissions could be achieved.

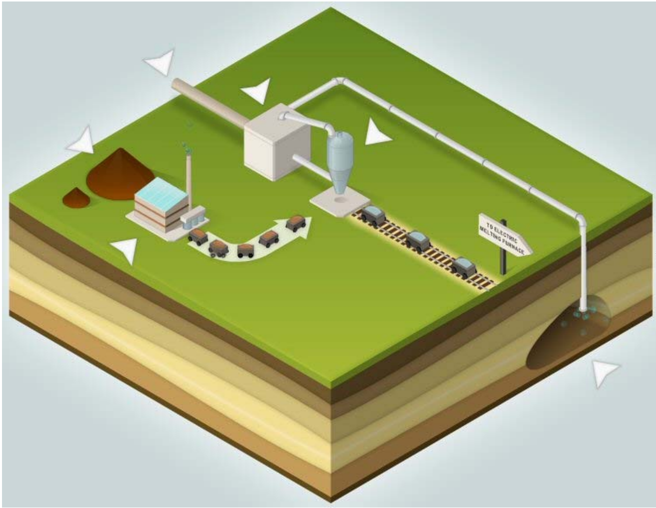


Figure 27 – schematics of the ULCORED process: the reactor is in the center; to the left is the pelletizing plant for iron ore; the grey box is the CO2 separation unit and the gas flows through a pipeline to the underground storage site (from www.ulcos.org)

There are also other programs addressing this challenge: along with ULCOS, they are part of the *CO_2 Breakthrough Program* of worldsteel - the international Iron & Steel Association, a Forum for the various initiatives to exchange about their progress [64].

Japan has a large national program led by the Japanese Iron and Steel federation (JISF) called COURSE 50, which focuses on the development of a new amine scrubbing technologies for blast furnace gas and the use of hydrogen separated from coke oven gas, a by-product of the steel industry [65]. The ready-to-use technology concepts should be available by 2030.

POSCO, in Korea, runs its own program, with various dimensions including the adaptation of CCS to the FINEX and to the COREX process and the development of an ammonia-based scrubbing process [66].

The American Iron and Steel Institute (AISI), in North America, runs a program where high-temperature electrolysis is examined at MIT, hydrogen reduction of iron ore in the laboratory, preparatory to transposing to a flash furnace reactor, at Utah University, mineral sequestration at Columbia University and CO_2 collection from EAF fumes using lime at Missouri Rolla University [67].

A Canadian program, run by the Canadian Steel Producers Association (CSPA), has a strong focus on the use of biomass in iron and steelmaking as a substitute for fossil fuels, as biomass per capita is quite important in this large country [68].

Arcelor Brazil has been reporting its development of a biomass steel production route based on sustainable plantations of eucalyptus trees, production of charcoal and small charcoal blast furnaces [69], which is already used in Brazil but at a small scale (300,000 tpy BF) and is most probably a local solution.

There are also participating programs from Bao Steel in China, China Steel in Taiwan and SAIL in India [57].

The rationale of all of these programs is similar to ULCOS'. They are less advanced in terms of making Breakthrough Technologies available and their progress is not widely reported yet. These are the main reasons why this chapter is heavily based on ULCOS' approach, which is very typical of what is done elsewhere.

The long development lead time of Breakthrough Technologies shows that there is no simple recipe for cutting the present CO_2 emissions of the Steel Industry by 50% or more (the objective of the ULCOS program): new technologies have to be developed, which means a high level of risk, incompressible development time, large budgets for R&D and then large capital expenditures to convert steel mills to the Breakthrough processes. Moreover, the economic viability of these solutions, which definitely are not no-regret, will depend on the price of CO_2 and on the implementation of a level playing field for climate policies all around the world that avoid "carbon-havens" and therefore carbon leakage, especially out of Europe.

With all these caveats, the Steel Industry can cut its emissions significantly and continue to provide a material that the world needs to ensure a good life to its citizen and cut CO_2 emissions in other sectors.

There is project of MASDAR and Emirates Steel in Abu Dhabi to capture CO_2 in a DRI Steel Mill as an end-of-pipe feature and to use it for EOR in the local oil and gas fields. There is little information available about the details of the project, but it is equivalent in size to what the European call a demonstrator.

Both the ULCOS-BF and the UAE projects should go on stream around 2015, with full CCS implemented.

4. Energy requirements and emission reductions for CO_2 capture

What would be the consequences for the energy requirements in the process and in the sector? What would be the consequences for upstream emissions, such as those relating to coal mining or transport? What are the potential CCS-related emission reductions in the sector?

CCS for the Steel sector

This section will refocus on CCS for the Steel sector, because it is the main concern of this book but also because implementing CCS seems to be the quickest way – in the 2020's - to delivering significant cuts in the CO_2 emissions of the sector.

The first point is that CCS will be implemented in the Steel Industry without matching any of the existing CCS categories, which have been defined with the context of energy generation in mind: indeed, in the Steel sector, the major part of the generation of CO_2 is related to the reduction of the iron oxides that constitute iron ore. Oxyfuel combustion, pre- or post-combustion capture chemical looping do not mean much in an industrial context where there is no combustion and no oxidation either – except very locally inside the reactors. Figure 29 presents the various CCS concepts applied to the steel industry and to a combustion process.

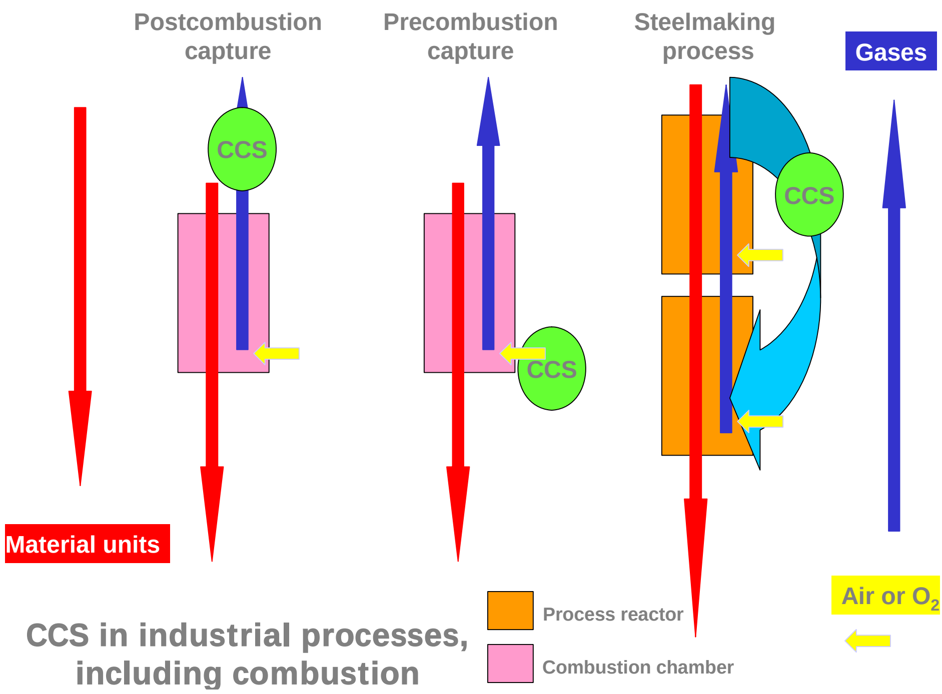
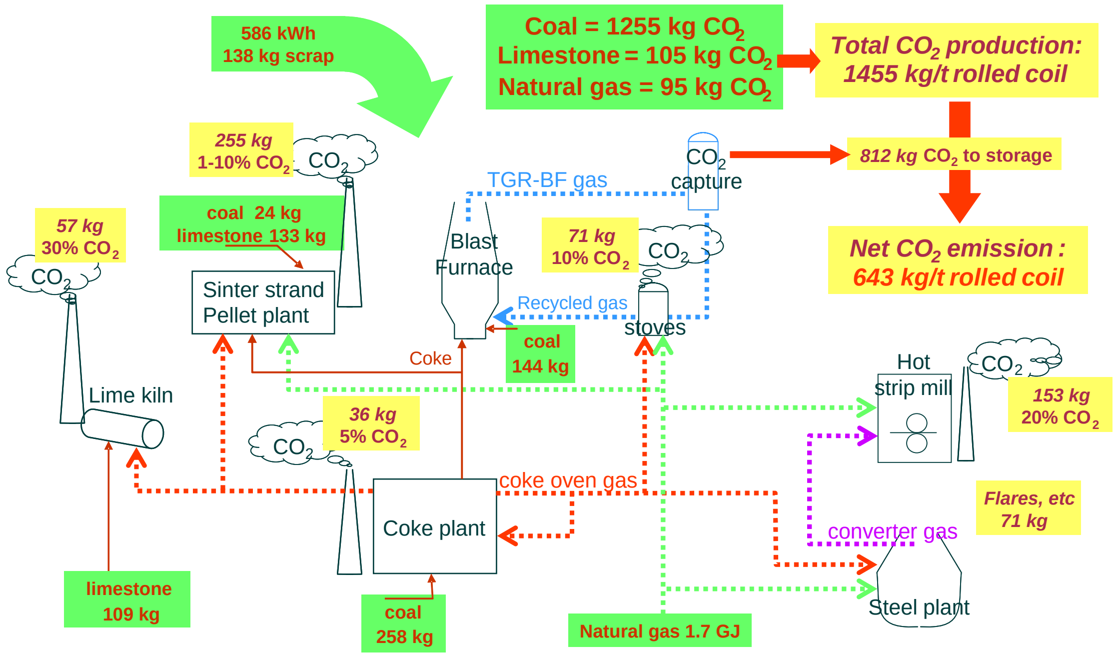


Figure 28 - Implementation of CCS in process industries including combustion

The proper concept to apply to the TGR-BF is that of *in-process CO_2 capture, with oxygen operation.* The oxygen part is similar, but not identical to oxyfuel operation. The recycling part is original and is the key reason why some energy savings and the corresponding cut in operating cost are gained. The same concept applies to the ULCORED process, which also includes use of pure oxygen and in-process recycling of the shaft top-gas, in addition to other features like a series of shift reactors in the recycling loop.

The HIsarna process is slightly different from the two other processes as it does not involve a recycling loop for the gas: the smelter gas is oxidized at the cyclone level, where some reduction is carried out along with combustion to preheat and melt the ore. There is a counter current flow of the gas against the iron stream, in which its chemical energy is fully exhausted.



CO_2 emissions from a TGR-BF steel mill

Figure 29 - simplified flow sheet of an Integrated Steel Mill operating with a TGR-BF, showing carbon-bearing material input (green boxes), CO2 emissions, expressed in volume (kg/t of hot rolled coil) and concentration in the flue gas (%).

Figure 29 show the carbon and CO_2 mass balances of a steel mill operating with TGR-BF. Emissions are cut by 65% compared to the non-ULCOS benchmark steel mill of Figure 23 (and by 56% in the steel mill itself, due to the carbon saving introduced by the process). Capturing the flue gas of an extra stack, like the that of the sinter plant, would bring the reduction at the level of 75%.

The most striking feature of the top gas stream from which CO_2 is recovered is the high concentration of CO_2, around 35%, which is significantly more than in the top gas of the conventional blast furnace.

Capture technologies call mainly on the following phenomena:

- sorption separation either by adsorption or absorption under different physical and chemical processes; or:
- cryogenic separation by fractional liquefaction; or:
- physical separation achieved by pushing the gas through membranes or molecular sieves.

Physical and chemical adsorption (respectively physisorption and chemisorption) processes depend on the nature of the CO_2 trapping material (respectively a reactive liquid vs. a porous solid) and on the physics that will be used to restore and release the CO_2 following capture (by lowering the pressure or increasing the temperature in the first case and heating up in the second case). The nature of the bonds between the sorbate and the surface differ under physisorption and chemisorption processes, physical processes utilize, for example, hydrogen and dipole-dipole bonds, while chemical processes utilize, for example, covalent and ionic bonds.

All of these operate either in batch, by capturing CO_2 in a first stage and then releasing it in a second stage, or continuously in the filtration process used with membranes. Other solutions propose to capture CO_2 and store it immediately, by mineral sequestration for example [70].

Some of these technologies are mature and have been used at a large scale in specific industrial applications related to CO_2 or other gases such as hydrogen: this is the case of amine scrubbing (based on AMDEA), and of physical adsorption systems such as PSA (Pressure Swing Adsorption) or VPSA (Vacuum Pressure Swing Adsorption), complemented by a cryogenics unit designed to purify the CO_2

stream. Others are under development or are still only operating at too small a scale to constitute a benchmark on which to design a system for the steel industry: liquid ammonia scrubbing [71], capture in clathrates [72] or by lime [73], and membrane technologies [74].

The following discussion will only take on board mature technologies, which will clearly introduce a bias in the conclusions, as CCS is a technology that will be deployed from 2020, a period when some of the emerging technologies may have matured. There are strong expectations, for example, that new chemicals, amines or other families of molecules, will be developed to replace AMDEA with much lower needs for steam and energy. The same is said of membranes and, actually, most research teams claim large development potentials, some of which are bound to solidify.

The technology proposed by the ULCOS program to incorporate capture in the TGR-BF is physisorption.

Figure 30 and Figure 31 show the equipment which was used in the Experimental Blast furnace (EBF)[14] during the large scale TGR-BF experiments carried out by ULCOS in Luleå and the physical principle of its operation [63]. It is a VPSA built by Air Liquide, a partner of the program. This technology was chosen for two reasons: it was the simplest and cheapest solution, hic et nunc, to collect CO_2 from the off gas of the blast furnace and to produce a recycling stream of gas where the concentration in reducing gas, mainly CO, would be maximized. In these experiments, the CO_2 stream was not stored.

In a larger scale experiment, like the one that is now being organized to follow up on the EBF trials in the ULCOS program at the size of a commercial Blast Furnace[15] [75] (ULCOS II, ULCOS-BF) - a necessary step to scale up the technology, the gas will be stored in a deep saline aquifer and therefore a higher level of purity in CO_2 is required. Further purification of the stream, using cryogenics, i.e. fractional liquefaction of the gas, is hence necessary, which also generates an extra stream of reducing gas which is also recycled in the BF. In this case the optimized system consists of a combination of a PSA and of a cryogenics unit.

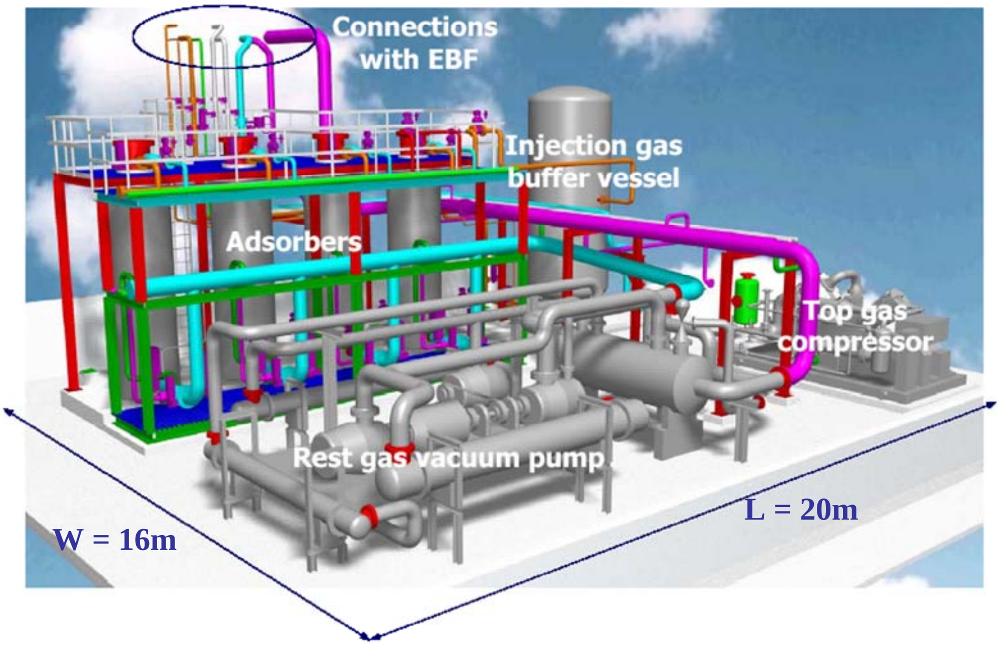


Figure 30 – view of the VPSA of Air Liquide used during the ULCOS TGR-BF experiments in Luleå

Detailed studies, carried out by ULCOS, show that chemisorption technologies, like amine scrubbing, physisorption ones, like VPSA or PSA, and cryogenics, have different domains of optimality, the con-

[14] The EBF is a 1.1 m BF that produces 1.5 t/h of hot metal. A production BF produces between 50 and 500 t/h depending on its size.
[15] The pilot planned for Eisenhüttenstadt is 0. 6 Mt/year and the Florange Demonstrator 1.4 Mt/year.

centration of CO_2 in the stream of gas to be treated being one of the most important. At the level of concentration found in the BF case, and even more clearly in the TGR-BF case, the physisorption schemes are the best, in terms of technical performance and cost, both operating and capital.

This is also true if CCS is applied to a DR route, like ULCORED [76]. In the HIsarna case, which directly delivers a very-high concentration of CO_2, a cryogenics unit is enough. On the other hand, if CCS needs to be applied to the other stacks of the steel mill, then an amine scrubbing unit would be the best solution.

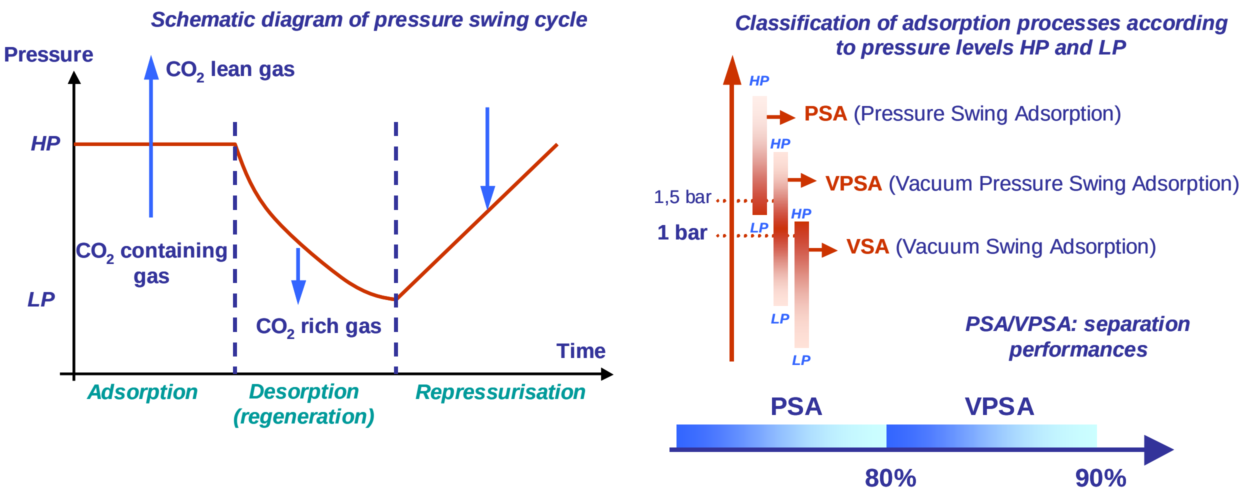


Figure 31 – principle of the PSA CO_2-scrubbing techniques (left) and various domains of application and performances of the variant techniques, PSA, VPSA and VSA. (source: Air Liquide in ULCOS)

These conclusions might be Eurocentric, i.e. dependant on the local conditions in terms of price of energy and steam. Indeed, the Japanese COURSE 50 program, which is also developing a capture technology for the BF top gas, has selected a chemisorption solution [77].

The different conclusions may also be due to different time horizons considered for estimating the potential of the capture technologies. Indeed, the amine washing considered in the ULCOS program is based on the present state of the art of this fairly common technology, i.e. on the use of commercial MDEA amines that exhibits an energy need for restoring the sorbant of 3.2 GJ/t_{CO2}. R&D is under way to improve this performance (down to 1.8 GJ/t), to work at lower temperatures and to use wasted heat: the Japanese COURSE 50 national program, for example, has promised to deliver this new technology 10 years from now.

An important point is the concentration in CO_2 reached by the various technologies. The EU directive on CO_2 storage does not specify this concentration because it is a complex question that is related to what technologies can deliver under actual industrial circumstances and to the intention of the legislator of avoiding that CO_2 storage collects other waste gases. The purity in CO_2 has clearly an impact on cost and it should only be as high as necessary in terms of storage, i.e. on the ability to turn CO_2 into a condensed fluid at an acceptable cost, a threshold that is above 90% but not necessarily 99% or more.

The features of the various capture technologies that are available today for the steel industry are shown in Table 5. The ranges, which have still to be validated by long enough experiments, are rather broad, from 96 to 100% and plead in favor of broad targets to be chosen in future legislation to leave room for choosing the best technology in a flexible way and to avoid specifying it, de facto, in legislation.

Table 5 – comparison of the mature CO_2 capture technologies for the Steel Industry. The top small table shows the composition of the input gas in the case of a TGR-BF.

INPUT GAS		
CO	%vol (dry)	45
CO2	%vol (dry)	37
N2	%vol (dry)	10
H2	%vol (dry)	8

		PSA	VPSA	VPSA + compression and cryogenic flash	Amines + compression	PSA + cryogenic distillation + compression
Recycled gas (Process gas)						
CO yield	%	88,0	90,4	97,3	99,9	100
CO	%vol	71,4	68,2	68,9	67,8	69,5
CO2	%vol	2,7	3,0	3,0	2,9	2,7
N2	%vol	13,5	15,7	15,6	15,1	15,4
H2	%vol	12,4	13,0	12,6	12,1	12,4
H2O	%vol	0	0	0	2,1	0
CO2-rich gas captured						
CO	%vol (dry)	12,1	10,7	3,3	0	0
CO2	%vol (dry)	79,7	87,2	96,3	100	100
N2	%vol (dry)	5,6	1,6	0,3	0	0
H2	%vol (dry)	2,5	0,6	0,1	0	0
Suitable for transport and storage ?		**No**	**No**	**Yes ?**	**Yes**	**Yes**
CCS process						
Electricity consumption	kWh/t CO2	100	105	292	170	310
Capture process	*kWh/t CO2*	*100*	*105*	*160*	*55*	*195*
Compression for storage (110 bar)	*kWh/t CO2*	*-*	*-*	*132*	*115*	*115*
LP steam consumption	GJ/t CO2	0	0	0	3,2	0
Total energy consumption	GJ/t CO2	0,36	0,38	1,05	3,81	1,12

5. CO_2 storage

There is no specific requirement on storage in the terms of reference for this report.

This is puzzling in itself, because storage, and, to a lesser extend, transport, are the area in CCS where the largest uncertainties probably lie. Moreover, the investment costs associated to T&S (Transport and Storage) are of the same order as those associated with capture and this raises issues, for example to finance demonstrators.

The point that C&S operating costs should be a minor part of the overall CCS OPEX should not hide this very serious and important difficulty.

The issue of storage was discussed at length during the Abu Dhabi seminar and it was pointed out that the knowledge about the geology of the underground layers, which are candidates for storage, is not sufficient to warrant an easy deployment of CCS, as a lack of knowledge is analyzed as a risk by economic players, which delays their decision making. This is especially true of deep saline aquifers, which are located at depths different from those examined for water, oil or gas exploration. This may be even truer for emerging and developing countries than for developed ones. Therefore, there is a clear need for increasing knowledge in the area and this is a job for the National Geological Surveys: the quicker it is carried out, the quicker CCS deployment can be safely planned, beyond the present general and rather unfocused encouragements.

We reproduce below the content of the storage chapter in [20].

Storage of CO_2 can take place in geological reservoirs (geostorage), in the ocean or by the mineralization of some other compounds, chemical reactants or rocks (*ex situ* storage).

Ocean storage

Ocean storage has been going through a moratorium and is therefore never seriously considered as an option by industry at the present time.

Mineral sequestration

Mineral sequestration is an option which has been examined seriously in the ULCOS program for example [73] and also in the worldsteel one [78,79].

The concept is simple: some minerals such as magnesium-rich ultramafic rocks (peridotites, serpentines, gabbros, etc.) can react spontaneously (negative enthalpy of reaction) with CO_2 and form carbonates, which stand below CO_2 on the oxido-reduction scale [80]: the compounds are usually stable and the only difficulty of these schemes is to master the kinetics of reactions, which naturally take place in the realm of geology, with the corresponding time scales. Some of the reactions may involve lime or magnesia and bicarbonates may be also formed.

A scheme specific to the steel industry proposes to use slag, especially steelmaking BOF slag, as the reactant that will be used to absorb CO_2 by a chemical reaction: there is a phase in that slag, called larnite (Ca_2SiO_4) and present at the level of 30 to 40%, which can react with CO2:

$$\tfrac{1}{2}\, Ca_2SiO_4 + CO_2 \rightarrow CaCO_3 + \tfrac{1}{2}\, SiO_2$$

with an enthalpy of - 22 kcal. In addition to larnite, slag may contain as much as 6% free lime (CaO), which also reacts with CO_2 to form the same calcium carbonate. The use of slag has been studied in the ULCOS program [81], where it was shown that the reaction can proceed at moderate temperatures (90°C), high pressures (100 bar), and moderate times of reaction (90 min) if the slag is ground (50 µm) to liberate the calcium silicate, mixed with water to produce a slurry and kept agitated during the reaction process. 70 % of carbonatation is achievable under these conditions, with means that 1t of slag can capture 250 kg of CO_2.

Comparing this amount of stored CO_2 with the Steel Mill emissions and the amount of slag which is generated in parallel, shows that only 1.3% of the total CO_2 generated by the Steel Mill (0.1 CO_2 Mt compared to total emissions of 7.2 Mt/y) can be sequestered in this way. The ULCOS program conclusion was that this was not measuring up to the level of the challenge and did not match in any way he 50% mitigation target that was its goal.

Now, if mineralization was to provide more sequestration, then more reactant would have to be used, roughly 100 times more. This shows the level of the logistics involved, as it would amount to 25 times of mass of steel produced. Proponents of mineralization do not suggest moving the rock to the Steel Mil, but rather the gas to the mine. This however is a proposal that needs more detailed elaboration before it can be considered as an option compared to geostorage.

Utilization of CO_2

Schemes based on the utilization of CO_2 will not be discussed here for several reasons.

Direct use of CO_2 as a gas or as a supercritical fluid has a very small potential of CO_2 mitigation compared to the emissions of the Steel sector and, moreover, they will eventually be released to the atmosphere, which makes it difficult to have them qualify as a storage solution.

Transforming CO_2 into less oxidized species, for example fuels (like ethanol), requires energy in larger quantities than those that were release when CO_2 was produced from coal or other fossil fuels: that some of the schemes suggest to use renewable sources does not make them globally more attractive.

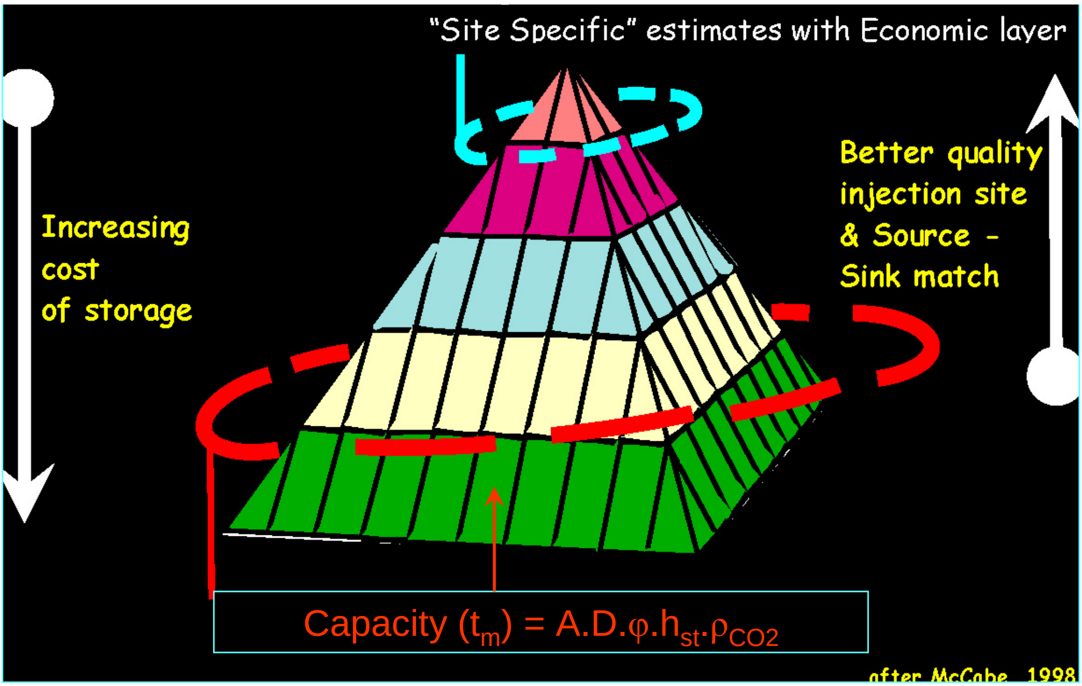


Figure 32 – resource and reserve concepts as applied to CO2 storage (source: BRGM in ULCOS)

Geostorage

Beyond the initial studies, where surveys of potential storage sites have been investigated from existing knowledge of the geology of vast regions, the search for sites that can adequately deliver the storage service that a large steel mill would expect over the long time is still only in its infancy.

The analogy with the concept of resources and reserves, used in the case of oil, gas or ore fields and deposits is strong: the initial estimates for example of the Joule II project that gave a figure of 806 Gt in Europe are similar to resources [82]. The storage capacity that a steel mill needs to identify prior to launching a site validation relates to reserves and, more precisely, proven reserves! These constitute the bottom and the tip of the pyramid shown in Figure 32 respectively. The ULCOS program compared a database of existing steel mill sites in Europe with one of geological structures supposed to be favorable for storage, i.e. onshore & offshore saline aquifers with or without lateral seals, low-enthalpy geothermal reservoirs, deep methane-bearing coal beds and abandoned coal and salt mines, exhausted to near-exhausted oil and gas reservoirs [83].

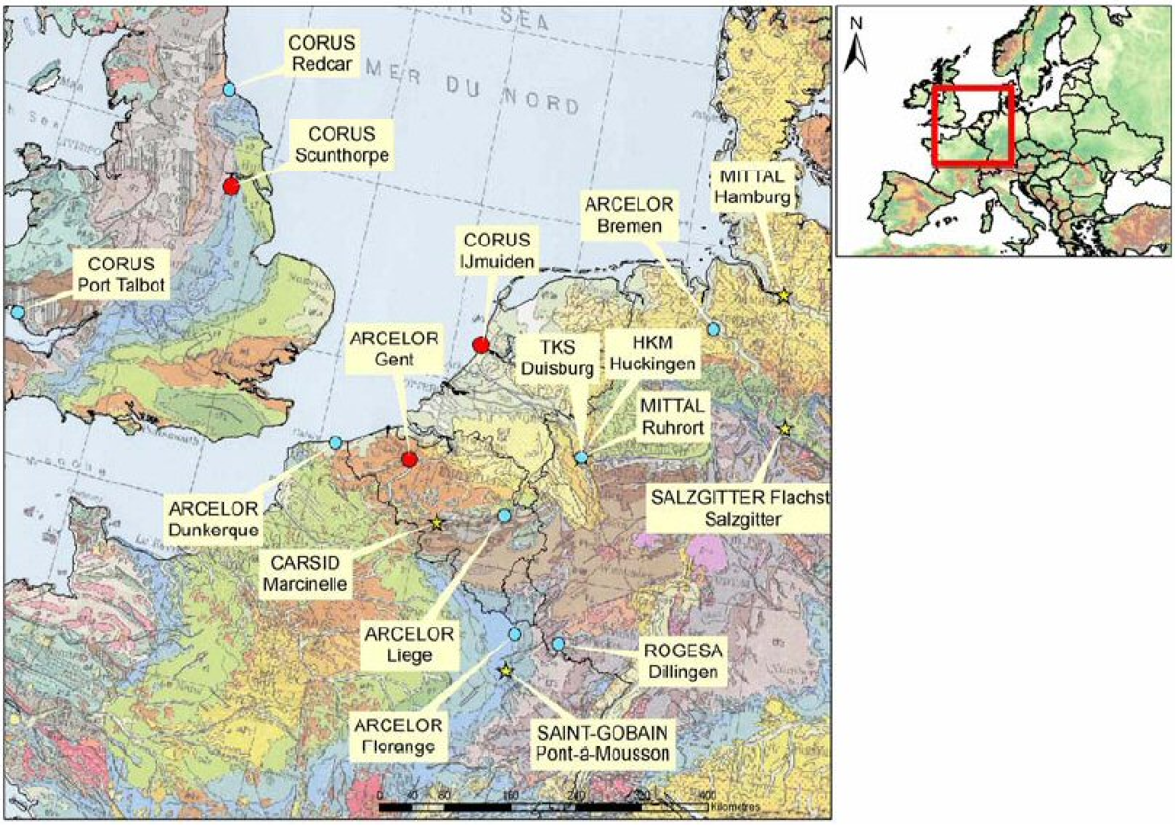


Figure 33 – Steel Mills (stars and red & blue dots) and geological structure showing potential for CCS

Figure 33 gives as an example of a part of Western Europe, where the major Steel Mills are shown with their underlying geological structure, where the North sea basin, the Ardennes massif, the Ruhr graben and the Paris basin have the geologists' preference for offering storage opportunities. Potential storage sites are present almost everywhere in Europe, close to the existing Steel Mills (100-200 km) [83].

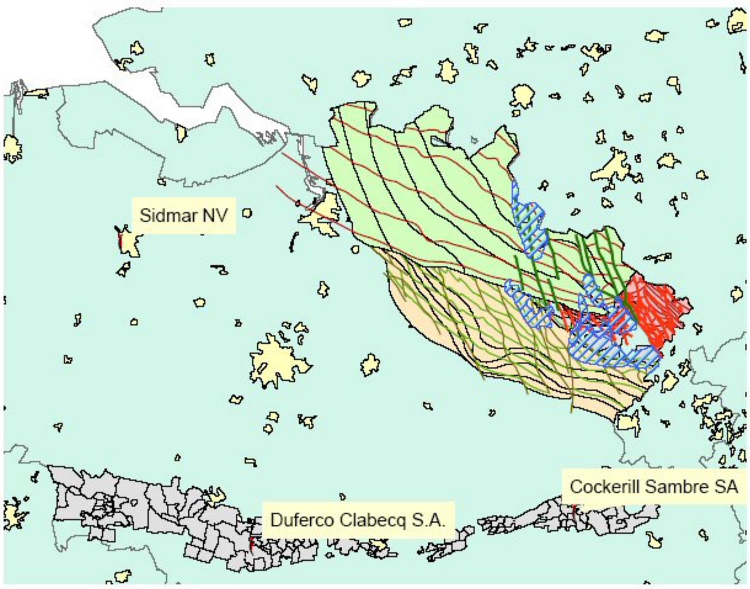


Figure 34 – Geological structures favorable for storage in Belgium, close to the Gent Mill of ArcelorMittal (Sidmar)

Five sites have been selected for identifying storage site more precisely: Scunthorpe (CORUS), Sidmar-Gent (ArcelorMittal), Taranto (RIVA), IJmuiden (CORUS) and Fos-sur-Mer (ArcelorMittal). Figure 34 shows the area close to ArcelorMittal Works in Gent, where the Dinantian aquifer (beige), the Bunter aquifer (pink), the Cretaceous aquifer (green) and coal fields are all candidates for storage, with potential injection points in the dashed area [83].

More detailed investigations are necessary to identify a site. They usually include the analysis of existing geological data from previous drilling campaigns that were conducted when the are was searched for oil or gas, modeling of the site to assess its size, capacity (geographical extension and porosity) and injectability [83]. Then dedicated campaigns of geophysical measurements are necessary to complement the existing data, which are usually insufficient. Some experimental drillings complete the process to lead to a full assessment of the potential of the site. This stage requires an exploration permit. Actual injection can then theoretically start, if an operation permit has been secured. These steps have been started by various players in the Steel Industry but most are not public yet.

Transportation to the sites would be carried out either by dedicated pipes or by batch transport, mainly ships (barges on rivers and sea vessels on the ocean, although some projects are planning to start operation by hauling CO_2 in trucks).

In the longer term, the collection of CO_2 and its transportation towards a field of large storage sites will most probably be organized at a regional level. Networks will be built in various regions and form a series of convergent but separated networks, which have been compared to a sunflower field, as shown in Figure 35 [84]. The emergence of such networks can be inferred from various initiatives, led by industrial operators, which have expertise in geological ventures, like the oil or the gas industry, or which have streams of CO_2 to store (like the Steel or the Power industry), by regional associations (like the *Yorkshire forward* initiative [85], or the Fos or le Havre ones [86]). At the end of the process, various operators will propose storage as a service to local regional communities, in consortia led by industry, regional organizations or financial operators.

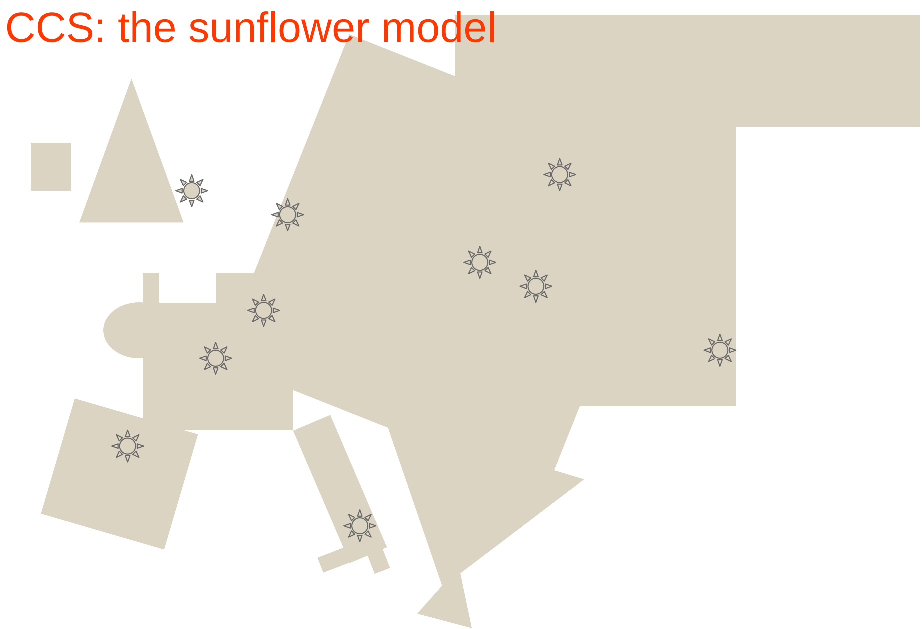


Figure 35 – the "daisy grid" model of CCS in Europe

6. Current activities and projections on role of CCS

What are the research programs going on in the sector? Are they privately or publicly funded? What are the current experiments and (if applicable) larger-scale demonstration of CO_2 capture in the sector? What role do optimization models indicate CCS would play in the sector and what are the main assumptions behind those projections?

These issues have been addressed in the previous chapters.

Programs are privately and publicly funded, in every country in the world. Public funding can be up to 100%, like in Japan with the COURSE 50 program. The ULCOS I program has been funded at the level of 44%. The level of public vs. private funding of ULCOS II has not been disclosed yet, but the structure of the funding makes it clear that it will be more than 50%.

A vision of a calendar for the deployment of the ULCOS technologies has been proposed as shown in Figure 36 and Figure 37. These are rough estimates, visions that are probably rather optimistic.

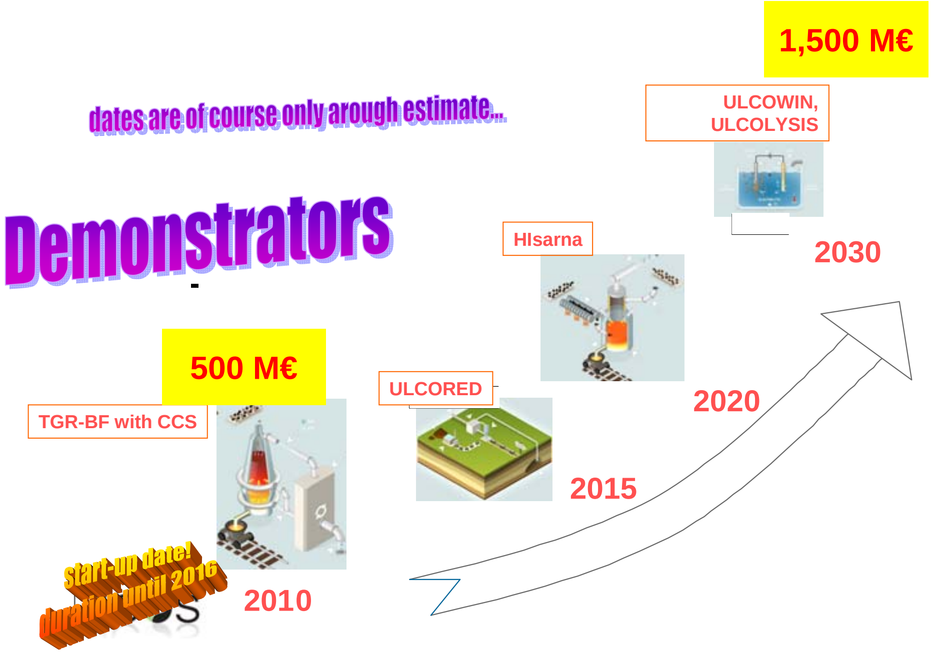


Figure 36 – deployment of the various ULCOS technologies in terms of demonstrators. The date shows when the demonstrator will start being built: design, erection and start up will last at least 5 years.

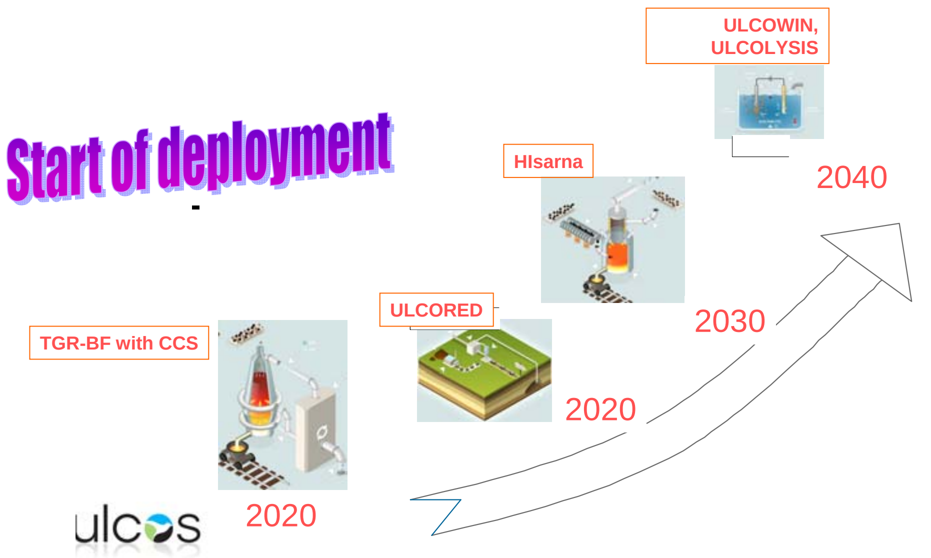


Figure 37 – commercial deployment of the various ULCOS technologies.

If a longer term perspective is adopted, in line with the vision of a post-carbon or low-carbon society and of a closed loop society, then the vision shown in Figure 38 would be of the essence. It shows a future extending over 2 centuries, which would be somewhat preposterous if the storyline was taken as a real projection, and is purporting to say that a post-carbon society is likely to emerge, if the Climate challenge is indeed acted upon competently, towards the end of the present century, while economic growth would continue beyond that transition to ensure that the shift of economic paradigm and of technological episteme takes root and takes over from the previous one until some acceptable level of well-being is achieved all over the world. Then, if and when society stabilizes around a smaller material economy, then it could become close-loop as far as basic materials such as steel are concerned. Of course the times of these transition may be off by as much as 50 years, and the order of the assumed "peaks" can be reshuffled[16], etc. The shear concept of a peak is also a matter of conjecture, for population, or almost everything else: peak may be plateaus and what is called there loosely a GDP peak might actually better be termed the time when prosperity and CO_2 emissions have become uncoupled.

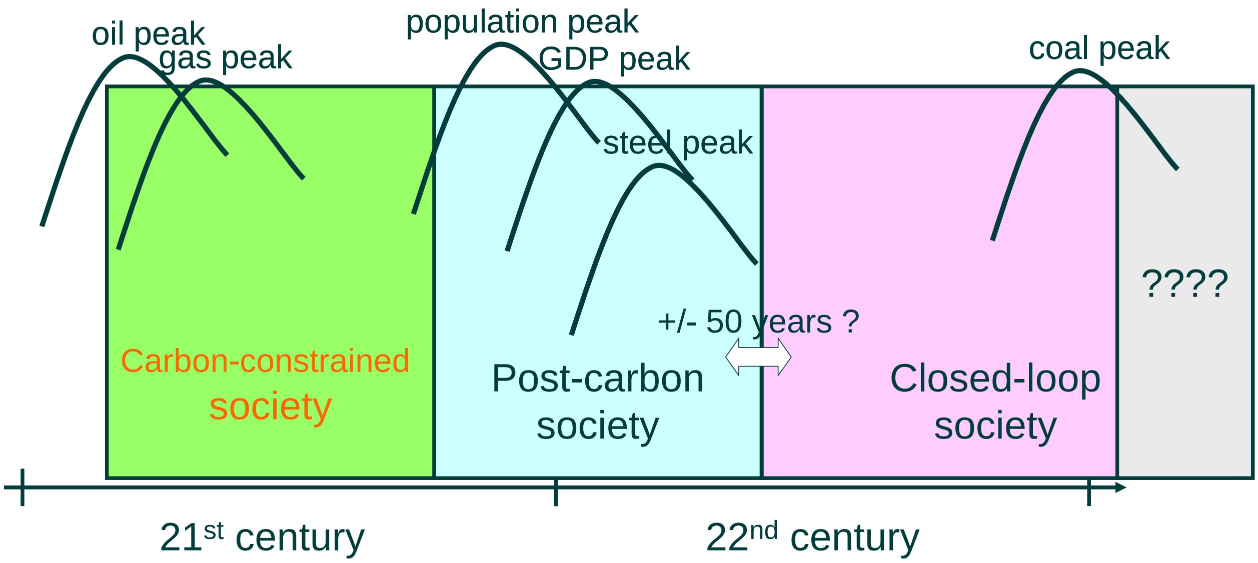


Figure 38 – vision of carbon-constrained and post-carbon societies from [87]

Until this future societies can take over, if they ever do, steel made from carbon and thus with CCS will be necessary for a long time, then carbon-free options can take some market share and eventually, in a very far away future, recycling can shoulder most of the needs; but the later proposal is not likely to happen soon and in between, CCS will be needed in a lasting way for the Steel sector.

This is in that sense that we have already stated that CCS is not a bridging technology for the Steel sector.

The present review, being a review of what is actually going on in the development of new carbon-lean process technology in the Steel sector, is very focused on the EU and thus could be considered as Eurocentric. Moreover, the advance of the EU work in this field is directly related to the political landscape there, where a strong climate agenda has been pushed forward consistently for a long time.

If technology can be driven by a political vision, technologies are not necessarily ethnocentric. This is the case in the field reviewed here. Steel production technology is global: regional differences are small and related to materials supplies on the one hand, also a global matter, and to the status of the market on the other hand and of its needs in terms of level of quality and sophistication of the applications, a more local matter but one that is controlled by downstream processes which do not intersect with climate change issues.

[16] and some of them may be pushed forward into the future, like the assumed *peak gas,* due to the use of shale gas and of other unconventional gas resources.

What is local and regional is the political vision which is built to answer the climate challenge. In this matter, the status of CCS is not clear everywhere in the world: people are wary that it is only used in a very limited number of cases and may see it as a simple solution for the "rich" countries to exonerate themselves rather easily from their "responsibility" in the past accumulation of GHG in the atmosphere, the present cause of global warming; they also do not necessarily have a detailed knowledge of the potential for CCS in their own area – an ignorance which they share with developed countries.

Last, the issue of how to pay for these expensive technologies is as strong in developing countries as in developed ones. They have had a tool at their disposal, though, CDMs, which is not available to developed countries. This point, which clearly creates a dissymmetry between North and South, will be picked up later.

Another point is that we have centered our discussion on geological storage. This is indeed the only available solution today, in spite of on-going research based on a broader definition and acceptance of the concept.

It was pointed out that biomass can be considered as a storage option. This is right in a general sense and the political drive, for example, to have primeval forest management as a key tool to managing worldwide emissions is part of that worldview.

In a particular sector like the Steel sector, however, biomass can probably bring local solutions, and, indeed, this is already practiced in Brazil and is the subject of active research in the world CO_2 Breaktrhough program (Australia, Canada, Brazil).

How far these solutions can be extended and how much they can contribute to the global reduction of emissions of the steel industry is another matter. In Brazil, charcoal-based blast furnaces account for 10 Mt/yr of production, i.e. 10^{-6} % of the world's. Estimates have been made of how much land would have to be converted to biomass for steelmaking and it has been demonstrated that this land is available with much leeway and under sustainable forestry conditions [88]: they point out to land in central Africa or central South America, which is not connected to harbors for exports or to steel producing regions at the scale required by a global solution. On the other hand, the conflict between using land for growing foodstuff or energy crops is a real one, especially in view of the upcoming need to feed the growing world population until it peaks towards the end of this century [89].

Thus the jury seems out on the matter and the issue is clearly out of the hands of the Steel sector: it is an international issue due to this food issue and also to the fact that building a global logistical system to move huge amounts of biomass around would have to be build at a world level from scratch.

In the "short term", i.e. within the climate change temporality which seems to be calling for action as soon as 2020, it is not yet an option.

7. Estimated investments and costs

What are the costs of applying CO_2 capture to the industry? Costs should in any case be expressed as costs of CO_2 captured (or maybe avoided) and if possible in added costs per unit of product and up-front investment costs. What are the assumptions behind the costs? It is important to indicate whether costs are dependent on energy prices or other resource costs, such as steel prices. If there is readily available information available, what might be the cost reduction as a consequence of learning and economies of scale in the sector; what does the learning curve look like?

I am very reluctant to review existing published data on costs, both OPEX and CAPEX, as I am convinced that they are overly optimistic and thus quite misleading. Moreover, there aren't any, as far as I am aware, which relate to the Steel sector reliably, anyway, or these are quotes that are unsubstantiated.

I remember statements in Australia, 5 years ago, where total CCS cost was estimated at 10 $/t of CO_2. Then common wisdom placed the cost at less than 50€/t. In the CCS international conference in Paris, in December 2009, speakers were quoting a range of 50 to 100 €/t. Rather paradoxically, the costs quoted are going up while people dissert on the learning curve, which should bring these costs down!

What is really needed at this point, rather than publishing low figures probably to encourage actors to adopt the technology, is actual demonstrator experiments, which will come up, in due time, with real, robust and substantiated cost estimates.

There are data in the general literature quoting costs for CCS in the Steel sector, for example in [31] and [23] (40-50 US$/$t_{CO2}$). These two examples, however, are misquotes[17] and they are repeated over and over. There is no sound basis for publishing data in this area: of course, all projects make assumption on the cost but the assumptions are very uncertain. The uncertainty, that [23] estimates at 30%, is much larger, probably much more than 100%.

The on-going demonstrators are being run for the purpose of reducing this uncertainty and the enormous risk that it entails!

Now, of course, assumptions on CO_2 abatement price have been made to run the economic models. However, in the case of the POLES model for example, the results are not very sensitive to these assumptions. What this modeling says is that the cost of CCS should be less than several hundreds of € (between 100 and 600€) in order to play a role. Whether this can be achieved, especially the lower target, is still an open question.

[17] See cover email

8. Characterisation of the industry

Table 6 –steel producers ranked by production level

2008		2007			2008		2007		
1	101.6	1	116.4	ArcelorMittal	41	6.9	41	7.3	Salzgitter[5]
2	37.5	2	35.7	Nippon Steel[1]	42	6.9	43	6.9	voestalpine
3	35.4	6	28.6	Baosteel Group	43	6.8	45	6.6	Panzhihua Steel
4	33.3	4	31.1	Hebei Steel Group	44	6.5	38	7.8	Jianlong Group
5	32.4	3	34.0	JFE	45	6.5	44	6.8	BlueScope
6	31.7	5	31.1	POSCO	46	6.4	46	6.4	Metalloinvest
7	27.7	11	20.2	Wuhan Steel Group	47	6.4	47	6.4	Beitai Steel
8	24.4	7	26.5	Tata Steel[2]	48	6.1	58	5.2	Guofeng Steel
9	23.3	9	22.9	Jiangsu Shagang Group	49	6.1	50	6.1	SSAB
10	23.2	10	21.5	U.S. Steel	50	6.0	56	5.4	Erdemir
11	21.8	8	23.8	Shandong Steel Group	51	5.9	53	5.9	AK Steel
12	20.4	12	20.0	Nucor	52	5.9	51	6.1	Mechel
13	20.4	13	18.6	Gerdau	53	5.7	52	6.0	Nanjing Steel
14	19.2	15	17.3	Severstal	54	5.6	42	7.0	Ilyich
15	17.7	17	16.2	Evraz	55	5.4	59	5.0	Tonghua Steel
16	16.9	14	17.9	Riva	56	5.3	54	5.6	Xinyu Steel
17	16.0	18	16.2	Anshan Steel	57	5.2	55	5.5	HKM[6]
18	15.9	16	17.0	ThyssenKrupp[3]	58	5.1	63	4.5	Sanming Steel
19	15.0	19	14.2	Maanshan Steel	59	5.0	57	5.3	CSN
20	14.1	21	13.8	Sumitomo Metal Ind	60	4.7	61	4.6	HADEED
21	13.7	20	13.9	SAIL	61	4.5	66	4.4	Tianjin Tiantie Group
22	12.2	24	12.9	Shougang Group	62	4.4	71	4.0	Hebei Jinxi Group
23	12.0	22	13.3	Magnitogorsk	63	4.3	60	5.0	Steel Dynamics
24	11.3	30	9.7	Novolipetsk	64	4.3	68	4.1	Pingxiang Steel
25	11.3	26	11.1	Hunan Valin Group	65	4.3	64	4.5	Ezz Group
26	11.0	27	10.9	China Steel Corporation	66	4.0	70	4.1	Nisshin
27	10.4	23	13.1	Techint[4]	67	4.0	69	4.1	Tianjin Steel
28	10.0	28	10.1	IMIDRO	68	3.9	62	4.6	Zaporizhstahl
29	9.9	25	11.6	Industrial Union of Donbass	69	3.8	81	3.0	JSW Steel
30	9.9	29	10.0	Hyundai Steel	70	3.7	72	4.0	Lion Group
31	9.8	34	8.8	Baotou Steel	71	3.7	74	3.5	AHMSA
32	9.2	31	9.3	Taiyuan Steel	72	3.7	83	3.0	ICDAS
33	9.0	33	9.0	Anyang Steel	73	3.6	67	4.3	SIDOR[8]
34	8.2	32	9.1	Metinvest	74	3.6	76	3.5	Hangzhou Steel
35	8.2	36	8.1	Celsa	75	3.5	91	2.7	Hebei Jingye Steel
36	8.1	37	8.1	Kobe Steel	76	3.5	75	3.5	Chongqing Steel
37	8.0	35	8.7	Usiminas	77	3.4	93	2.7	Commercial Metals
38	7.5	49	6.2	Rizhao Steel	78	3.4	73	3.6	Essar Steel
39	7.4	39	7.6	Benxi Steel	79	3.4	77	3.5	Tokyo Steel
40	7.0	40	7.4	Jiuquan Steel	80	3.1	79	3.2	Vizag Steel

What industries are involved in the sector? What are the dominant companies? Does the sector consist of many smaller companies or is the global picture dominated by a limited number of players? Is the industry risk-averse or risk-seeking; innovative or conservative; globally active or primarily supplying a domestic market; heavily regulated or fully free?

The Steel sector is composed of Steel Companies, a statement that seems tautological but is probably not, with other sectors in mind. Its value chain of steel production, upstream, includes raw material suppliers, coal and iron ore as well as alloy producers for additions (ferroalloys, but also aluminum, zinc, tin, etc.), electricity facilities and gas producers (oxygen, nitrogen, argon). Equipment manufacturers provide the equipment that the steel mill uses for running its processes.

The 12 largest companies represent only 21% of world production, while the largest one accounts for 9% of it. The Steel sector is thus not very concentrated.

Is the industry risk prone or adverse? Worldwide, the industry has been able to adapt very quickly to changes in demand, upwards and recently downwards. Technologies seem to be stable (i.e. to change slowly or not at all), but this is actually not the case, as even if processes still bear the same names, like the blast furnace, they are in details operated in very deeply changing conditions: energy consumption, for example, has been cut by roughly 60% over the last 50 years [90]. In the field of low-carbon operation, the steel industry RTD programs are exemplary and quite advanced compared to what is going on in other basic materials industries.

Innovation is very related to risk and therefore the attitude of the industry toward innovation is similar to that related to risk.

As mentioned earlier, international traded steel amounts to 40% of production. This is a high figure, which creates an international price signal that is differentiated between regions by transportation cost. This also probably explains why the trend is for best technologies to become the standard all over the world. Differentiation between players is thus not based on process technologies.

The Steel market is not particularly regulated any longer[18] but operates in a rather pure market economy.

An important point is to estimate how big an impact the carbon value can have on the steel business, as compared to other commercial activities. This is done fro example as in Figure 39, where the carbon intensity (t of CO_2) is compared to the revenue of the sector, measured in 10^3 $ [91]. Industries have very different sensitivities, as the figure shows rather obviously, which is a way to express that utilities and even more so materials industries are more sensitive to the price of carbon that oil and gas.

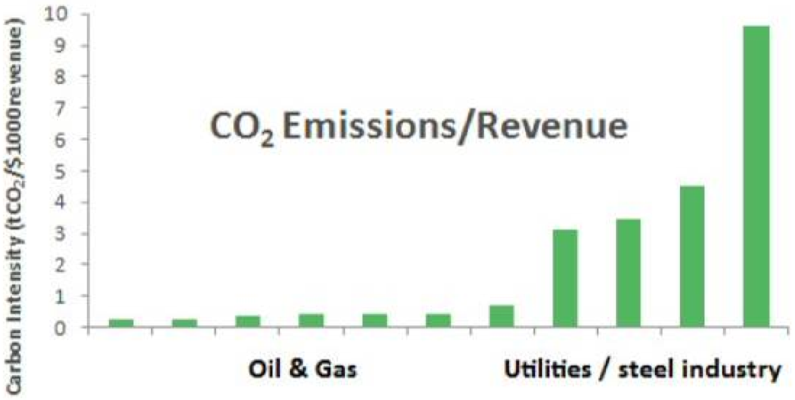


Figure 39 – carbon intensity of various industries measure as a fraction of revenue

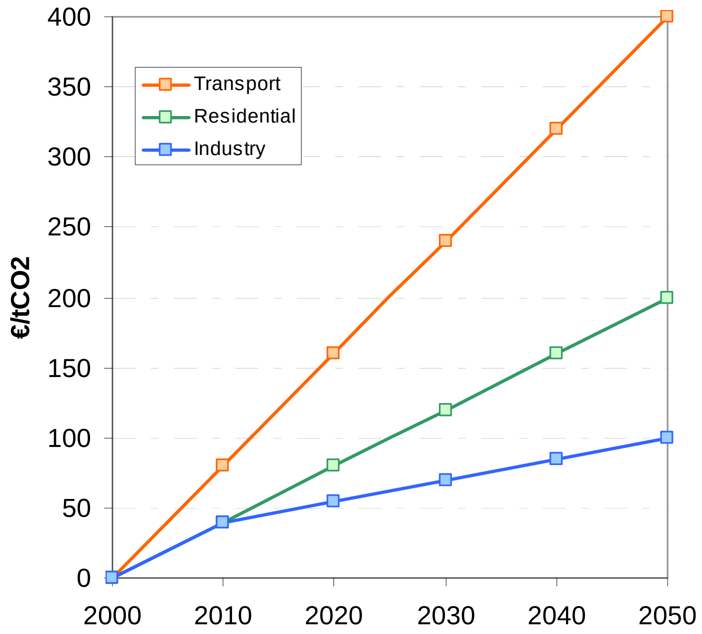


Figure 40 – carbon values designed in 3 major sectors (transport, residential and industry) to produce the same reaction in terms of CO_2 mitigating cuts

This has led the ULCOS program to propose a differentiated carbon value depending on the sector, with a criterion of imposing a level of carbon pressure on each sector that would give the same effect

[18] This was quite different 20 years ago, when the Steel sector was going through the dark ages of the 40 piteous years. The heavy restructuring which accompanied a huge increase in labor productivity led many of the companies into bankruptcy, which were accommodated by nationalization, in Europe especially.

in terms of carbon mitigation level. The rationale is that the value of carbon is not determined by a physical market, where some well defined product is exchanged between operators on an equal footing, but is an artificial construct, a kind of market metaphor designed to make economic players react to a price signal.

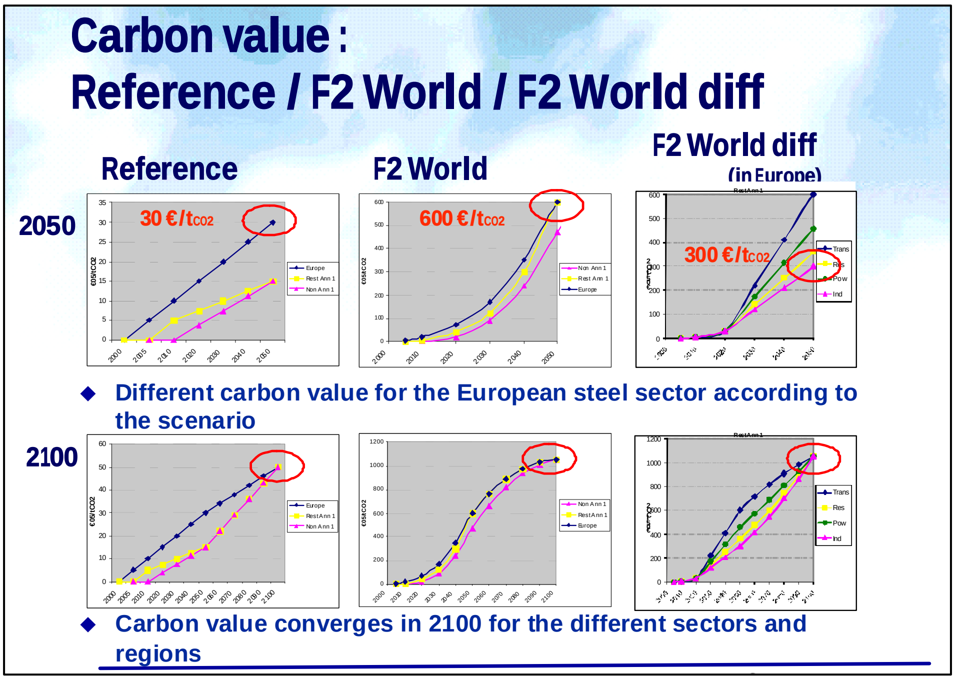


Figure 41 – time dependence of differentiated carbon value As a function of time until 2050 and 2100, with comparison with to same-carbon-value scenarios

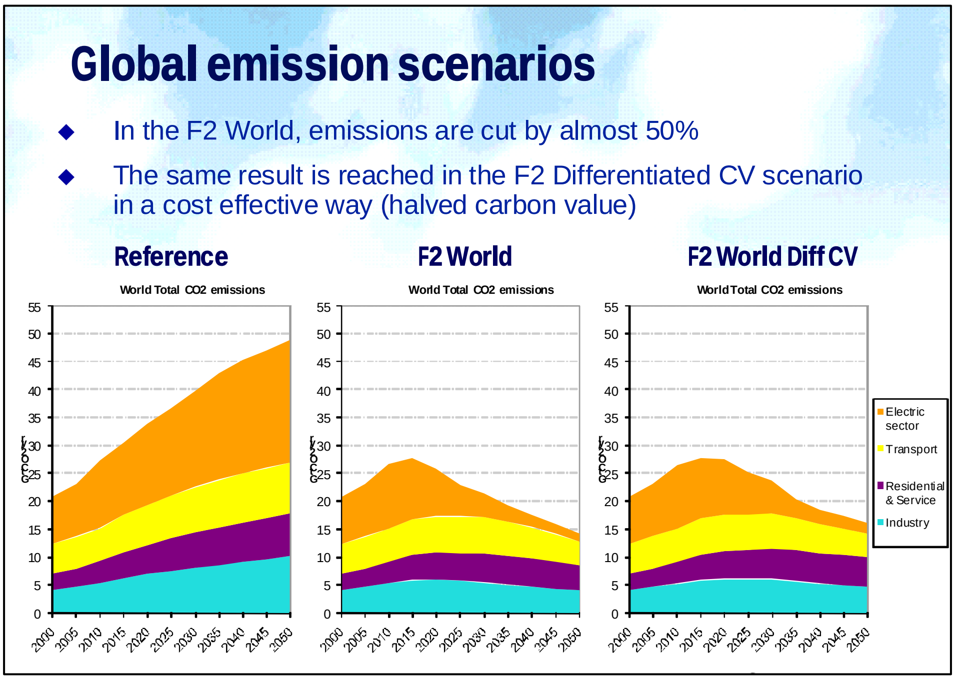


Figure 42 – results in terms of global emission scenarios for the ULCOS/POLES modeling work; the differentiated carbon value assumption is shown to the right.[19]

The price proposals modeled with the POLES model over the period extending until 2050 are shown in Figure 40, with more details given in Figure 41 as to how they were implemented in the series of foresight scenarios used in the ULCOS studies as compared to the other same-carbon-value scenarios.

[19] Already shown as figure 18 at the request of the reviewers

Figure 42 demonstrates that the differentiated carbon scenario indeed achieves the expected level of cuts, but at a lower cost for the industry and carbon emission sectors.

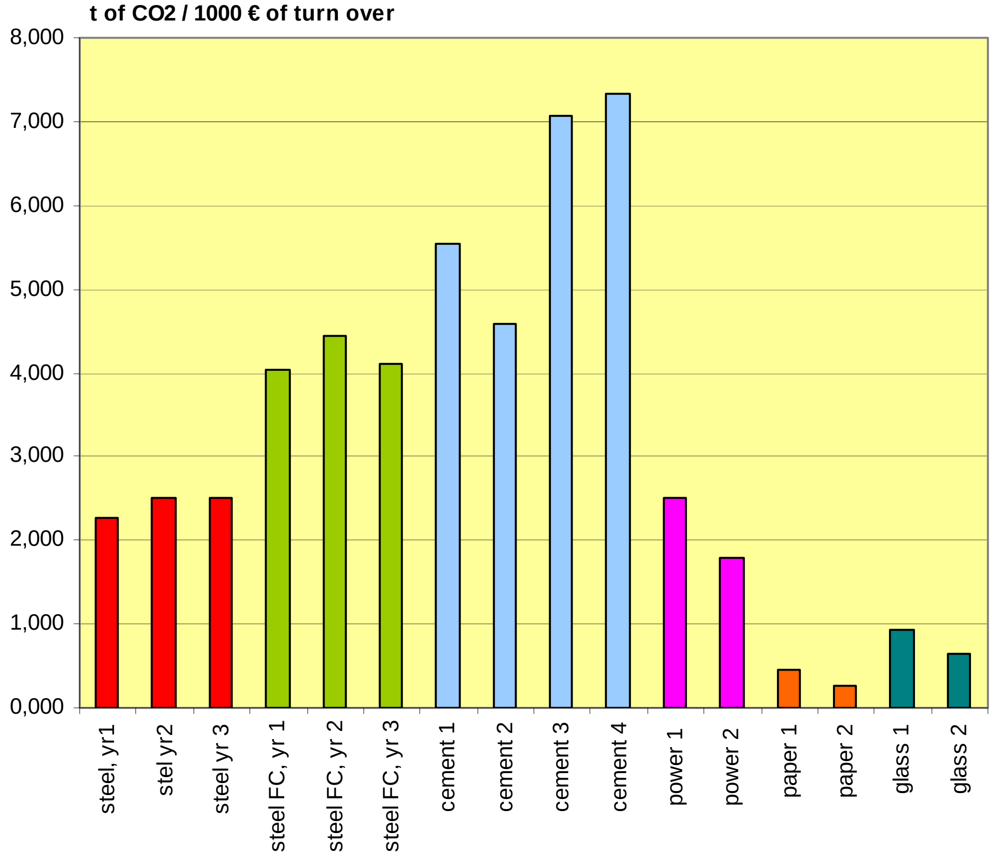


Figure 43 – carbon intensity (t/1000$ of turn over) of various materials producing sectors

A similar analysis on the carbon intensity of the turnover of various material sectors is shown in Figure 43 [92]. They show the dependency of various materials on carbon (steel, flat carbon steel = steel FC cement, power generation, paper, glass; the index represent different companies in the same sector, like cement 1, cement2, etc.), normalized by the market price. Cement is most impacted and then steel. This also pleads for the differentiated carbon value concept presented before.

All of the comments made until now in this section apply to the Steel sector, irrespective of its geographical base.

The area where a strong difference exist is the value of carbon, which is likely to be inhomogeneous between developed and developing countries, at least at a given time in the short and middle terms. This would be a cause for carbon leakage, i.e. for a rebound effect that would create great stress in the Steel sector of developed countries and make no contribution whatsoever to the reduction of global emissions.

There is therefore a possibility of the steel industry relocating from high-cost carbon countries to low-cost carbon countries.

The effect is compounded by the CDM mechanism. The value of carbon that it embodies is quite different from that brought by an ETS mechanism: CDM is related to an actual cost of abatement, while ETS generates a market price. The risk is low in the first case, higher in the second. This is particularly in favor of the CDM beneficiaries, as long as the price of CO_2 is low, like today.

With the kind of "buy out of indulgences", that CDM constitutes, the party which finances CDM can continue to produce CO_2, while the party that benefits from them can avoid generating them. There is no physical compensation between the two sides, only a virtual compensation: thus emissions can be avoided in a different sector from where they are generated or through increases of capacity: "additivity" is therefore not guaranteed.

9. Current environmental legislation and pressures

How is the industry regulated, in which regions, for greenhouse gases or (if relevant) for other environmental pressures?

Environmental regulations apply to the Steel sector in the same manner as to any other sectors.

The worldwide environmental regulation picture is known from other sources, with the hues of local geopolitics. International gradients are strong, sometimes discontinuous, for example between EU regulations, very "advanced" in terms of carbon constraints, and North American or Asian ones. Carbon intensive industries claim that this introduces a strong risk of carbon leakage, which would grow all the stronger as the price of carbon goes higher. Some projections for 2050 calculate costs at 400 €/t of CO_2 or higher, which would create a gap of twice this amount per ton of steel, if a level playing field is not met by that time: it would be utterly unsustainable for companies located in such carbon-heavy regions.

10. Major gaps and barriers to implementation

Based on the above and in those categories, what are the major gaps and barriers to deployment of CO_2 capture in the sector? This section will be the basis of the actions and milestones of different actors and stakeholders in the later sections of the roadmap. The following areas should be considered when addressing this: technical, policy, legal, financial, and market and organizational requirements.

The major barriers to the development of carbon-lean steelmaking technologies and, in particular of those that are based on CCS, are discussed below under the headings suggested by the UNIDO staff. Since these matters are closely related and self blocking, the various paragraphs could actually be read in a random order!

Technologies

Today, low-carbon technologies for the Steel sector are under development under various programs in many countries in the world.

The worldsteel *CO_2 Breakthrough Committee Meeting* is an exchange forum, where most of the effort in the area is regularly presented and discussed [103]. The largest programs are under way, in terms of size and budget, in Europe (ULCOS), Japan (COURSE-50) and Korea (POSCO). The EU program started earlier and has a closer time horizon than the Japanese program. The timeline for the Korean program is not published. There are also on-going programs in the USA (AISI), Canada (CSPA), Australia (a Bluescope + OneSteel consortium) and Taiwan (China Steel), which are either less ambitious in terms of mitigation level or still at a rather conceptual level in academic work carried out in Universities. What is happening in China is not reported clearly and India, which has decided to join the program, has not physically participated yet.

Be that as it may, it looks quite obvious that the earliest when the first technologies can reach a commercial stage is the early 2020s. The size of the innovations envisioned is such that it seems rather unlikely that programs can be accelerated beyond what already looks like a hectic pace.

Provided of course that the other caveats mentioned later in this chapter are taken on board and the underlying issues solved positively…

Policy

A policy framework, at international, regional and national levels is necessary. Of course, there are alternatives, dividing the planet not along national borders but across sectoral boundaries, the so-called *sectoral approach.*

Policies translate climate issues into political targets.

I reproduce below a presentation made at the International Conference on CCS regulation for the EU and China [84].

Some boundary conditions…

ArcelorMittal

- how to internalize CO_2 cost in the market economy?
  - ETS favored in Europe, and probably elsewhere soon / carbon tax / no constraint! / non-monetary incentives (standards, labels, voluntary agreements)
  - *one carbon value for all… or not?*
  - *share the burden with the value chain in a life-cycle approach?*
- international competition, level playing field and carbon leakage
  - some relief on that front if/as steel is considered as a carbon leakage industry in EU until 2020
  - however, the cap will still be decreased by 21% in 2020: more than what is achievable with existing technologies, while the BT will/might only be taking off by then!
  - what happens beyond 2020?
- steel needs CCS as a key part of the solution
  - access to storage sites at technical cost
  - needs sites close to its major production sites: do enough *safe* sites exist? Can they be developed quickly enough? Are players ready to go ahead and act by creating collection and storage networks?

Breakthroughs & CCS… (1)

ArcelorMittal

- issues with "penalties"
  - ETS (or a tax) system favors the 11th hour worker to the vineyard! Past efforts not rewarded
  - while Steel develops BTs, needs to pay for emission rights (in part or in full): double jeopardy!
  - ethical issue: equity between rich and poor?
- issues with timeline
  - timeline for BT development very tight!
  - timeline for CCS implementation and authorization: probably rather long!
  - timeline for meeting CO2 cuts: set for 2020 in Europe, not yet beyond
  - the 3 timelines do not match!!! Only 1 under industry control, 2 others depend on the Commission

Breakthroughs & CCS… (2)

ArcelorMittal

- issues with OPEX & CAPEX
  - BT technologies will cost (no-regret solutions available today have already been implemented!)
  - Steel may demonstrate some more energy savings along with CO2 cuts – some minor relief
  - extra-OPEX due to CCS to exceed profit margin: ought to be passed to final customer (risk of carbon leakage) or paid for externally (green subsidies?)
  - CAPEX for switching over to C-lean BT: 1300 G€ in the world!
- issues with technology development cost
  - development cost: ULCOS II (next step) estimated at 500 M€ +
  - includes development of CCS
  - need for state involvement, subsidies for research, bank loans for developments

Breakthroughs & CCS… (3)

- issues with deployment
  - timeline in Europe and in the rest of the world (beyond 2020?)
  - CAPEX and OPEX issues
- issues with CCS
  - necessary to obtain ETS rights for CCS, at least for as long as the carbon leakage risk is there
  - CO2 purity target should not add extra burden to Steel for arbitrary, bureaucratic reasons
  - on-going rush to "capture" storage sites with the risk of creating a monopolistic / oligopolistic system where prices expand in a new kind of bubble: storage sites are public goods and collection and storage service ought to be a public service?
- other issues
  - Risk: in terms of cost and in terms of success!
- Steel needs a sectoral approach that takes on board all the above issues!

Breakthroughs & CCS… (3)

- issues with deployment
  - timeline in Europe and in the rest of the world (beyond 2020?)
  - CAPEX and OPEX issues
- issues with CCS
  - necessary to obtain ETS rights for CCS, at least for as long as the carbon leakage risk is there
  - CO2 purity target should not add extra burden to Steel for arbitrary, bureaucratic reasons
  - on-going rush to "capture" storage sites with the risk of creating a monopolistic / oligopolistic system where prices expand in a new kind of bubble: storage sites are public goods and collection and storage service ought to be a public service?
- other issues
  - Risk: in terms of cost and in terms of success!
- Steel needs a sectoral approach that takes on board all the above issues!

11. Conclusions

The Steel sector, worldwide, is one of the major energy intensive industries and thus one of the major industrial emitters of CO_2 in the world – roughly at the level of 5% of anthropogenic emissions.

This is the case today and this will remain true in any foreseeable future, because steel is a core structural material, which is directly related to the technological episteme on which our societies are based; the trend has been robust over historical time and will remain robust over "climate change" temporalities. If the world is to continue growing, to accompany the growth of population still to come and the growth in standard of living which goes along with the fight against poverty, then steel will continue to be needed in high volumes: projections are for production roughly to double by 2050. Other materials will fare as well, but no other material is likely to replace steel in volume and in structural applications. Almost every artifact in the world today is either made of steel, in part or in total, and/or made from tools and machines made of steel: if steel has been branded as the cause of our present civilization [93], then removing steel altogether from our constructed environment would mean no less than its collapse.

It is fairly easy to find out how much energy the sector consumes and top-down estimates, like the IEA's, agree with bottom-up ones based on the aggregation of the consumption of all steel mills. The amount is on the average around 21 GJ/t of steel, with best performers at 17 GJ and "worst" ones at 50 GJ - or so it seems in a context where bottom up data are still scarce.

This is not the case for CO_2 emissions, where the uncertainty is very large in terms of data and where a lot of fuzziness is introduced by accounting rules, like the scopes I, II and III of the Greenhouse Gas Protocol, and by the legal status of the steel mills themselves, which may or may not include important plants in terms of emissions. It is not simple to reconcile top-down and bottom-up estimates and large efforts are under way to collect data and come up with accepted figures. Figures can vary from 1 to more than 2 in terms of sectoral average, while the spread between best and worst performers is also large and adds to this confusion in numbers. The only simple way to deal with this difficulty is to speak about some clearly defined model steel mills and to build a model Steel sector around them: such a steel mill would emit 1.7 t of CO_2 per ton of steel in an Integrated Mill, 0.3 t in an EAF Mill and 1.3 as the whole Steel sector. We won't venture further in providing more data in this conclusion, because they remain very fuzzy. It should be clear, however, that the sectoral emissions are certainly much higher.

The basic reason why CO_2 emissions and energy consumption cannot be pinpointed with the same accuracy, or rather, certainty, is that CO_2 has been considered, heretofore, as an end-of-pipe emission in the stacks where products of carbon oxidation are sent to the atmosphere, while energy is paid to suppliers according to well known market prices and commercial practices. The value of CO_2 is thus fuzzy for very many reasons, while the price of energy is not!

Looking for solutions to shift to a carbon-lean society, however, does not necessarily require to fully clarify these complex accounting issues.

Technological solutions are rather simple to explicit in terms of process routes. Implementing CCS is one of them and one of the major ones, according to the analysis of the ULCOS consortium. Non-CCS solutions are either long term and, even though quite promising (e.g. electrolysis of iron ore), will need time to develop at a large enough and credible scale and will need a major paradigm shift in terms of energy prices for electricity to become competitive with coal - and require other conditions for hydrogen and biomass to become a real alternative -, or are based on the confusion introduced by the artificial boundaries set around the Steel Mill: some solutions look indeed as if they have outsourced their CO_2 emissions and forgotten about them.

It should be clear by now that these breakthrough technologies still retain a level of technological uncertainty as they need to be demonstrated at a credible large scale. They belong to a technology optimistic view of the world.

With this analysis, CCS for Steel is not a transition or bridging technology, unless one plans for the 22nd century and beyond…!

A major uncertainty, beyond that related to capture technologies, has to do with storage. Pore volume available for storage is also known only in a fuzzy way, and a concept similar to that of reserves and resources, well known in the oil and mining businesses, has to be marshaled and fleshed out in terms of analysis and data. This introduces all kinds of difficulties, for example in terms of the time needed to obtain storage permits in deep saline aquifers. Stakeholders, like NGOs and local population, are or may be wary of CO_2 storage, for a variety of reasons, including NUMBY[20], but the fears and controversies are mainly fueled and driven by the prevailing uncertainty on knowledge.

It is important to note that CCS as reinvented for the Steel sector might be somewhat less of a cost burden than it probably is in the power sector, because the solutions exhibited for example for the ULCOS-BF process save energy, coke consumption and increase the productivity of the blast furnace. This, however, does not make the use of CCS a no-regret solution until the value of CO_2 reaches some high level, and thus raises issues of who can afford to pay for these extra costs.

There are also various difficulties related to the implementation of these solutions.

At the level of technology development, the costs are high, both CAPEX and OPEX, and the future returns extremely unclear in financial terms – they actually and plainly show up as negative in a conventional business model. Therefore, the financing of these programs – very roughly of the order of 1 billion dollars per demonstrator - is in question and solutions for marshaling support for them, especially from public funding, are needed. Such schemes are already being set in place in Japan, the EU, the United States, other individual countries, etc., but still remain uncertainty in terms of organizing real projects, which may cause delays with regards to the political targets on climate change.

At the level of implementation, the same is true, except that it is rejected to a fairly distant future in the temporality of strategic planning in the business world. Issues range broader, as the gradient between carbon values across world regions may induce carbon leakage, industrial vagrancy, offshoring of production and constitution of carbon havens. If these issues are not settled, and settled fairly quickly, the uncertainty that they create will slow down any decision on implementation, even at the level of strategic planning, and may eventually completely scuttle the concept of CCS in the sector.

The construction of a system to internalize a value of carbon in the economy remains unclear, except that an emission trading system, complemented by a tax system, seems to be preferred - with various recipes for the cocktail. Solutions like a differentiated carbon value among sector emitting CO_2 would be a welcome refinement.

It is not easy to understand how these carbon pricing "solutions" can help shift over to the breakthrough technologies that are necessary to cut emissions in a drastic way in the Steel sector, except that they might impose some kind of double jeopardy on the Steel sector, something that the Steel companies are seriously wary of.

Important also to decrease this uncertainty is the need for rules on CCS, especially on storage, that cover enough of the world to create a level playing field in this legal area as well. Rules are now clearer in the EU for example, but not everywhere else. These pieces of legislation and of the accompanying regulation needed to define the associated details ought also to have consequences in terms of accelerating the permitting processes, which cause one of the major delays today in the implementation of real demonstration projects.

Last, let's not forget that CCS only deals with one single greenhouse gas and that there are also non-CCS solutions. In the case of Steel, this means continuing to have a strong recycling economy, which is the case today for steel scrap and EAF steelmaking under market rules. There is no reason to believe that this will not continue spontaneously, except that any political measures proposed in the future should not somehow create rebound effects that would be detrimental to recycling – and vice versa.

One of the keys to success - if success is defined as the deployment of CCS in the Steel sector - is to spread out the creativity of finding carbon-lean solutions to making steel across the value chain or the life cycle of this activity. It is interesting to note in this context that LKAB, an iron ore miner of Sweden, is part of the ULCOS consortium; ULCOS is also related to HIsmelt, which belong to Rio Tinto, a major ore and coal miner in the world.

[20] Not Under My Back Yard

The concept of a CCS-ready steel mill was discussed in the Abu Dhabi seminar, in connection with a popular expression used in the power sector. It was first pointed out that the concept is not completely clear. In the Steel sector, like in the ULCOS-BF case, it is possible to imagine implementing in-process CO_2 capture, pure oxygen injection at the bottom tuyeres and recycling of the decarbonized top gas: this CCS-ready blast furnace would be a major technology shift, making more than a simple provision for later storage, made in terms of room left to connect to the gas pipe line through a pumping system.

Now, how geographically or geopolitically localized are these conclusions?

Since the most advanced program in the Steel sector for CCS and Low Carbon Technologies implementation has been going on in the EU, which is also the region where Climate Policies are rather advanced, some of the information reviewed here may be seen as Eurocentric.

Steel technology, however, has been global for decades and thus the way to analyze the climate change challenge in the Steel sector ought to be global as well. Solutions may be more local, though, and this has been acknowledged in the work done at worldsteel [94]: thus, countries where the level of biomass per capita is high (like Brazil, Australia, Canada, and Scandinavia in Europe, to mention CO_2 BP members), are looking at ways to use more biomass in iron and steelmaking; countries which have an access to cheap natural gas, available for the long term, will privilege direct reduction, initially without CCS unless they can "sell" as a CDM; countries with a cultural tradition of coal (including existing integrated steel mills) will go for an ULCOS-BF type of solution.

Geographic and industrial cultural is of the essence there, but the distinctions do not exactly match the North vs South, Developed vs Emerging economies split. Steel business, actually, is run by large global industrial groups, which operate steel mils in both kind of countries: see the examples of ArcelorMittal, Tat Steel (and Corus), POSCO, etc. They will regionalize their solutions, but from a global portfolio.

The major split is actually between countries with a carbon value due to an ETS or a tax system, or both, and countries without it on the one hand; on the other hand, there is also the distinction between countries that can apply for CDMs and those which finance them; of course, both systems overlap.

The dissymmetry these systems create may cause carbon leakage out of countries with a high carbon value, which is a rebound effect and a major one! A convergence of the systems is essential and depending on the speed at which this will take place, carbon leakage will be a major issue or not.

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13. Appendix 1: some comments about roadmaps

Existing roadmaps are many, as pointed out in the introduction.

A paradox lies at their core, due to the fact that they describe the future based on widely differing methodologies and disciples: prospective, foresight, future studies, technological forecasting, futurology, political science, socio-economic, etc. As far as CCS is concerned, this is particularly obvious: its extension has to be "forecast", while the concept is hardly a technology yet and its deployment has been limited to very few sites or to very small scales, compared to what is assumed to be needed to fight climate change effectively.

The reasons for this diversity are due to *limited available knowledge*:

- actual CO_2 emissions today are probably well understood at a global scale, but are rather roughly estimated at a sectoral level. This is indeed the case in the Steel sector, where estimates abound but no comprehensive database is publicly available yet[21].
- the discussion of future scenarios is also conducted in many different ways, a point which is neither widely acknowledged nor discussed critically in terms of what it means for decision makers at government, business and NGO levels.

  The difficulty is simple: technologies to cut emissions that may be used at the various time horizons of climate change discussion, from 2020 to 2050 and beyond, are very difficult to pinpoint, as many of them simply do not exist today. So-called breakthrough technologies have to be invented, validated and scaled up to industrial size, while others may exist but at a rather small scale on a limited number of pilots or, less often, of demonstrators. Moreover, the credentials of technological forecasting as a discipline over such long time has not been impressive in the past and there are no fundamental reasons to believe that it will fare better in the future. What many forecasting studies announce today is thus highly uncertain and speculative.

  An example of this are the IEA "predictions" that 100 CCS plants will be deployed by 2020[22] and 3400 by 2050 [6]. These predictions are actually not forecasts but statements of what ought to happen in order to match a long term temperature target - like a maximum 2.5°C temperature increase. They amount to a kind of wishful thinking and the corresponding Blue Map scenario is described more diplomatically by the IEA as *technologically optimistic.* It does not take on board any kind of realistic planning in terms of existing technologies, of marshalling the necessary financial resources nor of organizing the time schedule to get things done. It is actually very unlikely that the 2020 targets of 100 demonstrators will or even can practically be reached. Paradoxically, the longer term target might be easier to reach, although there is no real basis either for saying this with any kind of certainty.

  Even though identifying future technologies is difficult, most of the documents mentioned above do it anyway and do not always use the proper precautionary language that would be called for.

  The most common approach is the *normative or prescriptive approach,* which goes on roughly like this: since emission cuts are necessary, then they will be made and society will organize at political, economic and technological levels to get things done, no matter what, a kind of reformulation of the "blood, sweat and tears" of Winston Churchill in the second world war. Models and numerical simulations cascade down targets in terms of temperature increase, then of GHG build up in the atmosphere, of global emissions per year (over the next 50 years or more) and of emissions by activities, etc. Climate modelers contribute to the first figures, while social economists calculate the next ones. When this is done, everyone, be they country, industrial sector, or individuals, is left with a target to match and the freedom to do it in any way they see fit. Political scientists and real politicians are presently in the process of formulating these targets.

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[21] For example, *worldsteel* is presently collecting the information necessary to build this data base and has spent time defining the methodological rules for doing this.

[22] There are only 4 large-scale CCS demonstrators today, all of them dedicated to handling oil-related CO_2

At that point, some kind of rationale for marshalling existing and breakthrough technologies becomes necessary:

- a literature survey may be carried out to come up with a number of options, which are put together to paint a possible future (a *futurible*). This is done for example by the IEA in its numerous publications [6,28,29,30,32], but also by NGOs, which commission studies by consultants [95,96,97] or even by consultants which volunteer such studies [98]. The difficulty lies in the shallow information gathering, and the limits of their critical assessment, due mainly to the fact that they cover such broad areas that expertise on all of them has not been put together in the studies. The conclusions are often that technologies are already available, or will be soon, and that they have the potential to reach the pre-existing target. They lack substance to be fully credible. The only justifiable presentation would be to say that, based on knowledge available today, *it looks like* some solutions *might* be imagined clearly or *dimly* and thus, *if* encouraged and financed at the proper level, then they *might possibly* hold the promise of *perhaps* bringing the target within reach. These caveats are more or less always written in the fine prints of the documents, but they do not flash up in the executive summaries.
- there are cases where credible efforts to develop breakthrough technologies are under way, which will/should deliver them at some point in the future, if everything goes right in the R&D process up to a demonstrator's large scale. Examples of that are:
    - o the work on storage of CO_2 in deep saline aquifers, which is based on a great many research, pilot and demonstrator projects launched all over the world (see for example a list of EU projects in [99]),
    - o the ULCOS program of the EU Steel producers and consortium partners [25,100,101,102], or the *CO_2 Breakthrough Program* (*CO_2 BP)* of worldsteel [103].

  The technologies that these programs are pushing towards actual implementation are more credible than the ones mentioned in the previous item. They do however carry some level of risk or uncertainty, as history shows that innovations, especially breakthrough innovations, are not simply decided in a top-down way.
- then, there are very many cases where some kind of generic solution is pointed out more or less *ex nihilo,* without much substance, in a kind of magical ritual! Thus, CCS is often branded as a universal solution that can be applied to all industrial sectors, from chemistry, to steel, cement, the power generation sector, etc. Our own efforts to flesh out what CCS can mean in the Steel sector's context have taught us that there is no clear technology called CCS which can be acquired on a technology market and adapted to the particular case of the sector: beyond the very fuzzy and general concept, which is in no way an off-the-shelf technology, there is only room to reinvent a new technology, tailor-designed for the sector: this is a major R&D effort, the cost of which today runs at the estimated level of 1 billion Euros [76] - which brings us back into the category of the previous item. Many roadmaps also make long lists of technologies that would be nice to have: sectors usually do not commit to the fact that they will indeed become available, except for the rather special case of the coal-based power sector [17], which "promises" implementation of zero emissions on coal-based power plants by 2020, while NGOs tend to point out how easily the technologies can be implemented[23]. None of this carries much strength in terms of clarifying what might actually happen in a realistic way! And many statements ought to be read in the light of political or lobbying agendas, not of what they pretend to be saying!

- then, comes up the very important question of how and how fast can solutions be implemented, once they have been proven technologically sound and robust. Indeed, carbon-lean

[23] and thus do not "deserve" subsidies to a high level!

solutions today are mostly non-cost effective (so-called regret solutions), both in terms of OPEX and CAPEX: therefore, how to pay for both?

There are only 3 solutions to that riddle: either the customer pays, or the tax payer or an investor who would bet that in the future, these solutions would become profitable. The difficulty is compounded by the fact that many of these possible options are related to national or regional (as in the EU) rules, regulations and legislations, the discrepancy between which would create distortions between economies and markets and thus create rebound effects such as carbon leakage. These are very important, almost life and death issues for whole economical sectors and it is no surprise that they generate a lot of controversies. Steel trade associations are quite explicit in this area (see as an example [104]) in raising the risk of carbon leakage, should CCS implementation be carried out in an ambiguous way, leaving an uneven playing field among world regions.

The increase of the carbon value either in an ETS scheme, or in a tax framework, or in a mixture of both has been widely acknowledged as a solution. However, economic models predict very different levels for the carbon value that would make technologies tip over from the present carbon-intensive episteme to a carbon-lean one: 50 €/t of CO_2 or 500 €? And the issue of a level international playing field, for the sectors which are operating in a global, world wide market, has not been settled yet.

If the solutions are not found, or until they are found, the economy will not move beyond experimenting on research and demonstrator projects. Mitigation technologies will not be implemented!

Another important issue is the time schedule. Let's take the example of the ULCOS consortium, which is engaged today in a demonstrator program, called *ULCOS-BF*, where an integrated technology involving carbon capture on a commercial blast furnace in France[24] and CO_2 storage in a nearby deep saline aquifer will be tested for large scale validation. There are technical times to develop this project, which are related to designing and building large size equipment and to assessing the geological features of the storage site within the existing regulatory framework (permitting): at the quickest, the demonstrator can start operating with the full connection between capture on the blast furnace and storage at the end of 2015 and the full series of tests of the total process will be carried out in 2016 to answer all the questions raised by the combination. This does not make it realistic to imagine implementation on more blast furnaces before the 2020s. The technology would then need to be deployed with a kinetics that would bring low-carbon production on stream at a pace such as the global emissions would not be affected before the 2030s or later …assuming it is actually deployed, see the caveats of the previous paragraph.

This kind of time schedule is slower than what the normative scenarios posit as necessary. This is a matter that also needs to be addressed.

[24] It is not simply an end of pipe capture of CO_2, but a fully reinvented operation of the Blast Furnace (BF), with major changes in the equipment and on the way the process runs. It involves recirculation of the top gas into the BF after decarbonizing it and operation with pure oxygen rather than air. In the Steel sector, this is a breakthrough technology that needs to be developed by scaling up the technology carefully, in order to indentify all the difficulties that the new concept raises and solve them.

14. Table of matters

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