ULCOS: THE EUROPEAN STEEL INDUSTRY'S EFFORT TO FIND BREAKTHROUGH TECHNOLOGIES TO CUT ITS CO_2 EMISSIONS SIGNIFICANTLY

JP. Birat, F. Hanrot
Arcelor Research,
Maizières-lès-Metz, France

ABSTRACT

ULCOS is a large European program launched by a consortium of 48 partners, led by arcelor and a core group of steel producers, which was started in 2004 with the support of the European Commission (RFCS and 6FP programs) to search for breakthrough process routes that could, in the future, when fully developed, demonstrate the potential of large cuts in CO_2 emissions for the production of steel from iron ore.

The timescale for commercial implementation is the post-Kyoto period, i.e. 15 to 20 years from today.

The present paper presents the progress made in the first 2 years of this 5 year program.

Several concepts are being investigated in parallel: re-engineering of the blast furnace to incorporate CCS in the core of the process, smelting reduction with CCS capabilities, massive use of natural with more CO_2-lean technologies than today, hydrogen steelmaking and electrolysis of iron ore. Biomass also offers very attractive perspectives, while raising major challenges.

None of these new steelmaking routes are "no regret", which means that the European Steel Industry has already incorporated extensive energy saving steps in its present process technology and is working as close to thermodynamics limits as is cinematically and economically feasible, and that decreasing GHG emissions further means introducing breakthrough technologies that add significant costs to the operation of the Steel Mills.

They will also require much research and development before they can be proven and implemented commercially.

INTRODUCTION

The ULCOS program (Ultra Low CO_2 Steelmaking) is a large research program of the European Steel Industry and its industrial and research partners launched in September 2004 to investigate steelmaking technologies that have the potential of reducing the CO_2 emission of the Industry by a large amount, typically in the order of 50%. It is supported in the European Community by the 6th Framework and the RFCS programs through 3 complementary European projects [1,2].

The present paper summarizes the work carried out in the phase 1 of ULCOS and in framing the program of phase 2.

ULCOS PROGRAM'S TARGETS & STRUCTURE

ULCOS is a "concept development" program that explores fairly extensively a wide array of steelmaking routes with a high potential for CO_2 mitigation. The technologies call for breakthrough innovation in the steel industry's context, as they will need extensive research & development to mature into commercial processes, while showing a realistic target for being fully developed for the end of the 2010's. They should be in a position to be rolled out into production plants 15 to 20 years from now. Beyond the present program, a second and third step should thus lead to the deployment of the ULCOS technologies in the post-Kyoto period.

The CO_2 emissions of the Steel Industry are mostly generated during the reduction of iron ore into metallic iron, a step that is very intensive in chemical and thermal energy brought about by reducing agents. Coal, natural gas and electricity are thus currently used at a high level (18GJ/tsteel). The ULCOS program examines how the structure of the energy mix of a Steel Mill can be reshuffled to decrease CO_2 emissions. The energy intensity of the Industry today is close to the physical requirements of thermodynamics, reaction kinetics and heat transfer physics and cannot therefore be decreased very much below the level achieved by the best performers in the sector: ULCOS investigates specific technologies that purposely and specifically reduce emissions and thus uncouples energy efficiency from CO_2 mitigation. Of course, these routes remain constrained by the necessity to maintain low energy consumption and to produce the same sophisticated and changing material that steel has become, at competitive prices.

In phase 1 of the ULCOS program, about seventy different process routes have been investigated with the level of scrutiny necessary to build route flowsheets and to inform them in terms of raw materials and energy needs and of CO_2 emissions. This called for imagination for designing the routes, modeling them and carrying out small scale laboratory experiments.

The program is organized in subprojects (SPs), which bring routes into families (figure 1).

The skills and competencies of 48 partners were brought together to cover a wide field of expertise, from process engineering regarding steelmaking and supporting technologies to economics, future studies, agronomics of energy crops, etc. Most of the European flat steel producers participate as well as distinguished representatives of the engineering community, of the energy sector, of specific new fields necessary for developing the new technologies, mainly SMEs, and of the research institutes and universities across 11 European countries.

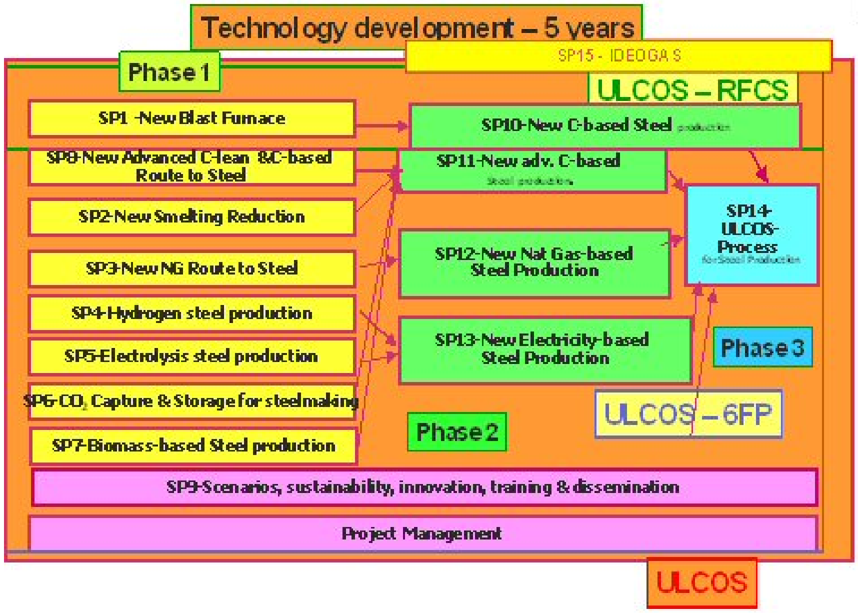

Figure 1: ULCOS' program structure

COAL-BASED STEELMAKING (SP1 & SP2)

The Steel Industry makes steel from iron ore mainly with coal, using a unique chemical reactor that ranks among the true technological feats of the 20th century, the Blast Furnace (BF). It combines engineering world records in terms of power (2500 MW), density of power (O.6 MW/m^3), output (10-15,000 t/day) and energy efficiency. The first part of the ULCOS program, supported by the RFCS, examines how to leverage on the sophistication of the modern Blast Furnace to cut CO_2 emissions.

The idea is not as paradoxical as it may seem, but aims at forcing the carbon to be used solely for the purpose of making hot metal (pig iron): indeed, today, the BF also gasifies coal and supplies energy that is used in the Steel Mill and exported as electricity to the surrounding community. If one separates CO and CO_2 in the top gas of the BF and recycles the reducing gas back at the bottom of the furnace, then this can in principle be accomplished. From a practical standpoint this means using oxygen rather than hot air to gasify the coal. Furthermore the CO_2 that is thus separated in the process is ready for storage. The Top Gas Recycling Blast Furnace (TGRBF) is thus a Steelmaking version of the Integrated Cycle technologies of the energy sector and of the "pre-combustion capture" concepts that CO_2 engineering has started to make familiar.

In phase 1, the TGRBF concept has been "validated" by modeling and laboratory or bench scale experiments and fleshed out in terms of segmenting the technological options relative to where to re-inject the top gas, what volume to inject where, and how to separate the CO and produce a clean-enough CO_2 stream. All the steel partners have been involved and a large number of the metallurgy research laboratories.

4 versions for injecting the recycled gas have thus eventually been proposed, with various proportions of top gas injected at the normal tuyeres and at a supplementary row of

injectors located at the base of the shaft: (almost) either all at the top row (version 1), all at the bottom row (3), or evenly distributed (4 & 2). The temperature of injection is also an issue, as well as the possibility to maintain pulverized coal injection at a high level. The best solutions, as judged by the modeling, are versions 4 and 2. They allow reducing the carbon consumption by 100 kg (400 to 300 kg/t_{HM}), which cuts CO_2 emissions by 15% without storage and by 60% with storage.

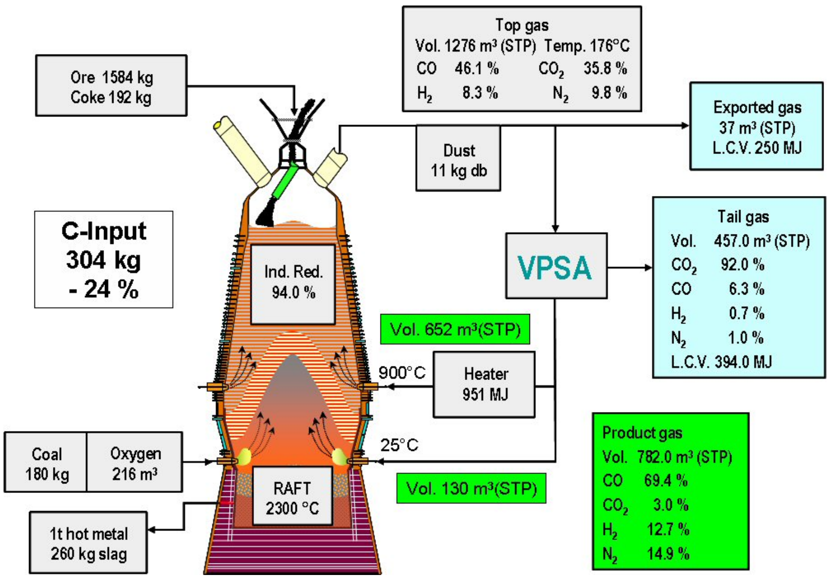

Figure 2 – TGRBF concept, version 1

The preferred solution for CO_2 capture is a VPSA, which wins the contest on efficiency and cost against PSA, membranes and amine washing. The vacuum option is necessary to avoid loosing CO in the tail gas and a cryogenic step is also necessary afterwards to make CO_2 storage possible. The high concentration and partial pressure of CO_2 in the top gas makes the solution very cost-effective compared to a solution for a power plant.

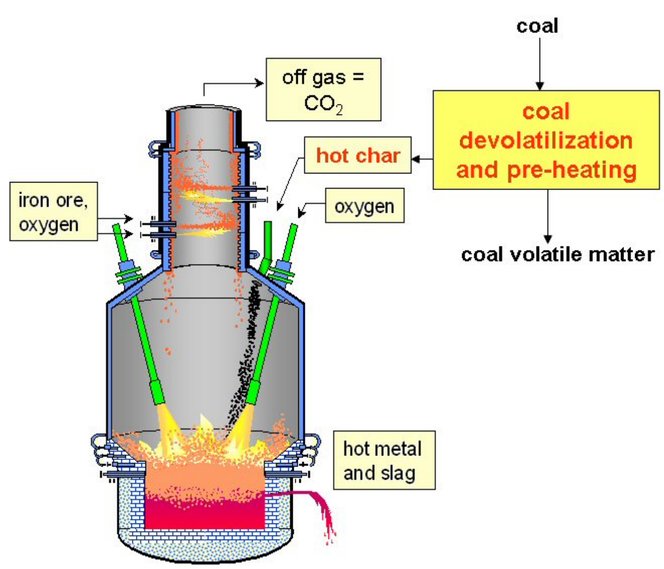

Figure 3 – process view of the ISARNA smelter and cyclone

Things are getting ready to start testing the TGRBF concept in its entirety on the pilot EBF of LKAB, complete with top gas recycling and VPSA purification, while experiments are also being prepared on a small production BF in Eisenhüttenstadt (arcelor) to test the shaft injection in a real 3-dimensional context.

path to reducing iron ore by coal is the wide family of smelting reduction processes, which is still mostly conceptual. Smelting reduction holds some appealing promises for CO_2 mitigation, as it can easily be run with pure oxygen, produce very concentrated CO_2 streams ready for storage, while cutting on carbon consumption, either because no preparation of raw materials is necessary or because the melting stage is carried out by carbon-lean electricity.

SP2 has investigated the ISARNA concept (CORUS, DCTS, arcelor), a combination of a cyclone reactor, reducing ore into wustite and melting it, and of a bath smelter, where the reduction is concluded by carbon and oxygen injection, a route made of an energy efficient RHF (or MHF) producing DRI that is further melted in an EAF (Paul Wurth, arcelor, CRM), a route based on a CFB (Circofer) plus EAF melting (voestalpine, arcelor) and a cupola like reactor, which is close to the OXYCUP concept. The selection process carried out at the end of phase 1 puts ISARNA and the RHF/EAF routes ahead for adoption in phase 2: both have a strong potential of carbon reduction, with a slight advantage to the smelter, while the former is more risky and raises more challenges than the latter, which is more incremental innovation over current practices.

At the end of phase 1, three routes based on coal, at the very least, hold a strong potential for reducing CO_2 emissions down to the ULCOS mitigation targets, provided they include a CCS step. Using charcoal, as a substitute to PCI in the BF, or as a full replacement of coal in Smelting Reduction opens up another path to more CO_2 mitigation. It could even turn negative and generate emission trading rights.

NATURAL GAS-BASED STEELMAKING (SP3)

Coal has been substituted by natural gas for producing steel in countries where gas has been abundant and cheap. The route, which includes a prereduction furnace and an EAF for melting, is the leanest in CO_2 today, due to the replacement of carbon by hydrogen form CH_4 and to the use of electricity. It accounts for 5% of the world steel production today, a proportion related to the price of gas vs coal.

Various solutions to cut emissions further and to reach here also a 50% reduction target have been examined in SP3. On the one hand, utilizing DRI in an Integrated Mill: either in the BF, in the BOF or in a dedicated cupola-like furnace called the AMF. On the other hand by re-designing the prereduction process itself to cut emissions. LKAB and MEFOS have led this effort of SP3.

The first concepts have looked at extending the use of DRI beyond its present domain of EAF steelmaking.

In the case of a BF, the most interesting concept is to carry out a limited amount of reduction in the prereduction furnace and to finish it in the BF itself: producing an LRI (Low Reduced Iron) with a 65% degree of metallization is an optimum distribution of the reduction work between prereduction and blast furnace. The material can be charged as part of the burden ($\leq$ 60%) and this does reduce the consumption of coke at the expected level

(600kg/tHM), which increasing the productivity of the BF. This is an interesting solution to cut emissions in the short term in existing Mills, if the price of LRI is right.

In the case of the BOF, DRI may be added as a substitute to scrap and ore. Moreover, if DRI is preheated as well as the oxygen, the amount can be brought up to 420 kg of DRI per ton of steel, as Saarstahl has calculated. Here again, a significant reduction in emission is observed, which could be used in the short term to reduce emissions, more or less under the same conditions as the addition of LRI in the BF.

The AMF concept is also promising, but needs more work and development, including the introduction of the top gas recycling concept and of CCS: by then it will look like a small version of the TGRBF fed with DRI or LRI and will be hard put to really compete with it in large, European-style Steel Mills.

The redesign of the prereduction process is based on the idea of saving energy by doing away with the steam reformer and cracking the methane by partial combustion, and of using pure oxygen. The recycling of the top gas is already part of the prereduction process, but this oxygen operation generates a stream of CO_2 that is pure enough for sequestration. In order to capture the CO_2, a VPSA seems again the best solution, but a Shift reaction needs to be carried out, which ends up in prereducing in a more hydrogen-rich gas than in the conventional process. This new concept has also the potential of a 50% CO_2 mitigation.

The output of SP3 is a strong candidate for phase 2 and two processes that can be used in a shorter term for intermediate levels of CO_2 mitigation have also been proposed.

HYDROGEN-BASED STEELMAKING (SP4)

Production of Steel using hydrogen directly is nil today: the Circored process has been shut down due to the high price of natural gas.

Hydrogen however is an effective reducing agent for iron ore and the studies carried out at LSG2M have brought the information up to date and embedded them in an original process model of prereduction. Reduction takes place faster (10x) at temperatures above 800°C than CO reduction, but heat has to be supplied as the reaction is endothermic. The main issue is to prevent sticking of the DRI, as it is planned not to use any carbon in order to be in a position to produce iron with extra-low carbon content. More research will have to be carried out on this matter in phase 2.

The laboratory data have been incorporated into a full flowsheet design by Siemens-VAI.

The only open issue concerns hydrogen production. It can be generated from natural gas by steam reforming (SMR) or from water by electrolysis.

Air Liquide has shown that it is possible to redesign the reforming step based on the fact that the purity of hydrogen can be moderate and on integrating CCS in the reforming process. The optimum flowsheet (HER or CMR) depends on the strength of the carbon constraint. The total route, i.e. H_2 generation by SMR + prereduction, is about as lean in CO_2 emissions as the similar route directly based on natural gas.

Electrolysis of water requires 5 kWh/ m^3 of H_2, but new developments project future values at 3.1 by 2020 (EDF). Under strong carbon constraints, the order of merit of energy sources would change and this would put electricity in a favorable position that would make this option attractive.

Hydrogen steelmaking is thus a route that has the potential of being very carbon-lean and economically attractive today in countries where gas is cheap, and in a longer term future in Europe, either based on SMR and CCS or on water electrolysis. The uncertainties lie with the competition of other sectors to consume hydrogen, as the transportation industry would be ready to pay much higher prices for it than the Steel industry.

ELECTROLYSIS OF IRON ORE (SP5)

Electrolysis is a technology that is commonly used to produce metals. There is no alternative for making aluminum or magnesium. It is catching "market share" as a process in the case of copper, zinc and, possibly in the future, titanium, tantalum, etc.. Electrolysis is also used for coating thin layers of metals on other metals (electrogalvanizing, tin-coating of steel) and for producing thin foils (copper electroforming). Concerning steel, the carbon-reduction route has become so efficient, large-scale and cheap that the price of electricity, an energy carrier that bears both the price of primary energy and of its transformation, has bared all expectation of using electrolysis for making it. Research on the subject is also rather limited.

Electrolysis of iron ore will be appealing if access to carbon-lean electricity becomes possible at a very large scale and the price competitive.

How to carry out electrolysis in an efficient way, however, was not clear at the beginning of ULCOS due to the lack of a basic corpus of knowledge in the field. Therefore, SP5 was devoted to exploring how to do this and was centered on experimental work, more so than the other SPs, and, by necessity, at a small scale.

An extensive search for possible electrolysis routes was carried out, covering electrowinning technologies based on water solutions of Fe ions and molten salt or molten oxide electrolysis at higher temperatures. The former imitate coating technologies familiar to the steel industry, while the latter mimick the production of aluminum or magnesium.

Electrowinning was investigated in acid solutions by CRM and BFI and in alkaline solutions by Arcelor, Labein and Aveiro University. Both technologies produced laboratory samples of iron, 1.6 kg in the case of alkaline. However, the acid route was too energy intensive, while the alkaline route turned out to be very lean in energy and to be potentially "easy" to scale up.

High temperature electrolysis (pyroelectrolysis) was investigated in molten salts by NTNU and SINTEF and by Metalysis, with the aim of producing solid iron, and in molten oxides (slags) by arcelor, Corus and Aveiro, with the aim of producing liquid iron. Molten salt electrolysis is either still looking for solutions in terms of electrodes or difficult to scale up to the large scale of carbon steel mill, although it might be quite appropriate for producing alloyed or high-alloyed steels. On the other hand, molten oxide electrolysis has exhibited the lower energy needs and attractive solutions for electrolyte and electrodes. It does raise quite formidable challenges, though, at a technological level and will need time and effort to be developed further beyond its present promises.

SP5 will continue alkaline electrowinning and pyroelectrolysis in phase 2.

CCS (SP6)

CCS is a newcomer in the field of technology and at the same a necessary condition to continuing using coal and carbon in a carbon-constrained world. The Steel Industry cannot take for granted that it will be possible to use CCS in the future, without investigating it from its own standpoint and constraints. This is true of the capture, which has to be carried out on Steel Mill flue gases, which have different features (CO_2 content, contaminants, volume, pressure) form the flue gas of a coal- fired power plant, for example. But it is equally true of storage, which calls for original solutions due to the volume to be stored (potentially 200 million tons in Europe per year) and the location of the sites that produce CO_2.

This SP was under the leadership of Statoil and called for expertise on gases by Air Liquide, GVS and SINTEF-PR, and on storage by geological institutes like BRGM and GEUS. Steel was also active (Corus, arcelor) and breakthrough concepts from CSIC and Armines (ENSMSE) were tested.

The main feature of steelmaking gases is that they are rich in CO_2, from 25 to 98% for the main streams, depending on the process. This makes it possible to select cheaper solutions, in this case the PSA technology. Because the quality of the CO_2 produced has to be guaranteed, vacuum (VPSA) complemented by a cryogenic purification step had to be added to the basic technology. This is a solution tailored to the needs of steelmaking, which is an important outcome of the program.

Storage in geological traps was investigated in terms of potential sites close to the main steelmaking sites. The large potential of aquifers was identified and it was concluded that the present knowledge of underground geology made it likely that it would be carried out within 1-200 km of most sites. A practical implementation is still a long way off though, but it is expected that the technology will progress of its own standing outside of the phase 2 of ULCOS.

The breakthrough capture technologies have made substantial progress during phase 1 (Armines and CSIC) and should be continued in more fundamental research programs than the phase 2 of ULCOS can provide.

BIOMASS AND STEELMAKING (SP7)

The history of Industry is in part that of the search for energy resources, that started as biomass and then moved on to coal, oil and electricity with the nuclear power and renewables avatars. The CO_2 challenge might produce a comeback of biomass, as it holds the promise of carbon neutrality, if very strict conditions are met in producing it.

SP7, lead by Corus and incorporating the expertise of institutes and laboratories working on biomass (CIRAD, BTG, ECN, CRM), has explored the various opportunities in terms of dedicated crops (plantations) or of agricultural residues, produced in tropical countries (where the light efficiency is highest) or in Europe, and of conversion into a solid (charcoal, arcelor-CPM, Kassel University), a liquid (bio-oil, BTG) or a gas (biogas or syngas, CRM).

CIRAD has built up a scientific case for stating exactly what carbon neutrality means and how it can be obtained. Some more work is necessary in this area during phase 2 to close the case.

Bio-oil is probably meant for the transportation sector, as it will be expensive with respect to the other forms of biomass. Biogas might be made from agricultural residues and used for example as a substitute to natural gas in prereduction processes, but its availability in quantity and quality is a question that remains to be solved in phase 2.

The most obvious practical solution for producing biomass for the Steel Industry is charcoal, from plantations of eucalyptus trees grown in tropical countries (e.g. in Brazil or Angola) and converted there to be transported to Europe. PCI can be substituted fully by charcoal in large BFs (40% of the carbon input), while Smelting Reduction can accommodate more (up to 100%). Plantation technology is mature and has advanced to a remarkable level of excellence in Brazil. Progress has to be made on the conversion process, by designing continuous, high productivity furnaces, possibly working under pressure, to replace Missouri kilns. Small BF running 100% with charcoal operate in Brazil (e.g. Acesita) and the challenge for ULCOS is to bring a version of this technology to Europe.

ELECTRICITY AND THE BLAST FURNACE (SP8)

SP8, led by EDF with partnership from Corus, arcelor and Europlasma, has investigated the likelihood of reviving the plasma torch technology developed for the BF in the 1980s and scaling it up to turn it into a strong CO_2 -lean route. The potential is to cut carbon consumption by 100kg in the BF (in addition to he 100Kg cut of the TGRBF) and emissions to less than 50% of the baseline BF.

A 10-15 MW torch has been designed, complete with a stream and innovative power supply and the technological problems of fitting a torch to each of the tuyere of a blast furnace solved. It should be stressed that the technology could be use with or without CCS, making it either a long term or a short term solution, where dedicated low-C electricity is available.

CONCLUSIONS OF PHASE 1 (SP9 & ULCOS' SMALL BUREAU)

The various process routes developed in SP1 to SP8 have been compared in SP9, led by Corus, on the basis of their flowsheets, energy consumption, CO_2 emissions and cost of making steel. A set of scenarios was developed, in which to carry out this comparison, as well as dedicated tools for doing this (e.g. a CO_2 calculation tool, etc.). Other tools have been developed for use in phase 2 (LCA, KPIs, local impacts).

The scenarios were at the core of a future study led by LEPII and based on the WETO and IPCC scenarios for the future (2000, 2015, 2030 & 2050) with various carbon constraints (BAU, 10-50, factor 2, F2 and factor 4, F4). LEPII has modeled the energy futures using the POLES model with the support of IPTS. Roughly 70 routes and 1050 scenario cases were investigated at arcelor.

Most solutions examined in the phase 1 of ULCOS (figure 4) bring about CO_2 reduction that range from 20 to 100% and can even become negative (thus storing CO_2, for example if CCS and biomass are used together). Applying CCS to the TGRBF is one strong solution as expected. Smelting Reduction is also a powerful one. Prereduction with CCS and low-C electricity are equally attractive, using natural gas, hydrogen and even more so biogas. Electrolysis is also a strong option with low-C electricity (figure 5), as is plasma in the BF, although it does not outperform the TGRBF with storage. CCS can always be used, even in conjunction with electrolysis (negative emissions), but is a necessity with coal to meet a 50% reduction target. Note that the energy consumption, although it varies somewhat with routes, is not a discriminatory parameter.

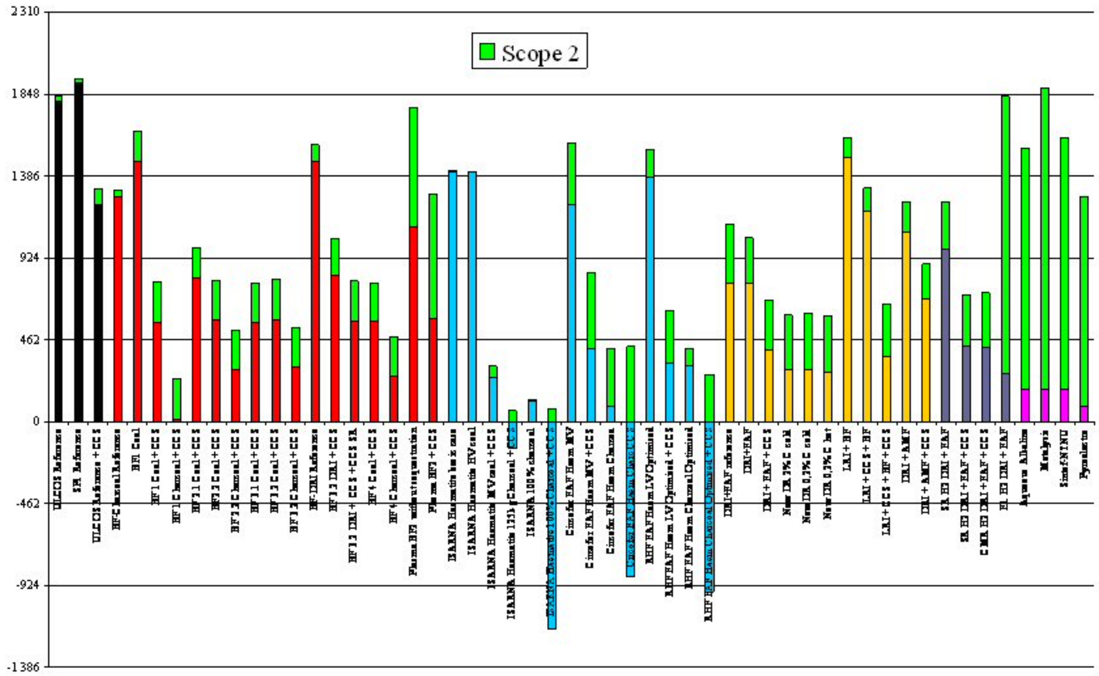

Figure 4 - CO_2 emissions, 370 g CO_2/kWh (grid value in Europe, 2000)- scope I + scope II

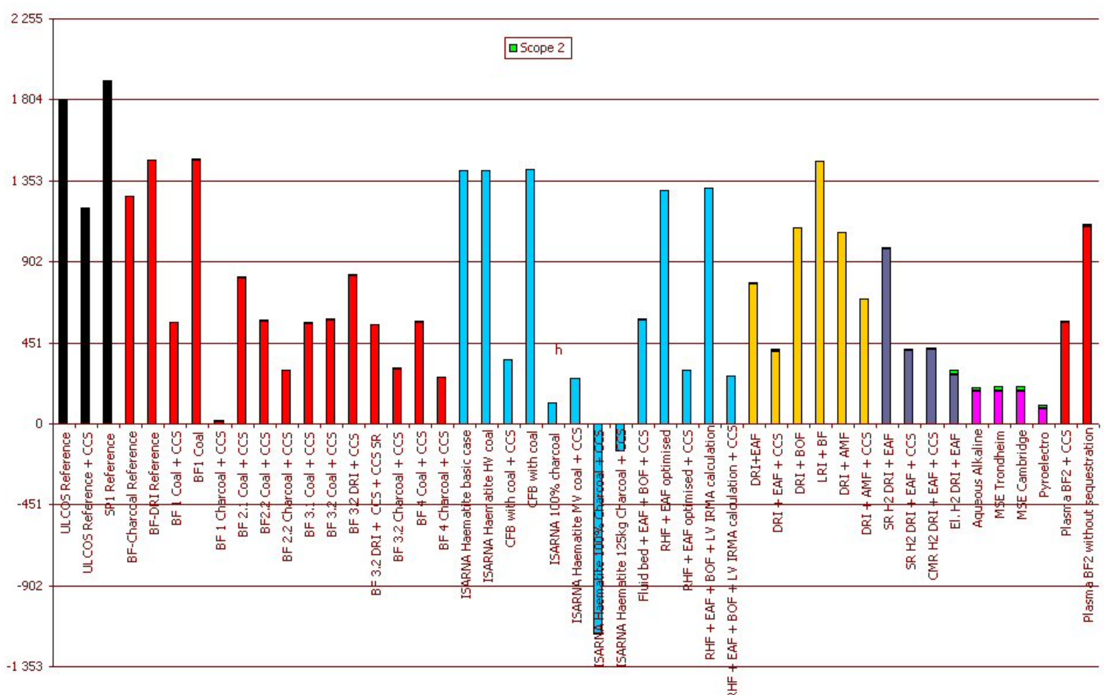

Figure 5 - CO_2 emissions, 5 g CO_2/kWh (dedicated nuclear power plant, 2000) – scope I + scope II

Cost wise, the picture is more complex and probably less certain, due to the complexity of the scenario modeling. It shows however that, today, the ULCOS routes are not competitive with the baseline BF route (see comments in the text on Smelting Reduction) and that only a positive carbon value will make them attractive. In the longer term, when the cost of carbon increases, they all, more or less, become competitive, often at an early stage (2015). In the longer term and under strong carbon constraint, a mitigation level of 50% is no longer sufficient as the cost of non-CCSed CO_2 becomes prohibitive. By then, the order of merit of energies has changed and electricity seems to hold a special status and to be able to compete with coal and natural gas on a cost basis. The future in a carbon constrained world will exhibit deep changes in the order of merit of energy sources. Therefore, the Steel Industry is likely to continue using coal (with CCS), natural gas and electricity, possibly to a higher level than it does today. The issues of availability and competition among users will be important, especially for biomass, natural gas and hydrogen. CIRAD has thus shown that it is likely that land can be dedicated to meeting the needs of the Steel Industry, at the very least at the level of Europe's production.

This conclusion and the former one on emissions justify that phase 2 has to retain a strong component on carbon with CCS, on natural gas and prereduction and on electricity and electrolysis.

Note also that phase 2 has produced a long list of technologies which are powerful, operational or likely to become so with additional research and pointed out to exciting concepts that need more basic research to fully mature. LRI in the BF, electrodeoxidation of iron ore are two examples (see list in the text).

PROGRAM FOR PHASE 2 (SP10-13 & SP15)

On the basis of the previous conclusions, a program for phase 2 has been framed, that should run until August 2008.

SP10 and SP15 will continue the work on the TGRBF route along the lines planned.

SP11 will be devoted to coal use in smelting reduction. Because the concept now needs to be tested at a large-enough scale, say an 8t/hr experimental set up, only one route can be examined in phase 2. ISARNA, which is at the same time the most promising and the most challenging one, has been chosen. SP11 will also host the work on CCS and biomass.

SP12 will be devoted to natural gas prereduction, but host the remaining work on hydrogen and biogas. It will be focused on the design of the new DR process, lean in energy (no SMR), oxygen based and incorporating CCS in the DR process itself.

SP13 will be devoted to electricity, mainly electrolysis of iron ore (alkaline electrowinning and pyroelectrolysis), to demonstrate them at a larger laboratory scale, and will host the survey on water electrolysis technologies for producing hydrogen.

SP9 will continue to compare the routes together, with refined, more detailed and more realistic tools.

CONCLUSIONS

The ULCOS program has been running according to plan: it has moved from phase 1 to phase 2 during its second year and produced a substantial amount of knowledge and of scientific and technological results.

The number of routes to be investigated in detail in phase 2 is 5, a 14-fold decrease compared to phase 1. They all hold promises for reducing CO_2 emissions and for economic viability in a post-Kyoto, carbon constrained world. Their number is related to the spectrum of energy that the Steel Industry is likely to use, which remains open and might evolve as to its order of merit in a far future. CCS is a necessity and biomass is a clever option to keep open.

The ULCOS program has also developed a fairly long list of technologies that may be used in the shorter term, with less ambition on CO_2 mitigation.

ACKNOWLEDGEMENTS

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