The "Cost Tool": operating and capital costs of existing and breakthrough routes in a future studies framework

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Nous pratiquons un impérialisme qui n'est déjà plus spatial mais temporel, celui du présent qui envahit tout. Il y a une colonisation du futur qui consiste à vivre à ses dépens, un impérialisme du présent qui absorbe et parasite le futur.

Daniel Innerarity, Le futur et ses ennemis, *Climats, 2008*

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The "cost tool" is a model that calculates the CAPEX & OPEX of the ULCOS routes. Along with the "CO_2 tool", it provides one of the key elements necessary for selecting the best routes: it was used for decision making when the program moved from phase I, where 80 different routes where under investigation, to phase II, where 5 routes only are studied further; it now provides updated information on the on-going routes of the last phases of the program. OPEX are calculated by an extension of the CO_2 tool, based on plant by plant simulation of the flow sheet, and CAPEX result from the concepts provided by the line SPs scaled by standard chemical engineering design rules. The tool is embedded in a sophisticated futures studies framework, using the same long-term(2050) scenarios as the economic modeling of energy futures carried out by LEPII [4], which assumes a series of futures ranging from mild to strong CO_2 constraint. This gives an unusual vision of when and how the CO_2 externality will be internalized in the economy. Indeed, as claimed by the Steel Industry, the existing process routes are very efficient and, therefore, in the context of prices encountered since 2000, there are not any no-regret ULCOS routes. The selection of ULCOS routes has been carried out in coherence with the tool conclusions, although other, non-model based considerations have also been taken on board.

Introduction

The work presented here is part of the ULCOS program [1,2] and more specifically of SP9, the subprogram that is in charge of comparing the process routes under investigation during the course of the program and helping to select them according to criteria defined by the program Steering Committee. Indeed, one key element in the comparison is related to the CAPEX and OPEX of the route. This paper gives a description of the tool that was developed in order to carry out this task and shows some of the main results that it delivered.

The tool makes use of the output data delivered by the *CO_2 tool* [3] and calculates the full cost of the route, OPEX, depreciation of the CAPEX and various overhead and other costs. It does so in the framework of a futures study that explores various scenarios originating from the work carried out at LEPII and IPTS [4].

Discussing production, investment and total costs raises several types of questions and difficulties, however.

On the one hand, competition and anti-trust issues introduce strong restrictions in the exchange of such information among competitors. In order to avoid this difficulty, it was decided initially to work with model costs (hence not real costs) of 2000, a year when prices were in the historical and regular trend of the 1990's, i.e. a time before raw materials and steel prices jumped up sharply due to the tension between the exploding demand of China and other emerging economies and the more restricted offer of miners.

However, when it was necessary to update the model in 2007, it was no longer possible to continue working with these prices and costs, as they did not match the new reality of that year. Moreover, the project was getting closer to the point when it would move into larger scale demonstration, and it was essential to establish a set of prices and cost that reflected the experience of decision makers.

It was therefore decided to re-engineer the model and make it exactly match the operating cost of ArcelorMittal's west European steel mills in October 2007. This, however, made communication of the exact data no longer possible with project partners in their raw form. The presentation therefore switched over to one using indices, with 100 standing for the baseline steel mill in 2007.

On the other hand, publishing actual costs, as international agencies do on a current basis [5] may have mixed effects, especially when referring to future breakthrough technologies that are not yet fully developed.

The key issue is that costs are very uncertain, as the exercise carried out within ULCOS shows very clearly [this work]. Moreover, there is no simple way to estimate the uncertainties. When used within the limits of a focused study, like the present one, the data can lead to meaningful conclusions, provided that these are assorted with precautionary comments and caveats. Soon, however, the cost figures become part of a public set of data, that are used loosely by various actors, who take them at their face value. Various lobbies, industrial and political ones, use them to communicate and support their own agenda.

Last, future studies are constrained by the scenarios that they incorporate and especially by the set of technologies that they include in their technology data base. The latest IEA publication on CCS, for example [5], properly refers to ULCOS technologies but makes long-term projections on the basis of existing commercial technologies. We view this as a biased standpoint from the point of view of the present work. All the more so as decision makers might use the conclusions without the precautionary comments that accompany them for policymaking.

Scenario modeling

The scenarios used in this work originate directly from those proposed by LEPII [4]. Like the other decision making models, these scenarios have evolved over the duration of the project, because the vision of post Kyoto policies has become more precise. We have therefore used two slightly different sets of scenarios in year 2 (Y2) and year 4 (Y4) of the program.

Scenarios relevant for analyzing the Steelmaking routes that ULCOS is investigating have to be long term and take on board the main future trends to which the Program is trying to react proactively. This means that Global Warming issues have to be included, as well as the demographic and economic projections that are at the background of any future studies. Energy scenarios are also key to ULCOS' analysis, as the energy resource overlaps with the reducing agent resource on which steel production depends. The scenarios, based on IPCC analyses [6], are identical to the WETO scenarios prepared for the European Commission [7]. LEPII and IPTS have played the central role in defining them.

Four time horizons have been chosen:

- "today", or more precisely 2000, i.e. before the raw material market started to play havoc due to China's strong demand
- 2015, a transition date between the Kyoto and post-Kyoto periods.
- 2030 and 2050, which will be used to portray long-term futures, more or less rich in deep changes.

In the first two years of the program, four scenarios have been chosen, relative to carbon constraints[1]:

- a Business-As-Usual (BAU), reference or baseline scenario, that assumes that a mild set of carbon constraints, projected from today's situation, will be carried over until 2050. The major assumption is that CO_2 will be valued at 30€/t in Europe in 2050, the rest of the world introducing a value for CO_2 with a 10-year time lag.
- a scenario called "10-50", which describes a slightly stronger constraint, where the 2050 value of CO_2 is 50 €/t and the price is accepted uniformly worldwide. The value is 10 €/t in 2010 and 50 € in 2050..
- a scenario called factor 2, which assumes that emissions are down by a factor of 2 in 2050, in the whole world.
- a scenario called factor 4, which assumes that emissions are down by a factor of 4 in 2050, in the whole world. This is the working scenario upon which the European Commission [8] and a number of national governments (the UK [9], France [10], etc.) are basing their post-Kyoto negotiations.

In the later studies, a slightly different set of scenarios has been used, aligned with the present status of international negotiations on CC regarding the post-Kyoto period. The *reference* is the *baseline scenario* that assumes a very mild carbon constraint, stronger in Europe than in other annex I countries or in non-annex I countries: the value of carbon is thus assumed to raise up to 30 €/t of CO_2 in 2050. The *F2 world scenario* envisions a strong carbon constraint, where emissions are cut by a factor 2 with respect to 1990 levels, with a higher constraint in Europe (F4) – this corresponds to the present commitments of the EU and European National governments: the value of carbon, calculated by the model, would climb up to 600 €/t. The *F2 Europe scenario* is the back-up scheme that the EU has committed to – F2 in Europe, if the rest of the world does not implement any climate change policy.

Cost calculation tool

The cost calculation tool calculates the operating cost of making steel and the various other costs including investment. It is an excel file that feeds on the CO_2 calculation tool to access the route structure and flowsheets. Calculations are carried out for the various time horizons and scenarios.

To project costs and prices in the future, different methods have been chosen:

- the projections concerning energy have been carried out at LEPII on the basis of the WETO scenarios using the POLES

[1] the models used in ULCOS assume a monetary value for every molecule of CO_2 generated. The concepts of free allocated quotas, of "caps", of auctioning quotas and of trading emissions beyond allocations, which are used by legislation to accommodate special situations and which, therefore, change often and much, are not considered here. This, however, does not change the gist of the analysis, except that the CO_2 costs cannot be compared, stricto sensu, with ETS values.

ulcos

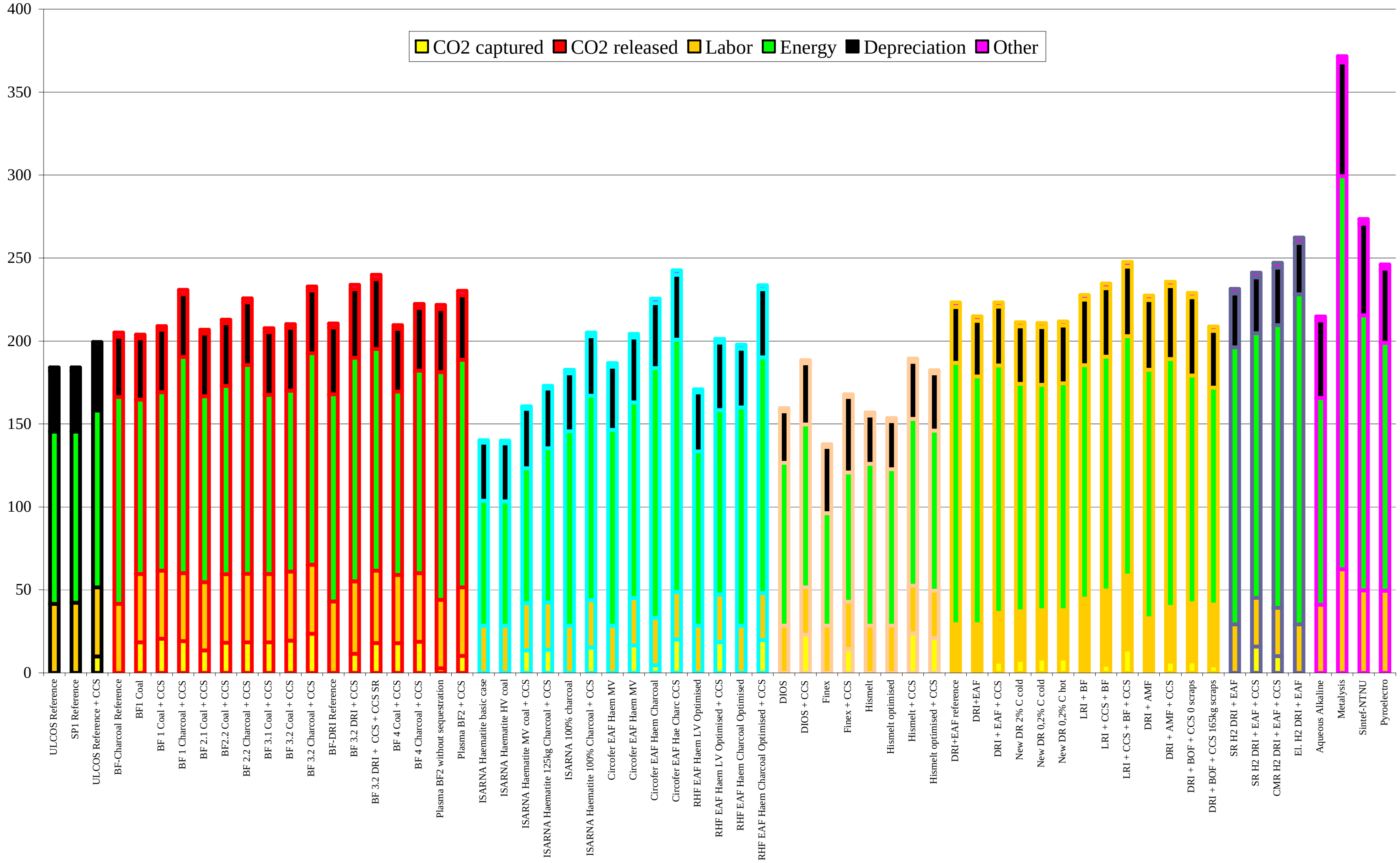

Figure 1 – Cost calculations, BAU, 2000 (phase I). 63 process routes are shown.

- model. Gross and net costs, excluding or including the cost of CO_2, have been calculated. Similarly, electricity has been treated in two different ways, depending on whether it is the major source of energy of the Mill (electrolysis of water or of iron ore, plasma BF), or if it is a marginal one. In the former case, a dedicated low-CO_2 production has been assumed, with a low-CO_2 content per kWh and a negotiated price, the latter with the grid mix' CO_2 and price.
- Labor costs projection assume an increase in standard of living (indexed on GDP growth, 1.8%) and a faster one of productivity (2,5%). Investment costs are indexed on labor cost.
- Reactants and raw materials prices are indexed on the price of energy, with different rules. Charcoal cost is calculated from CIRAD's data [cf. 11].

Due to the strong connection with the CO_2 scenarios, most costs and prices are strongly scenario dependant.

The tool produces model costs distinct from actual operating cost of any of the ULCOS steel partners.

Cost projections – phase I

The cost projections have been performed on a very large number of scenario cases (1080) at the end of phase I. A typical example is shown in Figure 1.

The color codes introduce a double distinction: the families of processes are shown as in the CO_2 cases [3] and the main components of the cost are separated in each bar: energy, labor, depreciation of capital investment, cost of CCS, cost of non-captured CO_2 (CO_2 released) and other costs. The notion of cost of non-captured CO_2 is new and has been introduced to understand the long-term scenarios, where this cost item may become much larger than the cost of CCS.

The level of prices shown for today may seem low, as the reference date is 2000 and the prices of raw materials have since been going up and down in a rather wild way, which is usually related to the high demand of China and to the conjectural limitations on supply that had been reached. This is not a trend phenomenon and to avoid the disruptions that it would create in the forecasting exercise, we have chosen an initial date which goes back before it started to take place.

Doing cost and price forecasting 50 years in the future is a risky and unusual exercise, which does not match any intuition that the reader may have. To get some grasp on the results that come out of it, we have shown in Figure 2 the trend of the scenarios at each time horizon, summarized by the average cost of steel for all the scenarios considered: the cost increase for the milder scenario (BAU is 0.75 % and, for the strongest scenario (F4), 1.75%. Both figures do not seem unreasonable.

The results presented in this overview are the present prices and the prices projected for the 4 scenarios in 2050 (cf. Figure 3 to Figure 7).

Present prices are lowest for the baseline cases, which goes to say that ULCOS' solutions are more costly than the best available technology: the cost of CO_2 has not yet been internalized in the economy and there are no routes that might qualify as "no regret", i.e. as offering cheaper total costs and high CO_2 mitigation at the same time.

Smelting Reduction pictures a different answer though, as it is shown as cheaper than the present routes: this is something of a conundrum, however, as Smelting Reduction is a paper technology today and does not have any "real world" cost. The cost advantage shown here is the translation in monetary terms of the process advantages that the experts expect (reduced needs in carbon and energy). Moreover, it has not been possible, within the time available, to fully normalize the way that the operating cost and the investment cost have been calculated by the various SPs and there is some lack of consistency among them.

Note also that some costs of avoided CO_2 are negative. They relate to cases where biomass is used and the CO_2 stream is stored at the same time, which amounts to pumping CO_2 out of the atmosphere and geostoring it. The value of this CO_2 is understandably negative.

In 2050, a time when deep changes have come - if they do come at all, the conclusions are completely different:

- the ULCOS routes are all cheaper than the baseline route, all and always, i.e. even in BAU;
- BAU and "10-50" scenarios lead to the similar levels of prices and therefore to the same order of merit of the various routes;

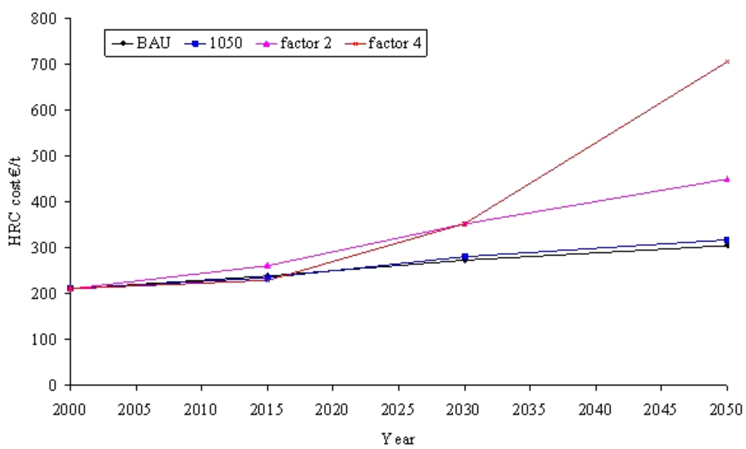

Figure 2 - Time evolution of steel total cost, according to the various scenarios

- F4 is the strongest and most disruptive scenario, as was to be expected: the price of steel of the baseline route goes out of the price scale (6 times the 2000 price!), due to the cost of CO_2, mostly. It would not be possible by then to build a BF without at least CCS. The level of CCS considered by SP1 and SP9 would furthermore be insufficient and more smokestacks would have to be treated, even to make the TGRBF option more favorable.

- Smelting Reduction is the most favorable option in any scenario, subject to the same comments as the simulations for today.

- The electricity-intensive options have become competitive by 2050, provided of course that they have been fully developed in between. They become the cheapest option in the strongest scenarios.

- the natural gas routes seem to be impedimented by the price of natural gas, that stays high compared to the other energy sources – except carbon without CCS attached to it.

- Biomass (charcoal) always comes out as a positive option.

It is difficult to analyze so many scenarios and to get a full picture of the results. To make things easier, we have build "futuribles[2]" maps, that show when the ULCOS solution becomes "no regret", i.e. cheaper than the baseline route at that time, while bringing about 50% of CO_2 mitigation at least. Results are shown for each family route, i.e. for each SP, from SP1 to SP8. The axes show time horizon, horizontally, and scenario or strength of carbon constraint, vertically. These are shown in Figure 8. Red means "regret" and green, "no regret".

All routes become "no regret" with time, earlier (BF, electrolysis) or later (natural gas, hydrogen, plasma BF). Electrolysis becomes green earlier than intuition would have suggested and natural gas later.

What seems even more important is the fact that the green area comes up naturally and smoothly and is not related to the F4 scenario: this means that breakthrough technologies will probably be needed before 2050 and under milder carbon constraint than those that the fearsome F4 scenario projects. It also means that the strongest paradigm shifts in technologies (electrolysis, for example) might make sense in the future, earlier and more widely than is generally recognized.

Of course, this will be true if and only if society as a whole puts a strong priority on solving the CO_2 issue in the full realm of its activities. The Steel Industry cannot act alone and neither can the European Steel Industry! A worldwide effort will be absolutely necessary.

Cost projections – phase II

The updated cost calculation tool has been used to estimate the operating costs (OPEX) of the various ULCOS routes, as well as the cost of avoided CO_2. We have not calculated the capital costs (CAPEX) as the data from the line SPs are not robust enough yet in that area. The simulations have been carried out for the whole set of futures scenarios. This is usual as far as cost calculations are concerned, but new, as far as we know, for the cost of avoided CO_2.

OPEX are shown in Figure 10, Figure 11and Figure 12for today and 2050, baseline and F2 world.

Today (Figure 10), the hierarchy of the various process routes is in favor of the baseline blast furnace among the BF routes.

The route with CCS at end-of-pipe is the most costly.

The TGR-BF routes are slightly more costly than the baseline, but less so than in phase I. This is due to the changes in raw material prices that took place since 2000, the reference time used in the previous set of calculations, in comparison with the change in energy prices. Indeed, if the coking coke price increased even more , then the TGR-BF might become cheaper than the baseline. It would also cease to be a costly solution and become a no-regret one. The relative increase in coking coal and energy prices, as experienced today, is however probably not a long term trend and the no-regret option is likely to be a temporary one. Anyway, we are in an area where the conclusions are very sensitive to the data and a very careful analysis remains to be carried out to fully understand the significance of these “fresh” results.

The OPEX of the Hisarna and ULCORED routes are shown as lower or higher than the baseline, but we cannot really state that this is significant. Of course, if the assumptions made in the modeling of these processes are confirmed, then the trend may actually be there. However, we cannot compare the routes of the different SPs at this fine level of details until costs can be estimated with exactly the same methods and tools.

The baseline 2050 OPEX (Figure 10) projections are not very different from today’s, mainly because the carbon constraint is rather weak in this scenario. Note, for the record, that electrolysis has become cost competitive.

The F2 world projections for 2050 (Figure 11) are much easier to analyze with a certain degree of confidence as this scenario is very contrasted. Indeed, in that case the baseline scenario is by far the most costly, because the price of CO_2 is very high (600 €/t CO_2). The cheapest scenario is electrolysis, with a dedicated access to low- CO_2 electricity, nuclear for example. The ULCORED routes fare better than in the phase I calculations, because the update of the

[2] *Futurible* is a neologism for *future possible*, in French

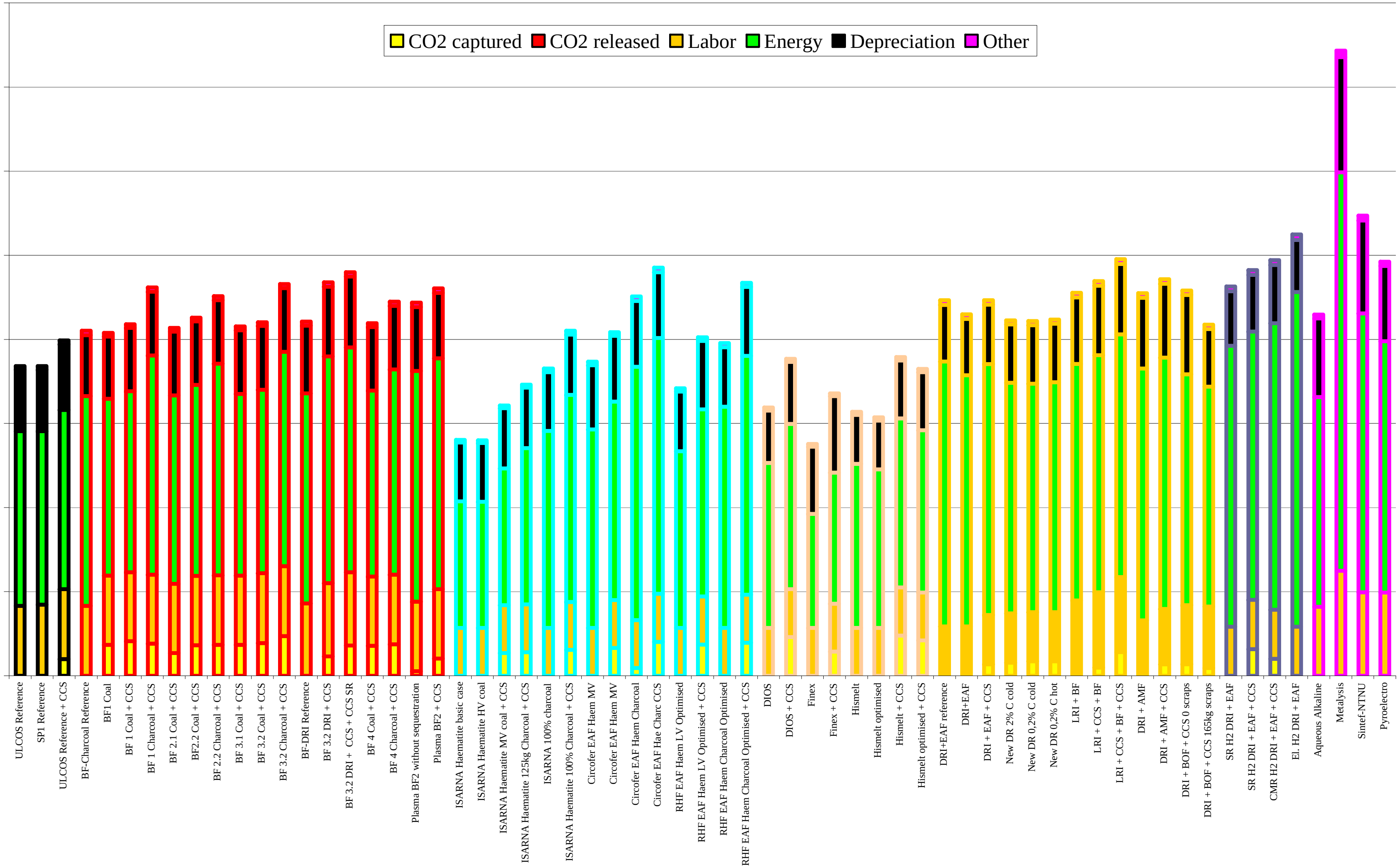

Figure 3 – Cost calculations, BAU, 2000 (the routes shown on the horizontal axis are the same as in [3]). Actual costs, shown vertically, have been hidden.

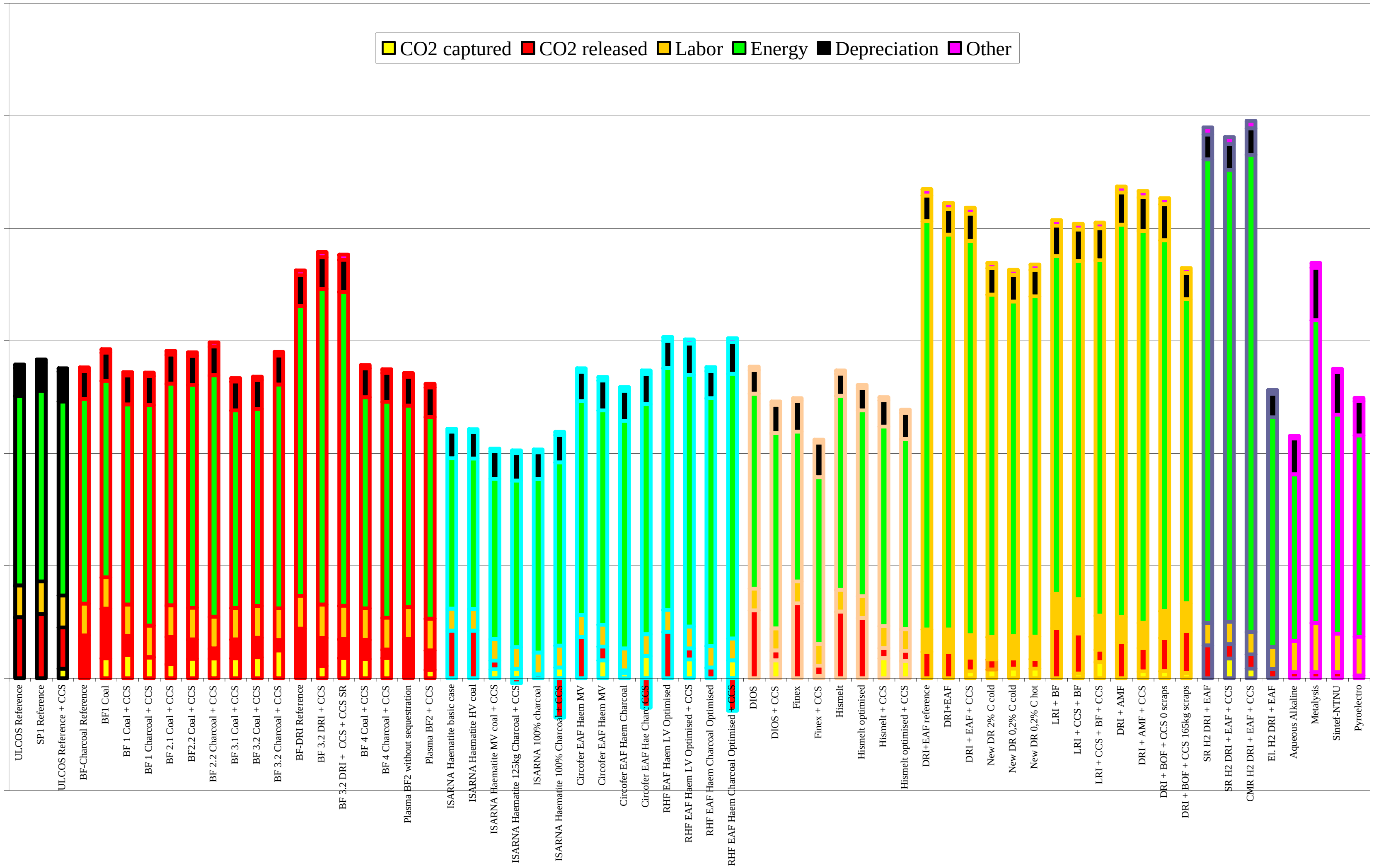

Figure 4 – Cost calculations, BAU, 2050

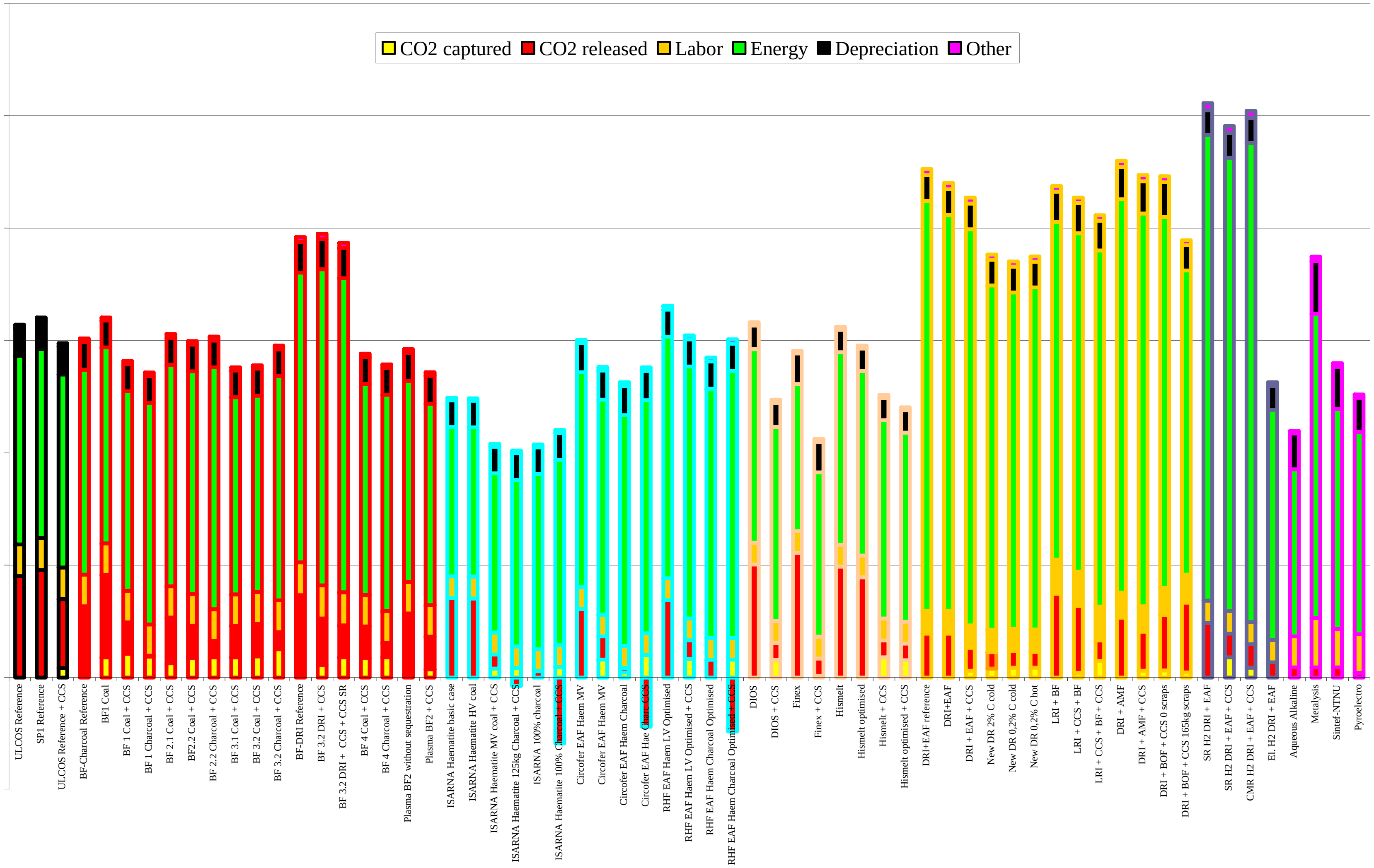

Figure 5 – Cost calculations, "10-50", 2050

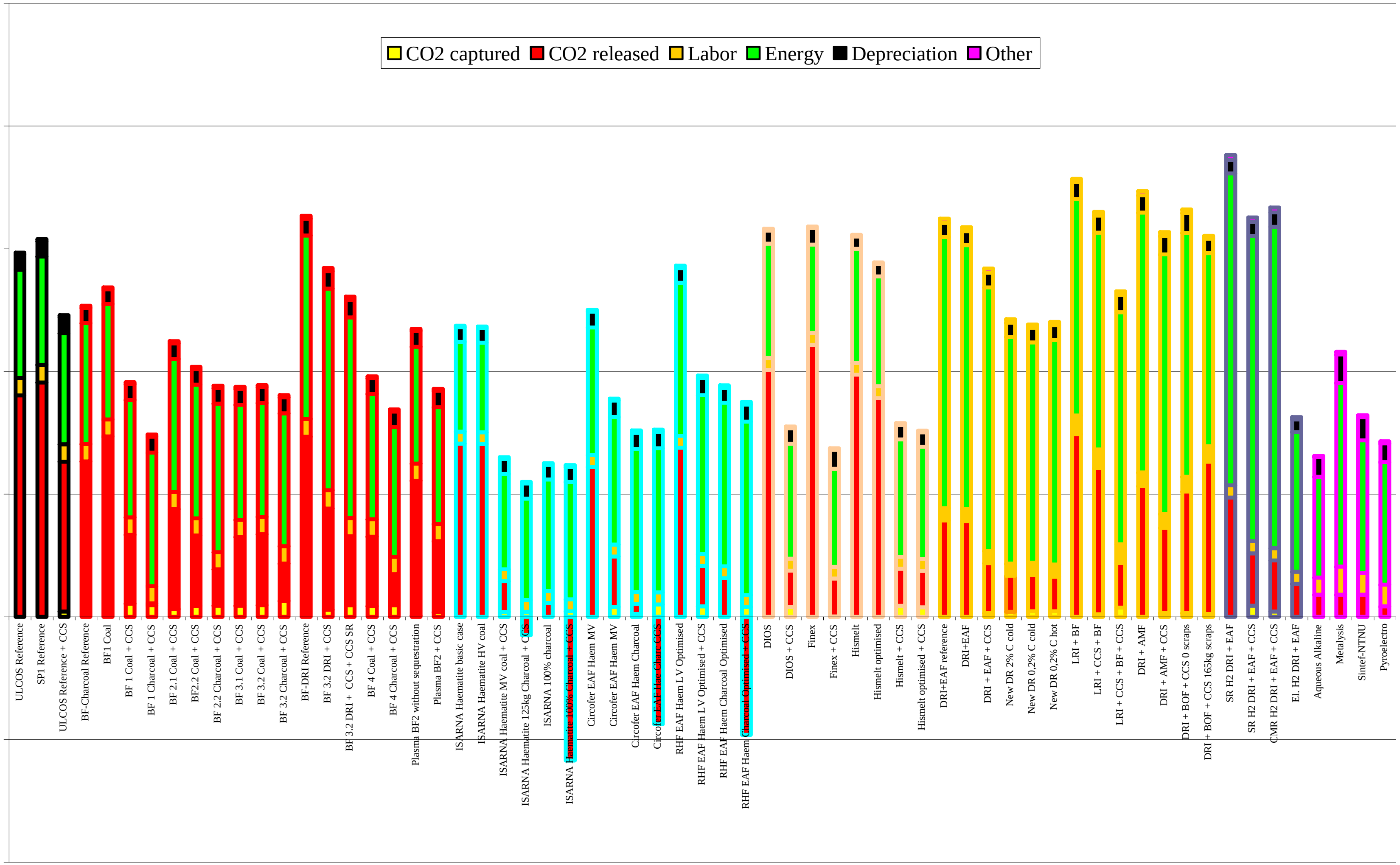

Figure 6 – Cost calculations, "Factor 2", 2050

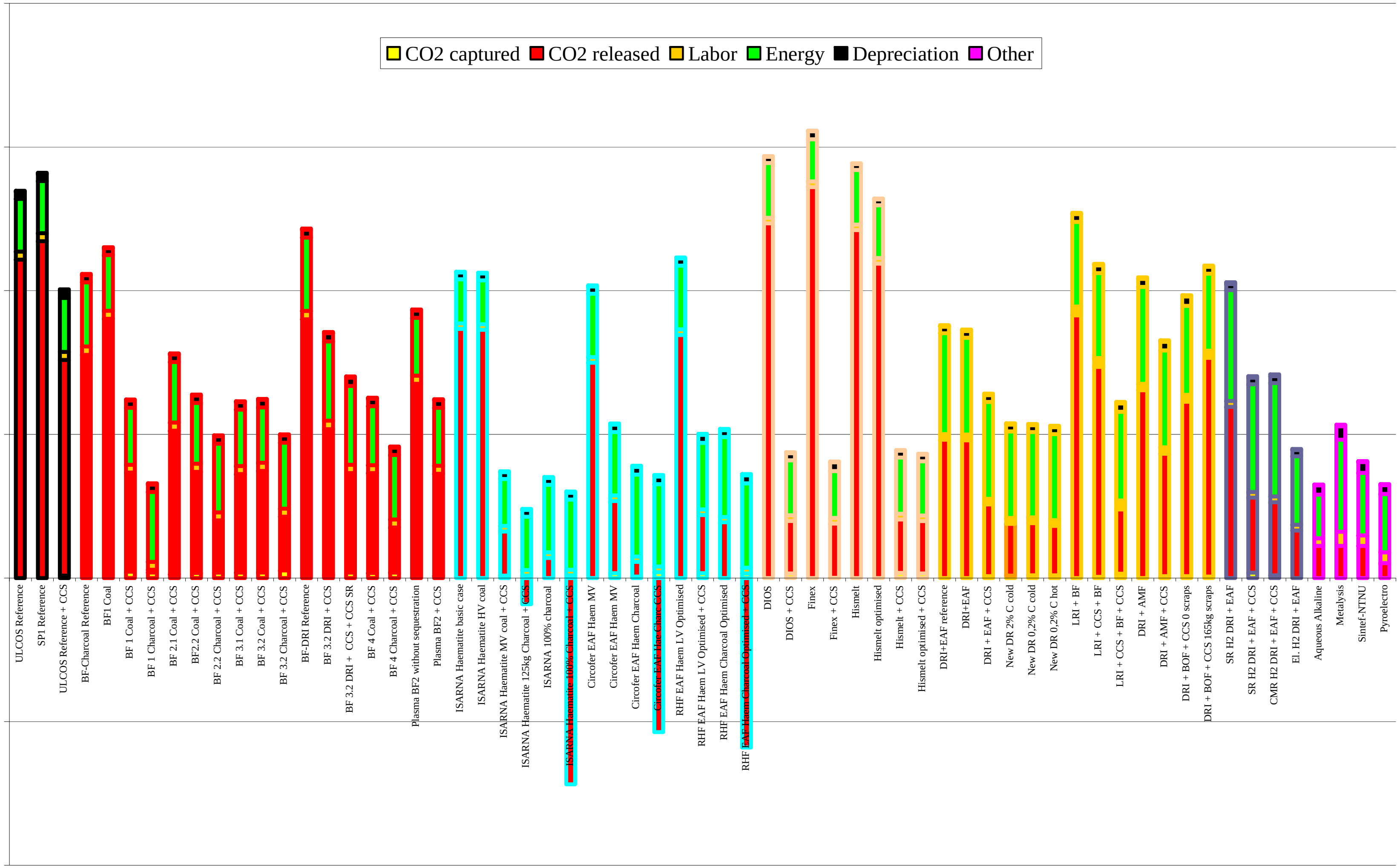

Figure 7 - Cost calculations, "Factor 4", 2050

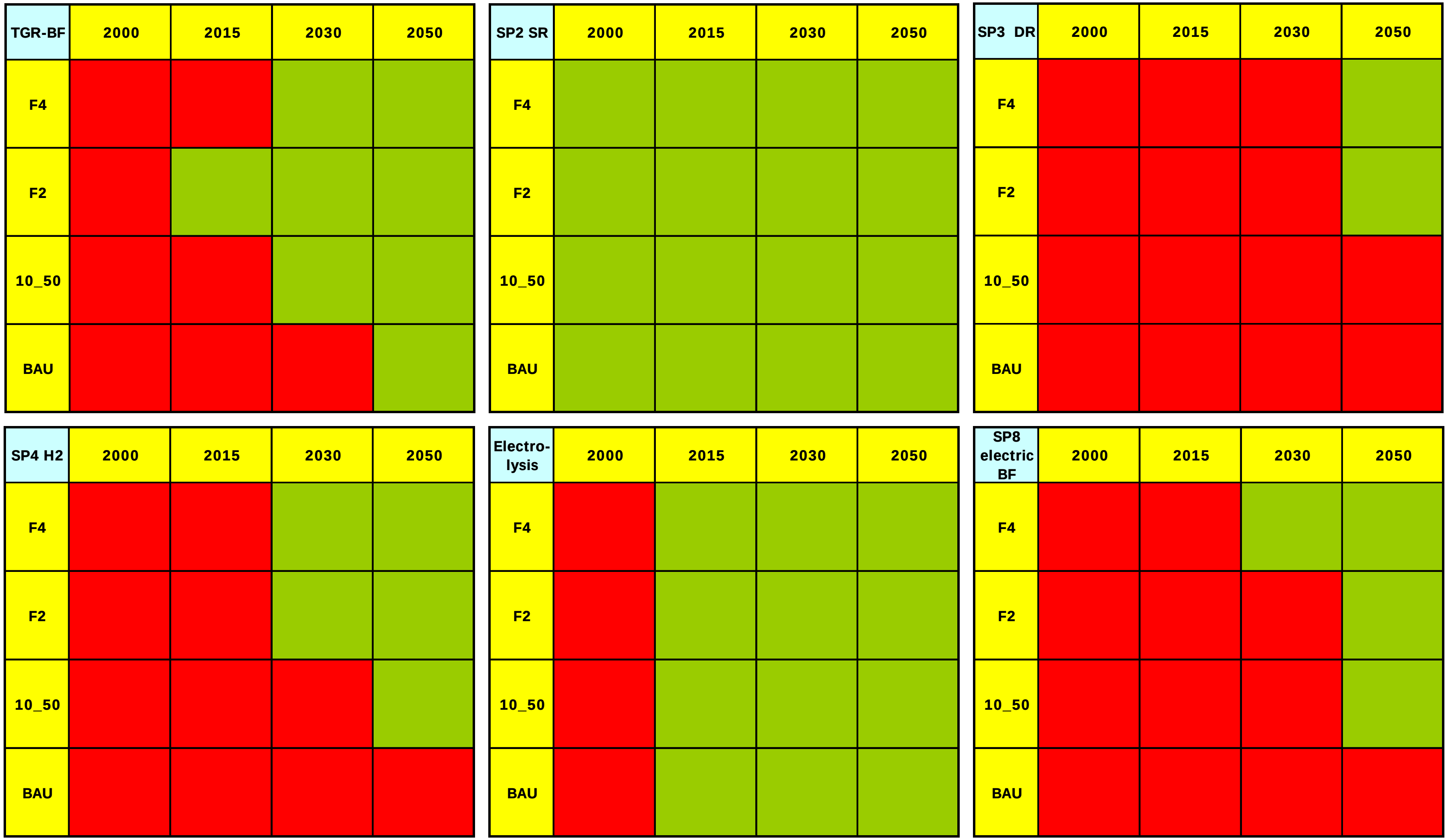

Figure 8 – Maps of futuribles for ULCOS' routes: route families developed by the various phase I SPs are shown from top left to bottom right, i.e. BF, Smelting Reduction, Direct Reduction, Hydrogen reduction, electrolysis and electric BF. The vertical axis shows foresight scenarios and the horizontal one horizon years. Solutions have been checked for their "sustainability", i.e. their ability to exhibit a cut in emissions of at least 50% as compared to the benchmark BF and a full cost of making steel less than that of the BF: red means no solution, green means solution.

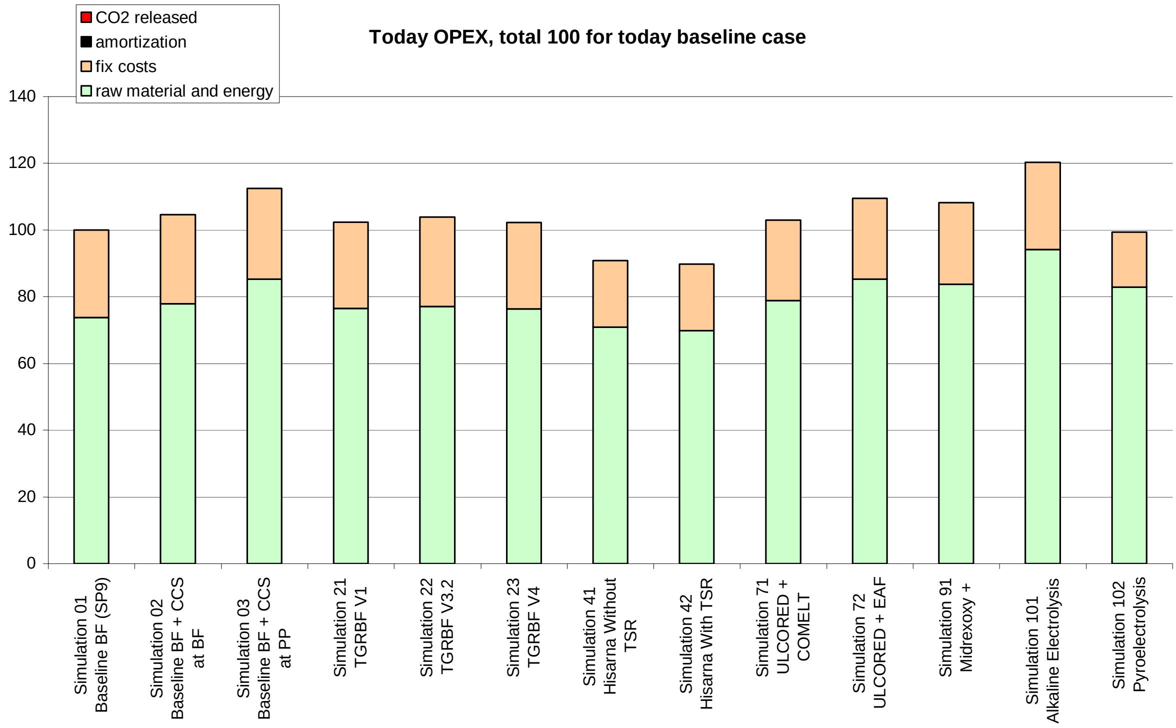

Figure 9 - OPEX today, index base 100 for today's blast furnace

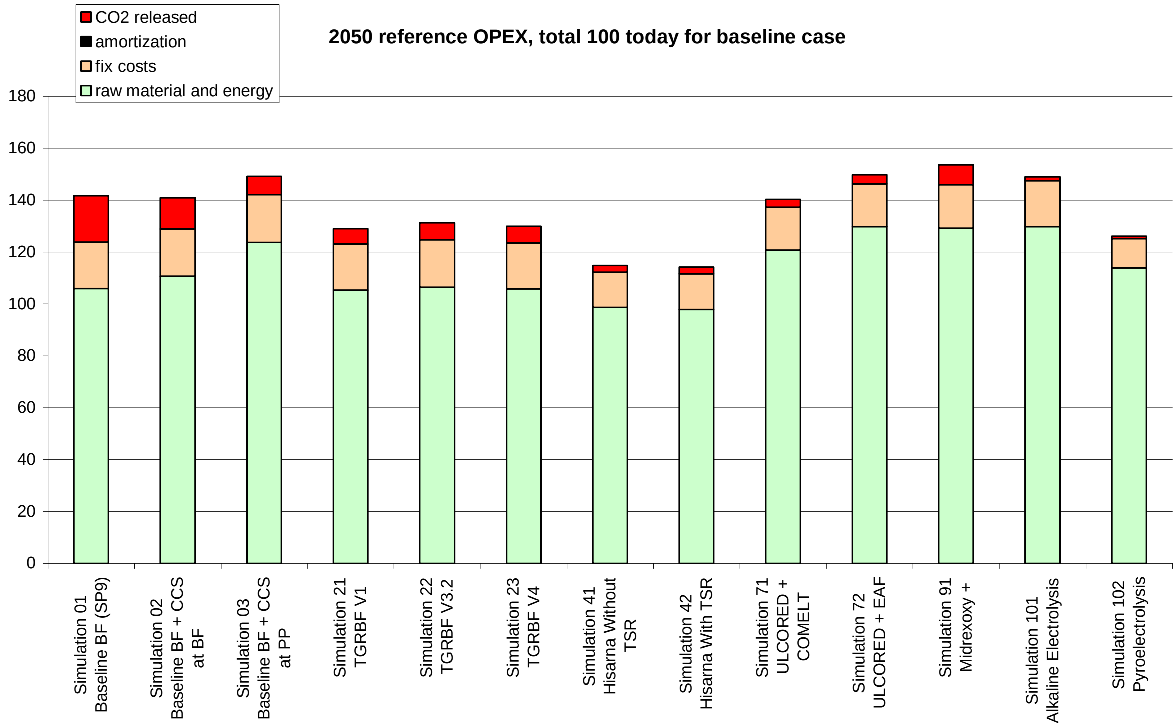

Figure 10 - OPEX for 2050 reference, index base 100 for today's blast furnace

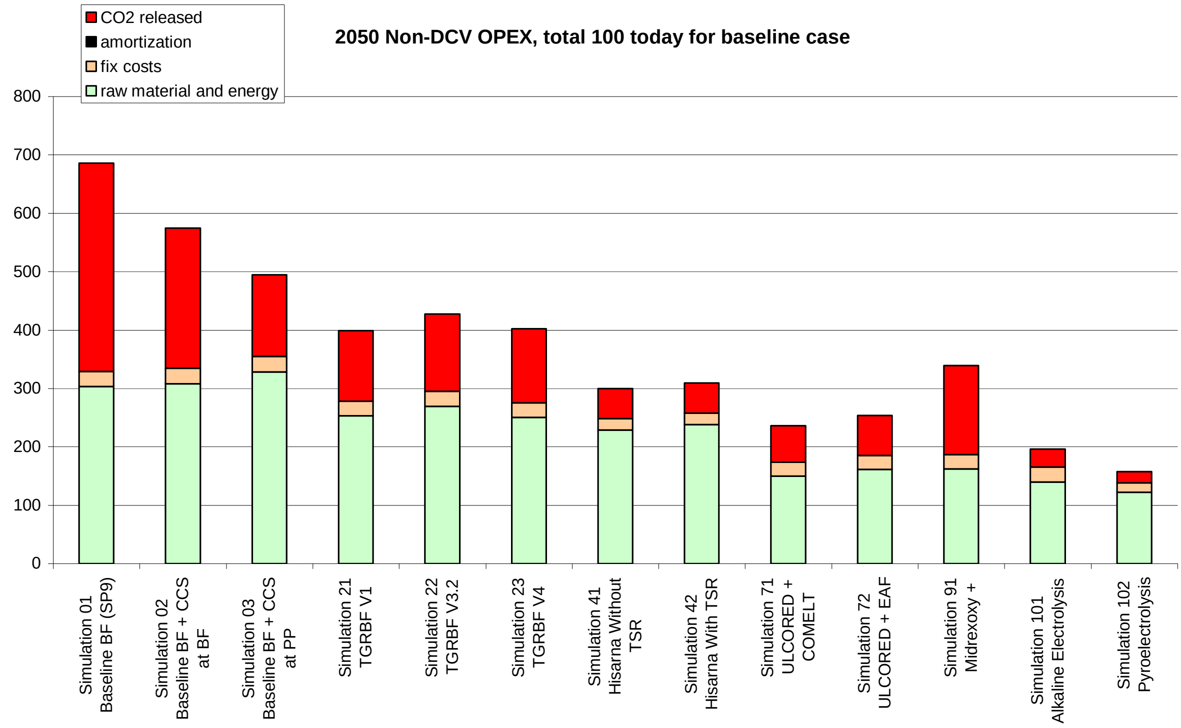

Figure 11 - OPEX for 2050 Non-DCV, Factor2 Europe scenario, index base 100 for today's blast furnace

POLES database now puts a lesser price burden on it. Hisarna does better than the TGR-BF.

These conclusions need to be further analyzed and confirmed at the end of the ULCOS I program.

We have also pictured the results by using a representation of the cost of avoided CO_2 (CAC). The CAC is a function of time in the kind of analysis conducted here and it does not bring any new insight regarding the conclusions. The concept may be useful when the CAC is compared in a simple way to the value of carbon at a given time (see further) but this does not help much when a long-time perspective is used as is done here.

Cost projections – specific investigations

The cost tool has also been used to carry out some specific comparisons between various competing options in the program [12].

An example is given in Figure 12 to Figure 14, where various options for CO_2 capture are benchmarked against each other in the case of the blast furnace route: the baseline blast furnace, 3 ways of capturing CO_2 as an end-of-pipe solution and 3 options, V1, V2 and V4 of implementing the TGR-BF concept (cf. Figure 12). NET stands for the energy network of the steel mill.

The CO_2 mitigation brought about by each of the 7 solutions is shown in Figure 13. The TGR-BF is much more efficient than the end of pipe solutions, except for the one where all the BF gas is burned in the power plant and CO_2 is CCS-ed at that level.

In order to take costs into account, at today's level, a CAC has been be calculated as shown in Figure 14 to balance mitigation against cost. The TGR-BF exhibits the lowest cost and solution 3 is no longer as attractive as it would have seemed on the basis of mitigation level alone.

This demonstrates once more why the TGR-BF is more attractive than end-of-pipe CCS applied on an otherwise unchanged BF technology. It also shows how the CO_2 tool can be used to examine a more limited issue. In this particular case, the use of the CAC concept proves useful.

Conclusions

This model, simple as it seems from an analytical standpoint, has the originality of coupling economic and financial calculations of the kind that are used to justify a new investment in a business to foresight scenario analysis, projecting deep into the future and based on some of most sophisticated econometric modeling available today.

It leads to conclusions that can be understood by technical experts in the field and by decision makers, an important prerequisite in our post-modern society, where the buy-in of stakeholders has to be organized careful like a communication campaign. This is actually a key distinction between classical science and future studies, especially as they address policy and strategic issues, which are framed and decided at the highest level – and therefore need to be expressed in a simple and intelligible rationale.

The conclusions can be summarized as follows:

- the qualitative criteria for selecting a breakthrough route relate to the feasibility of the technology, to the demonstration that it can be scaled up to the very large size of a modern steel mill and, until this is proven, to the belief that this is indeed the case.

- the main quantitative criteria for selecting a breakthrough route are the specific CO_2 emissions and the production costs. While the first criterion is rather straightforward to evaluate, once the process routes have been designed in enough detail, the second requires weaving together investment calculations and future studies. The former is clearly more precise, while the latter is uncertain and risky, although the holistic picture that is produced is rather robust. Anyway, there is not much else that can be proposed to base decision on a rational basis.

- a no-regret solution for producing steel with greatly reduced CO_2 emissions does not exist. This is due to the fact that CO_2 is not internalized in the present worldwide market economy in which the Steel Industry operates. Of course, the boundary between regret and no-regret is not very far from today's conditions and depends not only on the value of carbon but also on the price of raw materials: indeed, ULCOS routes all bring about some significant energy savings (roughly 15 to 20%) along with carbon dioxide mitigation and this why these two parameters control the OPEX. More detailed and quantitative conclusions are available, but cannot be published. They confirm, however, that ALL the ULCOS routes under investigation in phase II of ULCOS I have the potential, eventually, to provide solutions that will match the targets announced today for post-Kyoto[3].

- sustainability models [13,14] provide further intelligence on the ULCOS process routes, but they quite simply confirm that all pass the additional criteria that they bring to the forth.

The phase II routes have been selected on the basis of this rationale. Of course, some ambiguity remained and some more qualitative criteria were also used to bring down the number of routes from 80 to 5: a strict adherence to the 50%+ CO_2 reduction and the selection of what we felt were the" simplest" solutions. This is the reason why many routes, which are no longer investigated in the ULCOS program, still hold a strong potential for CO_2 mitigation [2].

Political issues are also quire important, as the steel industry operates in a global market and needs a level playing field among competitive materials and, geographically, all over the world, to continue this essential but expansive work and to avoid carbon leakage from the most carbon conscious regions of the world. The ULCOS breakthrough technologies will reach full maturity and will be deployed if and only if society as a whole puts a strong priority on solving the CO_2 issue in the full realm of its activities. The Steel Industry cannot act alone and neither can the European Steel Industry! A worldwide effort will be absolutely necessary.

From a methodological standpoint, the fact that the modeling rules have changed during the length of the study to accommodate the evolution of political thinking about mitigation of Climate Change provides a demonstration of the robustness of the kind of economic analysis that we have been carrying out collectively within ULCOS. The robustness is in the general conclusions, which have not changed in the phase II study compared to the phase I study. However, the detailed costs have moved around quite a bit and only the overall picture has stayed the same.

This robustness has also withstood the large changes in raw material and energy prices, which took place since 2000: a dramatic increase by as much as 300% in some cases and a drop under way at the time of print, which is likely to match that magnitude.

The downside of this, however, is that individual prices and costs cannot be used individually in other contexts: we have refrained to give monetary prices for the phase II study. The values shown for phase I are so out of range today, that they ought not be used in any other context.

We wish that other authors would be as conscious as we are of these methodological constraints and of the basic impossibility of producing cost and price projections that can be used out of context for any kind of decision making.

Acknowledgements

The present work is part of the ULCOS program, which operates with direct financing from its 48 partners, especially of its core members (ArcelorMittal, Corus, TKS, Riva, voestalpine, LKAB, Saarstahl, Dillinger Hütte, SSAB, Ruukki and Statoil), and has received grants from the European Commission under the 6th Framework RTD program and the RFCS program[4].

The quote from Daniel Innerarity is meant to show that not everyone today lives in the denial of the future!

Notations

BF: Blast Furnace

CAC: Cost of Avoided CO_2

CC: Climate Change

CCS: CO_2 Capture & Storage

[3] Provided that the conditions related to carbon leakage called "political" further in the text are met.

[4] Priority 3 of the 6th Framework Programme in the area of "Very low CO_2 Steel Processes", in co-ordination with the 2003 and 2004 calls of the Research Fund for Coal and Steel

DCV: Differentiated Carbon Value
DRI: Direct Reduced Iron
ETS: Emission Trading System
F4: Factor 4 scenario
F2 World
F2 Europe
CAPEX: capital expenditures
GHG: GreenHouse Gases
Isarna, HIsarna: successive names of the ULCOS Smelting Reduction process
Line SPs: SP1 to 8 and SP10 to 13 – subprojects of the ULCOS Program dedicated to developing the ULCOS process technologies
LRI: Low Reduced Iron
NG: Natural Gas
OPEX: operational expenditures
Phase I: the 1st 2 years of the ULCOS program
RHF: Rotary Earth Furnace
SP: subproject (1 to 15)
SR: Smelting Reduction
TGRBF: Top Gas Recycling Blast Furnace
ULCOS: Ultra Low CO_2 Steelmaking
ULCOS I: present, on-going program
ULCOS II: future, next-step program
Y4: 4th year of the ULCOS program
Y2: 2nd year of the ULCOS program

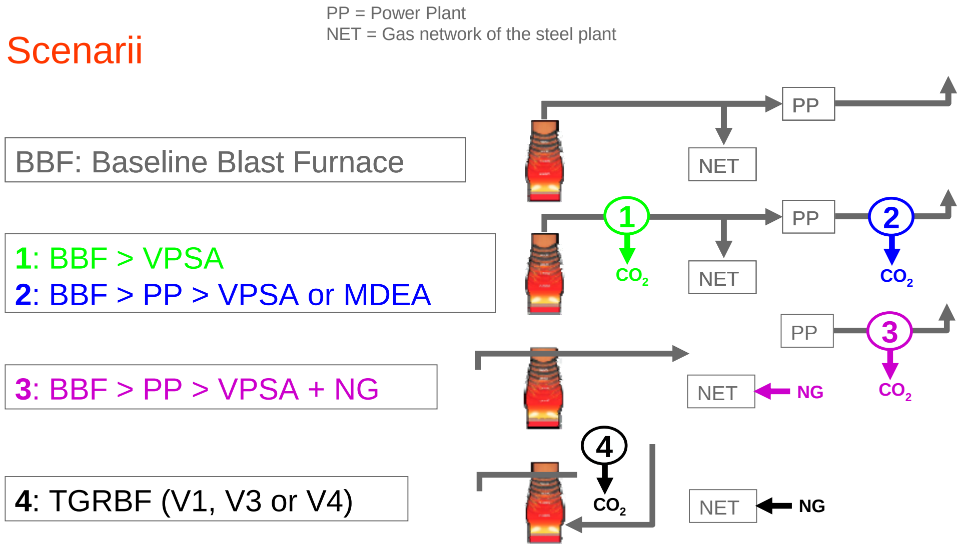

Figure 12 - Various solutions of implementing CCS on a blast furnace

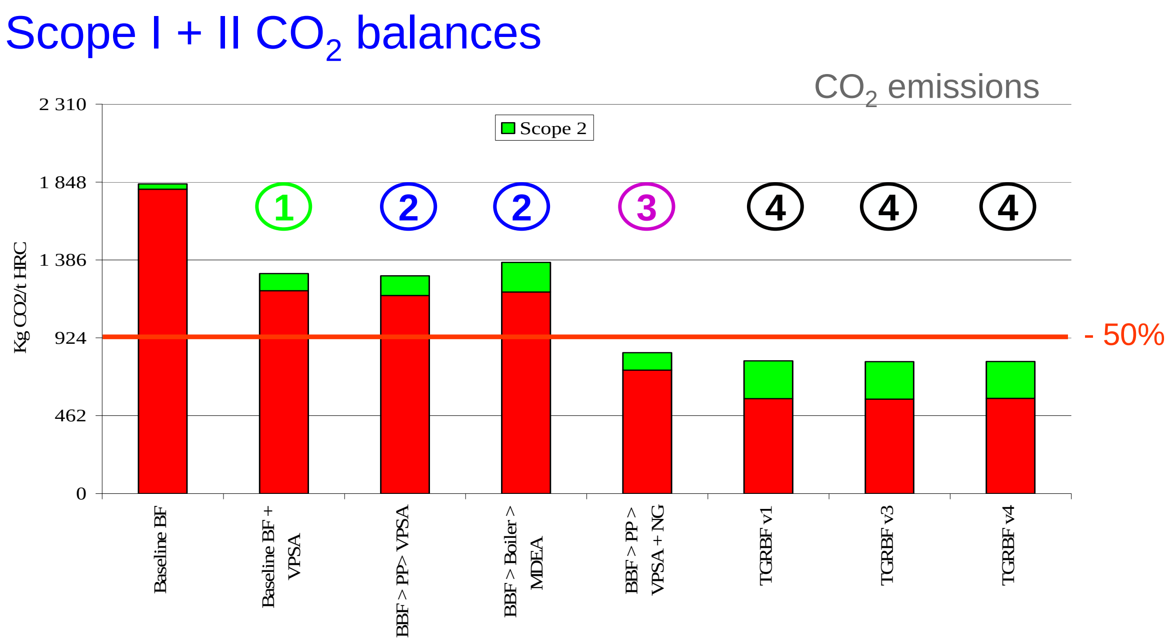

Figure 13 - CO_2 mitigation level for various solution of implementing CCS on a blast furnace (scope I and II CO2 balances)

Cost tool simulations

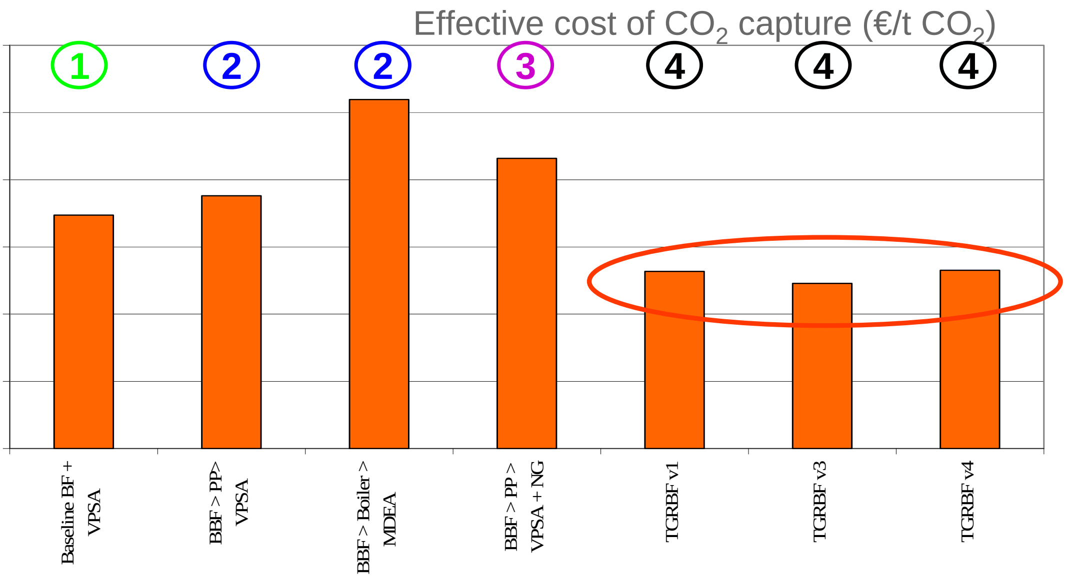

Figure 14 – Cost of avoided CO_2 (CAC) for various solution of implementing CCS on a blast furnace (CO_2 abatement cost figures have been hidden)

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