Sustainable steel

CO₂ emissions can be reduced 44% by replacing cement clinker with BF slag

The sustainability footprint of steelmaking by-products

Life Cycle Analysis (LCA), originally derived to assess the carbon footprint of manufactured goods, is being applied to production processes where it can be manipulated in a variety of ways each yielding a different result to claim the lowest carbon footprint for a particular process. This paper uses the example of blast furnace slag as a replacement for cement clinker and shows, depending on the method of allocation, a saving of 0.24tCO₂/t of steel produced or 0.64tCO₂/t of cement produced. By J P Birat*

BY- and co-products usually command low prices in their markets because they retain the image of a waste, which they are not. Legislation and practice are slowly changing this image and the scarcity of raw materials adds to the trend, especially when this causes prices to increase. With higher prices, greater preparation of the co-products is possible to turn them into true and sophisticated secondary raw materials.

A steel mill is a large logistical hub, with raw materials and energy as input and steel plus other materials as outputs. The terminology to designate the latter is ill-defined; the terms used include: co-products, by-products, residues, waste, emissions, pollutants, discharge, etc and are used in different contexts. This profusion of names echoes the conceptual hurdles that block the way when numbers have to be attributed to the co-products, either related to environmental footprints or to economic values, especially when both these are involved.

This paper focuses on the example of Blast Furnace (BF) slag, which is sold to the cement industry in large quantities as a substitute to clinker. The practice is a lively example of an industrial ecology synergy between two economic sectors. Both sectors, collectively, decrease their environmental footprints in terms of energy consumption, GHG emissions and resource depletion. Many issues arise, however, when exact figures have to be worked out to allocate a footprint to each partner in the synergy. Life Cycle Analysis (LCA) seems a good candidate to do that job, but, from a practical standpoint, this method can be implemented in so many versions that the answers end up as a series of very different figures, which confuse the issue rather than clarify it.

What is argued in this paper is that these difficulties are due to the fact that the underlying problems are not yet solved and that it is naïve to ask an approach such as LCA to solve issues related to the allocation of the cost of Climate Change to commodity materials such as cement and steel. Until these issues are cleared, it is proposed either to focus mainly on the synergistic benefits of cooperation between the two sectors or to accept different estimates of the footprint of the co-products in the two sectors.

This example is a typical case in point related to what we have called the collision between the ecosphere and the anthroposphere.

Cement & steel – a virtuous example

To illustrate this discussion and flesh it out beyond these abstract considerations, the story of cement and steel, two of the three most important materials in the world, in terms of volume (the other is wood) and thus of their vital importance in human artifacts and in the logistical part of the economy. These two materials entertain connections at the level of their production phases, following the rationale of industrial ecology [1,2].

Cement and steel are both made from natural, primary raw materials at high temperatures in large industrial reactors – a cement kiln or a blast furnace and oxygen converter. Primary cement and primary steel are not connected during their production phase.

Cements are artificially prepared compounds of lime, silica, alumina, and sometimes magnesia, ie of oxides of highly electronegative metals, usually prepared from carbonates in a high temperature process that releases CO₂ during calcining.

Steels are alloys made of almost pure iron, which are produced by reducing iron ores, mostly iron oxides, at high temperature using coal (carbon) as a reducing agent: the chemical reaction produces CO₂. Both materials are produced in very large quantities, more than a billion tonnes a year, and the chemistry on which their production is based requires a large amount of specific energy. This makes both ‘energy-intensive’ industries, and, as a conse-

*Abstracted from a paper presented by J P Birat, ArcelorMittal, Maizières, France Mittal jean-pierre.birat@arcelormittal.com presented at the Waste Recovery in Ironmaking and Steelmaking Processes, 13-14 December 2010 organised by the Iron & Steel Society of The Institute of Materials, Minerals and Mining (UK).
Steel mill
- 4.50Mt crude steel
- 2.11t CO2/tsteel
- 250kg BF slag/1HM
- 11t HM steel
- 800t clinker
- 20t slag

Cement plant
- 1.50Mt cement/yr
- 0.511 tCO2/tclinker due to calcining limestone
- 0.281 tCO2/tclinker due to combustion of oil in the kiln
- 0.861 tCO2/tclinker
- 0.351 tCO2/tclinker due to combustion of coal in the kiln
- 0.391 tCO2/tclinker
- 0.35 tCO2/tclinker due to combustion of coke in the BF
- 0.25 tCO2/tclinker
- 0.1 tCO2/t cement

Table 1 Main features of steel, slag and cement assumptions used in various methods of allocating carbon footprint

<table>
<thead>
<tr>
<th>Allocation methods</th>
<th>per tonne of slag</th>
<th>per tonne of cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical allocation 1</td>
<td>1.24t CO2/t slag</td>
<td>1.18t CO2/t cement</td>
</tr>
<tr>
<td>Physical allocation 2</td>
<td>0.54t CO2/t slag</td>
<td>0.52t CO2/t cement</td>
</tr>
<tr>
<td>Weight allocation</td>
<td>1.73t CO2/t slag</td>
<td>1.61t CO2/t cement</td>
</tr>
<tr>
<td>Economic allocation</td>
<td>0.01t CO2/t slag</td>
<td>0.01t CO2/t cement</td>
</tr>
</tbody>
</table>

Industrial ecology synergy

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CO2 saved per tonne of cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 – 0 synergy</td>
<td>0.91 tCO2 saved at the slag</td>
</tr>
<tr>
<td>Case 2 – all slag substitutes for cement</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The price the slag can command is very much derived from the closeness of the composition of slags to that of cement. Some of these slags can be sold as roadbed material, for which the natural material is stones from a quarry. Granulated slag is a more sophisticated product than bulk slag; its market value is higher and commensurate with the extra cost of granulation.

**CO2 issues**
Primary processes each have their associated CO2 emissions. It is intuitively obvious that implementing a synergy between the two activities by using BF slag to substitute clinker will decrease energy consumption and CO2 emissions on a global consideration. It will also decrease total investment in the two activities, steel and cement production, and probably cut operating costs, but this kind of intuition needs to be checked and validated.

A method to describe the synergy in terms of energy and CO2 is Life Cycle Analysis (LCA), which is widely accepted and one towards which the practitioner will spontaneously turn. As soon as LCA is selected as the analytical method, then a premise is accepted that issues are discussed in relation to a functional unit, in this case one tonne of BF slag. We will come back later on these key assumptions, which are often taken for granted, and seem convenient, but are not necessary and do not necessarily provide the ‘best’ answers to our questions.

There are several ways of implementing LCA and this plurality of options is actually related to the complexity of what is to be accomplished.

The second level of complexity arises due to the full introduction of economic parameters into the analysis, i.e. of looking for a solution to internalize the cost of CO2 into the economic system. This is an even greater challenge, as the price of CO2 may be low or nil.

Steel production generates slags, which are compounds of lime, silica, alumina and magnesia in large quantities (300 to 400kg/t of steel). The slag concentrates the elements of the ore that are not alloyed in the steel and which do not leave the process as gases or dust. The closeness of the composition of slags to that of cement is such that some of these slags can serve as secondary raw material for making cement. They are usually mixed with clinker at the final stage of cement production, i.e. beyond the high temperature kiln stage.

This creates a synergy between the cement and the steel industries. The slag materials are already organized at an industrial level. Blast furnace (BF) slag is recovered when tapped and quenched in water to produce granulated slag.

It exhibits the amorphous structure required for direct addition to cement clinker after grinding.

That price is close to the cost of clinker and it incorporates a transport ‘allowance’ from a small distance around the cement plant, of the order of 100km.

There is a lively commercial dimension to this market and other secondary raw materials, such as fly ash from coal-fired power plants, can compete with BF slag as an additive to clinker. The price the slag can command is very much constrained by the price of cement.

One should also factor in that bulk slag can be sold as roadbed material, for which the natural material is stones from a quarry. Granulated slag is a more sophisticated product than bulk slag; its market value is higher and commensurate with the extra cost of granulation.

**CO2 issues**

Primary processes each have their associated CO2 emissions. It is intuitively obvious that implementing a synergy between the two activities by using BF slag to substitute clinker will decrease energy consumption and CO2 emissions on a global consideration. It will also decrease total investment in the two activities, steel and cement production, and probably cut operating costs, but this kind of intuition needs to be checked and validated.

A method to describe the synergy in terms of energy and CO2 is Life Cycle Analysis (LCA), which is widely accepted and one towards which the practitioner will spontaneously turn. As soon as LCA is selected as the analytical method, then a premise is accepted that issues are discussed in relation to a functional unit, in this case one tonne of BF slag. We will come back later on these key assumptions, which are often taken for granted, and seem convenient, but are not necessary and do not necessarily provide the ‘best’ answers to our questions.

There are several ways of implementing LCA and this plurality of options is actually related to the complexity of what is to be accomplished.

The first level of complexity is due to the fact that creating such a synergy means that various scenarios have to be compared: this is due to the fact that decision making has to be mod-
The cement industry buys the product and the slag will displace cement made from conventional sources. In the longer term, if Climate Policies become more demanding as will most certainly happen, then these CO₂ figures will be translated into monetary terms. As already pointed out, this would be a major paradigm shift in terms of the value of basic materials, particularly of cement, but also of steel. Until this is acknowledged, the steel sector might prefer the highest value, i.e., the one related to the weight allocation, but, if it does, it might find it difficult to sell its slag, as it would burden the cement industry above its replacement value. This is typically a commercial issue, when the sector chooses what it pleases. On the other hand, CO₂ emissions are calculated based on a Global Warming. The physics of emissions, real ones or avoided ones, is important, thus the physical method would probably be best, but a comparison with what is avoided (the present emissions of the cement sector assuming substitution) would probably also be of interest, in a kind of system expansion: 0.91tCO₂/t cement are avoided and they are replaced by 0.54tCO₂/t cement, a gain of 0.40tCO₂/t cement or a 44% saving.

From the standpoint of cement, this figure is relevant, although the practice until now has been for the sector to claim that slag, fly ash and carbon ‘waste’ are CO₂-free. Hence, this sector has room for discussions and possibly negotiations. If one steps away from the concept of a functional unit, which narrows down the discussion to commercial and possibly parochial issues, and looks at the industrial ecology synergistic system that a steel mill (say, 4Mt output) and the cement kiln (1.5Mt output) constitute, then a slightly different picture emerges without synergies. For historically, cement production is part of an integrated steel mill’s operation, which also systematically included its own power plant, at least in most places in Europe. The system emits 9.8MtCO₂/t without any slag used, or, with full synergy, 8.8MtCO₂/t is avoided emissions of 0.96MtCO₂/t to the atmosphere. This does not allocate the savings to any of the sectors, just shows how virtuous for the planet the industrial ecology synergy is.

If the savings are allocated to steel, then the amount of CO₂ avoided is 0.24tCO₂/t steel and if one does the same for cement, then it amounts to 0.64tCO₂/t cement. (The two numbers are not cumulative; they express the same thing in different units). Both sectors have much to gain in pursuing these synergies.

Of course, this discussion is somewhat convoluted as it only focuses on subtle ways of performing an LCA. The issue for both sectors involved is somewhat more practical as the image of their material is at stake and material choices as well. In the longer term, if Climate Policies become more demanding as will most certainly happen, then these CO₂ figures will be translated into monetary terms. As already pointed out, this would be a major paradigm shift in terms of the value of basic materials, particularly of cement, but also of steel. Until this is acknowled-
edged by the materials sectors, it is very difficult to carry out CO₂ allocation on the sole strength of Life Cycle Thinking (LCT) as LCT is very fuzzy in this area, and because the issues go far beyond the scope of a standard LCA and, therefore, the occasion of providing LCI may be a good reason for forcing the issue and looking for solutions. But LCT and LCA methodologies do not offer any light to navigate through this long-term strategic issue.

Methodological conclusions
The discussion which has been carried out here for BF slag can in principle be extended to all by-products. It can also be used in a wider context, for example, the comparison between materials such as metals and cement, and materials which have a double status, as materials and as energy sources, such as wood or plastics.

The concepts of closed-loop and open-loop have been used in such a context, but not without ambiguities and the approach outlined here would be more fruitful in this particular case as well.

The case of biofuels would also benefit from such an approach and possibly many other complex cases, where the direct, almost brutal application of LCA methodology, does not work satisfactorily, as it leaves too many options open which are left for the practitioners to solve as they see fit. Complexity should be addressed as such and not through avoidance behaviour.

This discussion is also shedding light on how to use LCA ‘properly’[4]. LCA was initially designed as a management tool to give environmental insight for decision making related to consumer products which are mass-produced. Thus, it usually compares two scenarios and makes suggestions on the most preferable one. It is best used as a tool for designing new products or new solutions. However, LCA is used increasingly as a marketing tool to show the advantages of one solution against the assumed disadvantages of a competing one.

It is also used in more ambitious decision making, especially societal ones (as a basis of a carbon footprint, for example). When LCA is called upon to sort out the difficulties related to the internalisation of the CO₂ externalised into cement or steel prices, then, clearly, it is used beyond its scope.

LCA is the child of physics (by establishing mass – globally, per unit chemical species and per unit element, etc – and energy budgets) and of material accounting (by tracking down these physical fluxes with a very high level of detail, and, apparently at least, of accuracy). Because it is defined by standards, it is not bound by the law of physics: practically speaking, a system expansion does not conserve energy and matter[5]. This is a difficulty that easily leads to rebound effects, if the method is used in too general a context. There are also many other reasons for rebound effects[6].

Another distortion of the use of LCA is to focus exclusively on CO₂ or GHG emissions. LCA claims universality and the trade off is implication of the modelling of the real world. LCA is multicriteria. It provides a full picture of the global environmental footprint of the functional unit, not simply of the carbon footprint.

One may also wonder at the distinction between products, co-products, by-products, residues and waste, which has been introduced in the fields of law and regulation to solve important international trade issues in an opportunistic way. Nature does not abide with these different concepts.

All outputs from an industrial process have, in the long run, the same fate of going back eventually to the environment, directly or after being used by consumers or by an industry, at some end-of-life or after one or several steps of recycling. They may go back in their chemical form, or transformed into other compounds. The anthroposphere is thus giving back these products to the ecosphere, after borrowing them for a while.

Acknowledgements
The author thanks Jean-Marie Delbecq, Jan Bollen, Mauro Chiappini and Jean-Sébastien Thomas of ArcelorMittal for enlightening discussions on the topics of this paper.

References
1 J-P Birat, J-M Delbecq, E Hess, D Huin, Slag, steel and greenhouse gases, La Revue de Métallurgie-CIT, January 2002 13-21
2 M Chiappini, J-P Birat, By-product allocation, a case study: blast-furnace slag, SAM-3, Freiberg, 29-30 April 2009 (www.sovamat.com)
3 http://www.iso.org/iso/fr/catalogue_detail.htm?csnumber=37456
4 J-P Birat, J-S Thomas, Beyond Life-Cycle Thinking: the SOVAMAT initiative and the SAM seminars, ECObalance 2008, International Conference on Ecobalance, Tokyo, Japan
6 to be published in SAM-5 seminar, 2011