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 0.24tCO_2/t of steel produced or 0.64tCO_2/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 artefacts 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 CO_2 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 CO_2. 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-

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Steel mill	Cement plant	
4.00Mt crude steel/yr	1.50Mt cement/yr	
		0.51t CO_2/t clinker due to calcining limestone
2.11t /CO_2/tsteel	0.78tCO_2/t clinker	0.28t CO_2/t clinker due to combustion of oil in the kiln
	0.86tCO_2/t clinker	0.35t CO_2/t clinker due to combustion of coal in the kiln
	0.91tCO_2/t clinker	0.40t CO_2/t clinker due to combustion of coke in the kiln
250kg BF slag/tHM	1t cement = 0.90t clinker	
1t HM/t steel	1t cement = 0.95 t slag + 5% gypsum	
800€/t steel	60€/t cement	
20€/t slag		

Allocation methods

method	per tonne of slag	per tonne of cement
Physical allocation 1	1.24tCO_2/tBF slag	1.18tCO_2/t cement
Physical allocation 2	0.54tCO_2/tBF slag	0.52t CO_2/t cement
Weight allocation	1.72tCO_2/tBF slag	1.63tCO_2/t cement
Economic allocation	0.01tCO_2/tBF slag	0.01tCO_2/t cement

Industrial ecology synergy

Case 1 – 0 synergy	9.81
Case 2 – all slag substitutes for cement	8.85
	0.96

0.64t of CO_2 saved per tonne of cement
0.24t of CO_2 saved per tonne ot steel

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

quence, large industrial emitters of CO_2 from large individual sources. In both cases, CO_2 originates both from the combustion of fossil fuels and from chemical reactions.

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, ie beyond the high temperature kiln stage.

This creates a synergy between the cement and the steel industries, which has been organized at an industrial level. Blast furnace (BF) slag is recovered when taped and quenched in water to produce granulated slag.

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

This is probably the most important example of an industrial ecology connection between two industrial sectors in terms of volume.

This is also a clear example of how a by-product of the steel industry avoids the status of waste and becomes a co-product.

All this has good connotations and is pointed out as virtuous in industrial ecology classes and matches the rules related to waste, particularly the waste hierarchy rule and the 3, 4 or 5-R rules (Reduce; Reuse; Recycle; Recover; Residual Management).

When one looks at the economics of the connection and at the manner in which environmental externalities, such as climate change, can be brought into the picture, the matter becomes more complex and the ambiguity between a co-product and a by-product comes to the front.

The economic picture is fairly simple. The steel mills sell their granulated slag to cement makers. There is a market for slag, which decides on the market price of that commodity. 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.

CO_2 issues

Primary processes each have their associated CO_2 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 CO_2 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 CO_2 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 modelled, not simply a mass and energy balance around engineering systems.

The second level of complexity arises due to the full introduction of economic parameters into the analysis, ie of looking for a solution to internalize the cost of CO_2 into the economic system. This is an even greater challenge, as the price of CO_2 may be as low as zero – if one deals with emissions comprised in the quotas that the major energy-intensive industries have received for free until now. But if the free quota is exceeded, further allowances have to be purchased, presently at €15/t at today's market price a figure which will reach much higher values in the future, of, say, €50/t in the near term and even higher using projections that some long-term economic models deliver, such as €400/t. These figures can play havoc with the market prices of commodities like steel and cement and may exceed profit margins by an order of magnitude.

The numerical example that will be used is given in **Table 1**. It is derived from two former publications, the data of which might need a small update, but this has not be done here as the objective is to make a point, not to establish definitive figures.

We present the options below offered by LCA in steps:

- A first set of options is called *allocation*: a value of impact, in this case of CO_2, is attributed (technical term is allocated) to the slag.
- A second set of options consists in extending the scope of analysis by introducing a wider system into the discussion to bring it closer to reality, according to a method called *system extension*.
- A third set of options consists in explicitly discussing scenarios that will take place due to the use of slag in the cement industry. This is called *consequential LCA*.
- One may discuss the same issues related to a slightly different functional unit, such as a tonne of steel, or a tonne of cement rather than the tonne of slag that has been considered until now.
- Finally, the approach may get rid of LCA conventions altogether and propose something different and original, based on a more basic application of the industrial ecology concept, ie on the intuition referred to above.

Allocation LCA

The allocation method itself offers many sub-options depending on which specific allocation method is used[6]:

- The first method, *weight allocation*, is related to weight (or mass) produced. ie a tonne of hot metal is produced alongside 0.25t of slag and the CO_2 emissions can be allocated proportionally to theses respective masses. This means that the specific allocation (also called CO_2 factor or CO_2-intensity factor tCO_2/t) of hot metal and slag is the same, in this example 1.72tCO_2/t of steel and slag. This is a method that gives the same weight, figuratively and physically, to both product and co-product.
- The second method, *economic allocation*, is related to economic value, usually price:

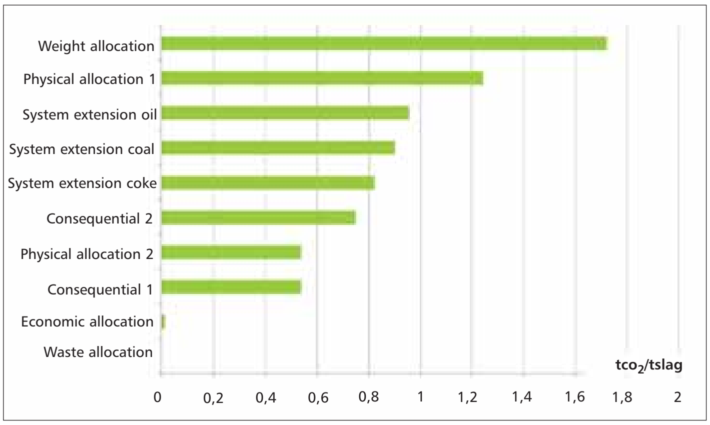

Fig 1 Estimates of the CO_2 burden of BF slag according to ISO 14040 accepted methods[1]

assuming, say, a price for steel of €800/t and €20/t for slag then the sales associated with 1 tonne of steel is €805/t (ie 1t steel + 0.25t slag). This translates into 0.0013tCO_2/t slag. The contribution of slag in this case is almost negligible, which in a sense is similar to assuming that slag is a waste without any environmental burden.

- The third method, *physical allocation*, is related to a physical analysis of the co-production of slag and hot metal. There are again several ways of doing this, just like there are several ways of modelling the operation of a complex chemical reactor such as a blast furnace:

– the method followed in Reference[1] is based on a full-fledged physical chemistry and process engineering model of the blast furnace and calculates how much CO_2 is generated due the production of an extra marginal amount of slag. This is probably what chemical engineers would present as the methods that describe most accurately the cost to pay for producing clinker substitute in a blast furnace. The answer is 1.24tCO_2/t slag.

– another method, requires less expertise in analyzing the blast furnace processand consists in allocating emissions according to the energy distribution between hot metal and slag in the blast furnace. The reason why this is called physical allocation is fairly clear. The answer then is 0.54tCO_2/t slag. Discussing why the two methods do not match goes beyond the scope of this paper.

- A fourth option is to consider slag as a waste and therefore as an undesired product of a blast furnace. Practically speaking, this is not quite what happens in the real world, as the charge of the blast furnace (its burden) is adjusted in order to make the slag match the requirements of the cement industry in terms of composition. In this case, the allocation is nil, 0.00tCO_2/t slag.

System extension

System extension consists of introducing the cement industry into the picture by saying that the slag will displace cement made from conventional sources, in this case made without slag. The production of cement generates between 0.78 and 0.91tCO_2/t cement, which means that the replacement of clinker by slag would avoid between 0.82 and 0.96 tCO_2/t slag. This value is fully unrelated to any of the values calculated from allocation methods. It assumes on the one hand that slag will indeed replace clinker, which would be a rather strong statement in a consequential LCA context, and that slag should be considered as a substitute for clinker with all the attributes of clinker given to slag, including CO_2 emissions.

Consequential LCA

Now let us try to propose a consequential LCA approach. This is entering into prospective methodologies or foresight studies and this opens up another Pandora's box and another fractal dimension in the analysis: again, many options are possible and a path would have to be chosen between them.

The question to answer now is what happens in the real economic world when the steel sector makes a tonne of slag available on the market as a clinker substitute? Here are some reasonable options:

- The cement industry buys the product and indeed uses it as a clinker substitute by reducing its own production of clinker (con sequential 1). This is similar to the system extension case discussed above. Of course, a full consequential LCA would have to take on board the upstream emissions of cement making, which has not been done in the example here; of quarries for limestone, but also of fossil fuels, electricity, etc.

- The cement industry buys the product but manages to sell more cement to the market. Thus, no replacement is taking place. The total amount of emissions related to the cement sector increases (consequential 2).

- The cement sector strikes a commercial deal with the steel sector and replaces fly ash by slag, thus turning fly ash into the waste that is usually considered to be its status and the power sector bears the full burden of its emissions unequivocally.

- etc.

These results have been combined in **Fig 1** to show how confusing the issue may appear to anyone who starts looking for a fair way out of the methodological difficulties that have been raised. An LCA practitioner will probably choose the option that best fits the standpoint taken for a particular study. It will be different if there is a mandate from the steel or the cement industry, or if the analysis represents stakeholders mainly interested in climate change, etc.

What would be a best practice that could be recommended for all of these approaches?

All the figures are related to slag on the assumption that an LCA of slag is carried out.

One may, however, discuss from the standpoint of steel, for example a functional unit made of one tonne of crude steel: the slag allocation, whichever would be chosen, would be removed from the allocation of steel and thus the 2.11tCO_2/tsteel would drop accordingly. If a physical allocation is assumed (physical allocation 2), then the value for steel would drop to 1.97 tCO_2/tsteel.

This value has no relevance to an economic value. The EU Trading Directive (ETS) for CO_2 emissions is based on actual physical emissions and does not incorporate a deduction (credit) for slag. On the other hand, steel needs to publish life cycle inventories (LCI), which are used by product designers and other stakeholders. In this LCA context, it makes sense to take a credit for slag – excepting that in any of the previous methods this is in principle possible. The steel sector might prefer the highest value, ie 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, CO_2 emissions are calculated because of Global Warming. The physics of emissions, real ones or avoided ones, is important, thus the physical method emissions 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: 0.91tCO_2/tcement are avoided and they are replaced by 0.54tCO_2/tcement, a gain of 0.40tCO_2/tcement 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 CO_2-free. Hence, this leaves 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/y output) and the cement kiln (1.5Mt/y) constitute, then a slightly different picture emerges without synergy. (Historically, cement making was 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 9.8MtCO_2/y with no slag used or, with full synergy, 8.8MtCO_2/y, ie this avoids emission of 0.96MtCO_2/y 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 CO_2 avoided is 0.24tCO_2/t steel and if one does the same for cement, then it amounts to 0.64tCO_2/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 CO_2 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 by the materials sectors, it is very difficult to carry out CO_2 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 CO_2 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 CO_2 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. ■

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