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Sustainability and circular economy – Why and how for ferro-alloy manufacturing

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Abstract – The principles of circular economy in relation to sustainability are discussed along with what can and cannot be achieved by a Best Available Technology (BAT) approach. Metal production processes are driven by the fundamental principles of thermodynamics and transient phenomena. In this context, the importance of physical, mathematical and numerical modelling of processes/reactors used in the metallurgical industry is emphasized as well as their limitations. The example chosen here is the ferrochromium refining CLU/AOD reactor. In this regard, an approach that combines physical cold-water experimentation with mathematical and/or numerical modelling including Computational Fluid Dynamics (CFD) is suggested in order to be able to verify the findings as well as to be able to scale up and design the reactors from bench to larger scale, and even to full scale. This concept can be named *Physical and Computational Process Dynamics*. Using this approach, one can achieve considerable improvements in reduction of energy and CO_2 emissions and hence in carbon footprint, and can find ways and means of changing our linear economies into circular ones. Furthermore, BAT targets can well be reached.

Is this enough? Or can a completely new paradigm of processing with much lower energy consumption and emissions be found that can be adopted in the mid- to long-term? From a fundamental principles point of view this change in paradigm is changing/altering the governing thermodynamics of the processes. Here comes the use of natural gas for ferro-alloy manufacturing. *Why and How?* Laboratory-scale experiments have confirmed its potential based on the principles of fundamental transient phenomena. Can this be possible on a large industrial scale – can it be used? If we are prepared to put our minds, energy, and necessary funds for further research why not, for *we have only this planet to live on at this point in time*.

Considering all the above and remembering the fact that the ice at both the Antarctic and Arctic caps is melting, which has the potential of even stopping ocean currents such as the Gulf Stream, and keeping in mind too the rather sad state of the ferrous metallurgical industry with respect to its emissions and high energy usage, we ask, *to what extent ferro-alloys might be affected?*

Keywords: sustainability, circular economy, ferro-alloys, process dynamics, best available technology

INTRODUCTION

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It is agreed universally that sustainability has three aspects – *ecological, social,* and *economic* – and it is not possible to achieve a particular level of ecological, social, and economic sustainability independently without achieving at least a basic level of all three forms simultaneously (Rankin, 2014).

In *ecological terms* sustainability (WBCSD, 2017) is achieved if the stock of natural capital (environmental resources) does not decline over time, or if resources are managed so as to maintain a sustainable yield of ecosystem services (such as the part of income that accrues to the owner of a finite resource, for example as the royalties paid by the mining companies to the state, are invested in the development of alternatives).

The *economic sustainability* (WBCSD, 2017) is defined in terms of the economy's ability to maintain material production or consumption indefinitely. As this is not possible without ongoing use of environmental resources, economic interpretations automatically imply that there must be environmental sustainability.

Social sustainability (WBCSD,2017) consists of the structures, institutions, and relationships that enable individuals to maintain and develop their human capital (health, knowledge, skills, well-being, and motivation required for productive work and the individual's emotional and spiritual capacity) in partnership with others and to be more productive working together rather than in isolation. It includes networks, communication channels, families, communities, businesses, trade unions, schools, voluntary organizations, legal and political systems, educational and health bodies, as well as social norms, ethics and values, and trust.

It is not possible for subsystems to be sustainable within an unsustainable global system. Sustainability is a property of the Earth system as a whole. A firm or organization is unlikely to be sustainable if the society at large is not sustainable. The only way forward then is to make the whole Earth sustainable through contributions from every aspect of *human endeavour,* as it is human beings themselves that created both this *civilization* and the *messy situation* we find ourselves in.

In the face of sharp volatility increases across the global economy, environmental problems and proliferating signs of resource depletion in connection with sustainability issues, the call for a new economic model is getting louder. In the quest for a substantial improvement in resource performance across the economy, governments and businesses have started to explore ways of reusing products or their components, and restoring more of their precious material, energy, and labour inputs. The time is right, many argue, to take this concept of a *'circular economy'* one-step further, to analyse its promise for businesses and economies, and to prepare the ground for its adoption (EMF, 2013).

Throughout its evolution and diversification, our industrial economy has hardly moved beyond one fundamental characteristic established in the early days of industrialization: a *linear model* of resource consumption that follows a *'take-make-dispose'* pattern. Companies harvest and extract materials, use them to manufacture a product, and sell the product to a consumer – who then discards it when it no longer serves its purpose. Indeed, this is more true now than ever before – in terms of volume, some 65 billion tonnes of raw materials entered the economic system in 2010, and this figure is expected to grow to about 82 billion tonnes in 2020 (EMF, 2013).

Whilst major strides have been made in improving resource efficiency and exploring new forms of energy, less thought has been given to systematically designing out material leakage and disposal. Any system based on consumption rather than on the restorative use of non-renewable resources, however, entails significant losses of value and negative effects all along the material chain. Against this backdrop, the search for a 'better hedge' and an industrial model that decouples revenues from material input while addressing sustainability and environmental problems has become essential and the 'not so new' concept of *circular economy* emerged.

METAL PROCESSING

Sustainability and circular economy

The term sustainable metallurgy/metal processing (including all the post mining activities resulting in the final product) is actually meaningless as these activities exploit nonrenewable resources and depletes them. The real issue here is to address the question, how can metallurgy (mining included) contribute to the transition to sustainability? Here *eco-efficiency* becomes particularly important along with *contributions* to the development of alternative (this also becomes part of social sustainability) and, one hopes, renewable products when the resource is depleted. In fact, sustainability here is all about environment and people. Eco-efficiency (Rankin, 2014, WBCSD, 2017) refers to "doing more with less". The general principles are to reduce material intensity; reduce all kinds of emission; reduce energy intensity; reduce dispersion of toxic substances; extend product durability; re-manufacturing; enhance recyclability; maximize use of renewables; increase service intensity, thereby changing from linear to circular economy.

Conversion from linear to circular economy and eco-efficiency – doing more with less – can and will be achieved by the following. First, improving and integrating significantly the existing processes across the board through an understanding of fundamental static and transient phenomena. A proper understanding of thermodynamics and phase equilibria, kinetics, mechanisms and transport properties related to processes should eventually lead to physical and mathematical modelling, simulation and optimization, resulting in satisfactory process control. Ideally, all the streams of processes should be feed streams for other processes – hence full integration. Secondly, designing the products to allow for re-manufacturing and adjusting/designing the processes accordingly. Thirdly, minimizing recycling as much as possible. Fourthly, elimination or at least absolute minimization of waste production and thus waste disposal. Finally, changing the process paradigm by designing new, novel and integrated (and obviously far better) sustainable alternatives with the correct processing strategies, once again through an understanding of the fundamentals. There should be a multi- or cross-disciplinary approach and teams to look into improvements and integration.

A circular economy is an industrial system that is restorative or regenerative by intention and design (Figure 1). It replaces the 'end-of-life' concept with restoration; it shifts towards the use of renewable energy; it eliminates the use of toxic chemicals, which impair reuse; and it aims at eliminating waste through the superior design of materials, products, systems, and, within this, business models.

Such an economy is based on few simple principles. First, at its core a circular economy aims to 'design out' waste. Waste does not exist—products are designed and optimized for a cycle of dismantling and reuse. These tight component and product cycles define the circular economy and set it apart from disposal and even recycling where large amounts of embedded energy and labour are lost. Secondly, circularity introduces a strict differentiation between consumable and durable components of a product. Durables such as engines, vehicles, or computers are made of what can be termed technical nutrients unsuitable for the biosphere, materials such as metals and most plastics. These are designed from the start for reuse. Thirdly, the energy required to fuel this cycle should be renewable by nature, again to decrease resource dependence and increase system resilience.

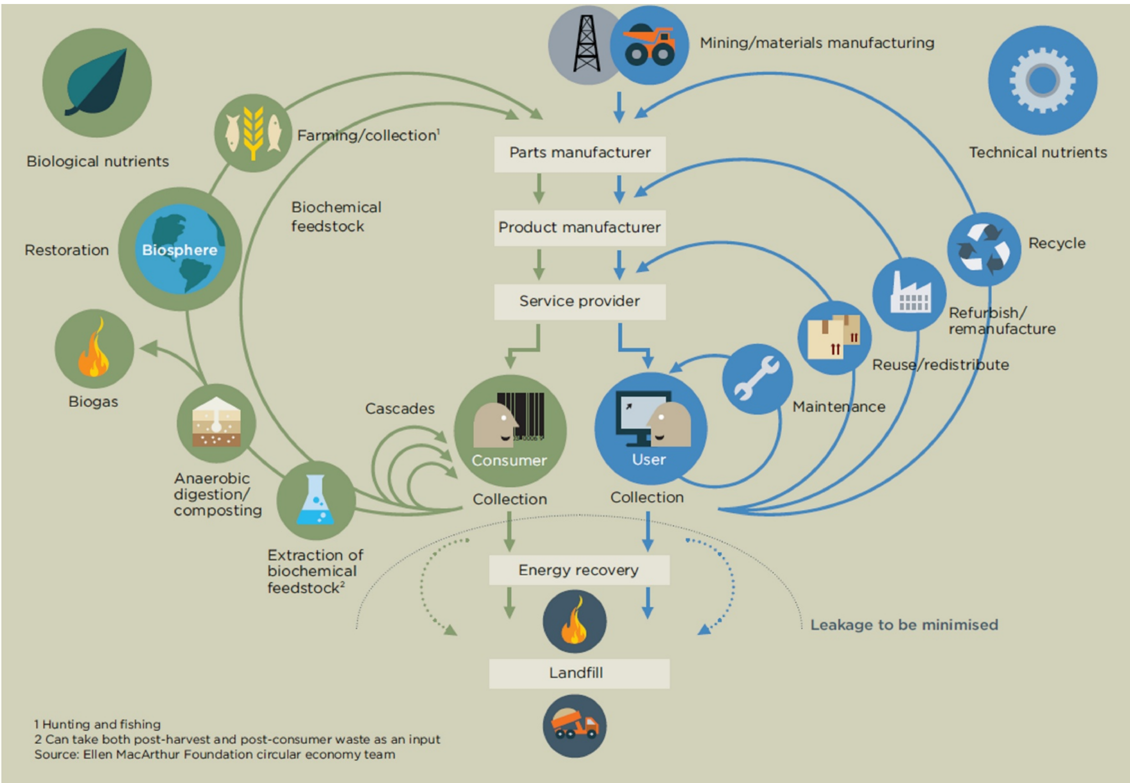

Figure 1: The circular economy – an industrial system that is restorative by design (EMF, 2013)

For technical nutrients, the circular economy largely replaces the concept of a consumer with that of a user. This calls for a new contract between businesses and their customers based on product performance. Unlike in today's 'buy-and-consume' economy, durable products are leased, rented, or shared wherever possible. If they are sold, there are incentives or agreements in place to ensure the return and thereafter the reuse of the product or its components and materials at the end of its period of primary use (EMF, 2013).

The *'the inner circle'* refers to minimizing comparative material usage *vis-à-vis* the linear production system. The tighter the circle – *i.e.*, the less a product has to be changed in reuse, refurbishment and re-manufacturing and the faster it returns to use – the higher the potential savings on the shares of material, labour, energy, and capital embedded in the product and on the associated rucksack of externalities (such as greenhouse gas [GHG] emissions, water, toxicity). The *'circling longer'* concept refers to maximizing the number of consecutive cycles (be it reuse, re-manufacturing, or recycling) and/or the time in each cycle. The *'cascaded use'* refers to diversifying reuse across the value chain, such as when cotton clothing is reused first as second-hand apparel, then crosses to the furniture industry as fibre-fill in upholstery, and the fibre-fill is later reused in stone wool insulation for construction – in each case substituting for an inflow of virgin materials into the economy – before the cotton fibres are safely returned to the biosphere. The *'power of pure circles'*, finally, lies in the fact that uncontaminated material streams increase collection and redistribution efficiency while maintaining quality, particularly that of technical materials, which in turn extends product longevity and thus increases material productivity. These four ways to increase material productivity are not merely once-off effects that will dent resource demand for a short period during the initial phase of the introduction of these circular setups. Their lasting power lies in changing the run rate of required material intake. They can therefore add up to substantial cumulative advantages over a classical linear business-as-usual case.

It is evident that reuse and better design can significantly reduce the material bill and the expense of disposal. However, how do these advantages stack up against a production system that has been optimized for throughput? How can the governing principle of 'selling more equals more revenue' be replaced? Moreover, how can the choice for circular products, and using rather than consuming, be rendered more attractive for customers? These important questions require a holistic and responsible approach and require very fundamental changes to our life styles and business practices.

In order for companies to materialize the savings associated with a circular system by reusing resource inputs to the maximum degree, they need to increase the rate at which their products are collected and subsequently reused and/or their components/materials recuperated. Apart from the automotive industry, few industries currently achieve a collection rate of 25%. When shifting from linear to circular approaches, the rule of thumb for optimization is *'the tighter the reverse cycle, the less embedded energy and labour are lost, and the more material is preserved'.* Today's recycling processes are typically 'loose' or long cycles that reduce material utility to its lowest 'nutrient' level. This is even truer for the incineration of waste. In a circular economy, by contrast, reverse activities in the circular economy will extend across an array of circles for repair and refurbishment of products, and re-manufacturing of technical components.

In circular economy, industrial ecology involves focusing less on the impacts of each industrial activity in isolation and more on the overall impact of all such activities. This means recognizing that the industrial system consists of much more than separate stages of extraction, refining, manufacture and disposal, and that the stages are linked across time, distance, and economic sectors.

The best available technology (BAT) concept

BAT is a relatively new approach for process evaluation. It is defined by the European Commission through EC Directive 96/61 Article 2 (11) as follows: the most effective and advanced stage in the development of activities and their methods of operation which indicates the practicable suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent, and where that is not practicable, generally to reduce the emissions and impact on the environment as a whole (Holappa, 2013). These principles simply mean reducing the consumption of resources, reducing the impact on nature and increasing product or service value. Hence from the point of view of metal process industries the relevant trends are

- Continuous/semi continuous processing,
- Increased process intensity,
- Process integration,
- Recycling,
- Clean production
- Flexibility of the processes

The above definition of BAT covers not only the technology used, but also the way in which the installation is operated. BAT takes into account the balance between the costs and environmental benefits. It is reasonable to expect an energy saving potential of 20 to 30% on a global level by adopting the BAT principles as widely as possible. With efficient integration, the benefit can be slightly higher. Another option in the case of carbon dioxide emissions is to introduce renewable biomaterials (*i.e.*, charcoal) as a substitute reductant for coke and to mitigate greenhouse gas emissions by CO_2

recovery. Once BAT procedure and the EC directive are achieved this will be the first stage in approaching *sustainability* and *industrial ecology* on the way to *circular economy.* Through the use of BAT current existing manufacturing operations can be improved significantly, there is none the less the thermodynamic limit (for energy consumption, CO_2 emissions, *etc.*) of existing processes, a limit below which it is impossible even with BAT practices to operate. Thus, the use and adoption of BAT is only a first step in the right direction to reaching circular economy and a livable planet. That simply means we need much more than BAT, and we should consider developing completely new and novel alternative processes with different thermodynamic limits of lower or no harmful emissions and lower energy requirements that will form the backbone of sustainable circular economy.

Implications for ferro-alloys

The annual average growth rate for stainless steel manufacturing, which is the main consumer of FeCr ferro-alloys, has been more than 5% a year driven mainly by demand from China and India (World Steel Association, 2014). Such growth is assumed to continue and even expand further by increasing demand from developing regions in Southeast Asia, Africa and South America. It is also expected that the amount of recycled stainless steel will be very limited due to the history of high tonnage stainless steel production being quite short. At 5% annual growth rate, the annual production of stainless steel can exceed 157 Mt by the 2050s, requiring the manufacture of around 48–50 Mt of FeCr (about 11.5 Mt produced in 2014). As for other ferro-alloys such as FeMn, FeSi, and SiMn, the increase in demand is determined by ordinary- and low-alloy steel making, which has a more modest increase of about 2.2% a year, and future growth is expected to take place mostly in developing countries (World Steel Association, 2014). However at 2.2% annual growth rate, the annual production of steel worldwide will exceed 3230 Mt by the 2050s and will require about 100 Mt of related ferro-alloys (around 40 Mt produced in 2014), which means that there will also be remarkable growth in these sectors of the ferro-alloy industry as well.

As all of these industries are very much in the linear economy mode with high carbon dioxide emissions and high energy consumption their long-term survival will, no doubt, depend on drastic changes in the correct directions. Obviously, the first step, which I believe already to be taking place, is to achieve BAT requirements. However, as mentioned previously the best that can be done with BAT are improvements of about 30%, which has a limited effect on conversion to circular economy. Nevertheless, even to achieve BAT targets, extensive and potentially coordinated research is required to understand the fundamentals of the processes in question. I call this approach *physical and computational process dynamics,* which depends on correctly determined and modelled thermodynamics, kinetics and mechanisms of processes leading into dynamics through physical model experiments and calculations, followed by mathematical and/or numerical modelling such as CFD (Eric, 2017). This approach can even be used for design and scale-up issues supported by appropriate test work. In this way, once the reactors/processes are modelled and simulated, strategies for best process control can be developed to achieve BAT targets, and ways and means of integration, waste minimization and product design issues can be addressed for converting our linear economies into circular ones. A simplified example of this (research) approach relates to the Creuset Loire Uddeholm reactor in ferro-alloy refining and stainless steel making. Figure 2 summarizes the example.

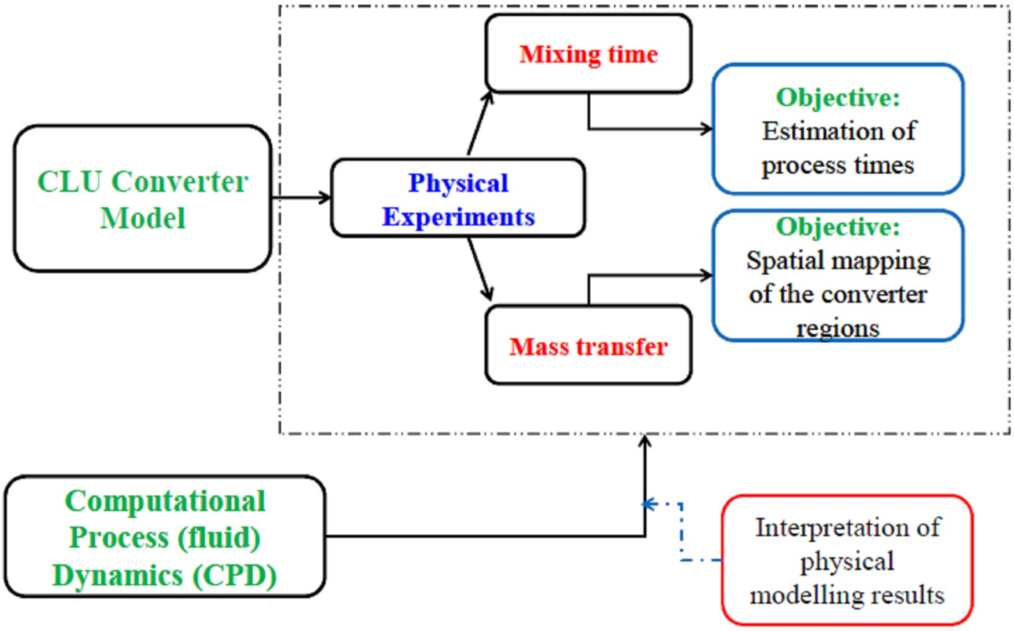

Figure 2: Physical and computational process dynamics approach adopted for a CLU converter

For an estimation of process times, mixing times were measured as a function of flow rate of the gas, bath weight and bath height using the physical model (Chaendera and Eric, 2017). The bath height in the vessel of the physical model – which had a diameter of 0.5 m (a fifth the size of the actual reactor) – was observed to have the largest effect on mixing time. From the experimental results obtained, a correlation that could be used to relate mixing time *(T)* to gas flow rate *(Q)*, bath weight *(W),* and bath height *(H)* was established as

$$T_{mix} = 4.39\, Q^{-0.73}\, W^{0.24}\, H^{1.12} \qquad [1]$$

which could then be scaled up to the real actual converter size for design purposes as

$$T_{mix} = 171\, Q^{-073}\, W^{0.24}\, H^{1.12} \qquad [2]$$

On the other hand, knowledge of the mass transfer characteristics of the bath in the converter operation is necessary for the following reasons: (1) to determine accurately the optimal gas-blowing rate for efficient stirring of the bath; (2) to make a choice of the refractory lining to be used (along with the slag chemistry); and (3) to determine the wear rates of the refractory lining during furnace operation, damage caused by the distribution of turbulence fields in the bath (which will also lead to the design of the furnace cooling circuit). Experimentally determined mass transfer coefficients using the physical model are illustrated in Figure 3 in the form of a three dimensional contour plot (Chaendera and Eric, 2017).

Furthermore, CFD (Computational Fluid Dynamics) modelling was applied (Akdogan, Taskinen and Eric, 2013) to the CLU to understand the hydrodynamic behaviour of the bath and to validate the numerical predictions with the physical model. At different gas flow rates and bath heights, a re-circulatory turbulent flow of the bath and a plume zone formed by the exiting gas was observed. These are shown in Figure 4.

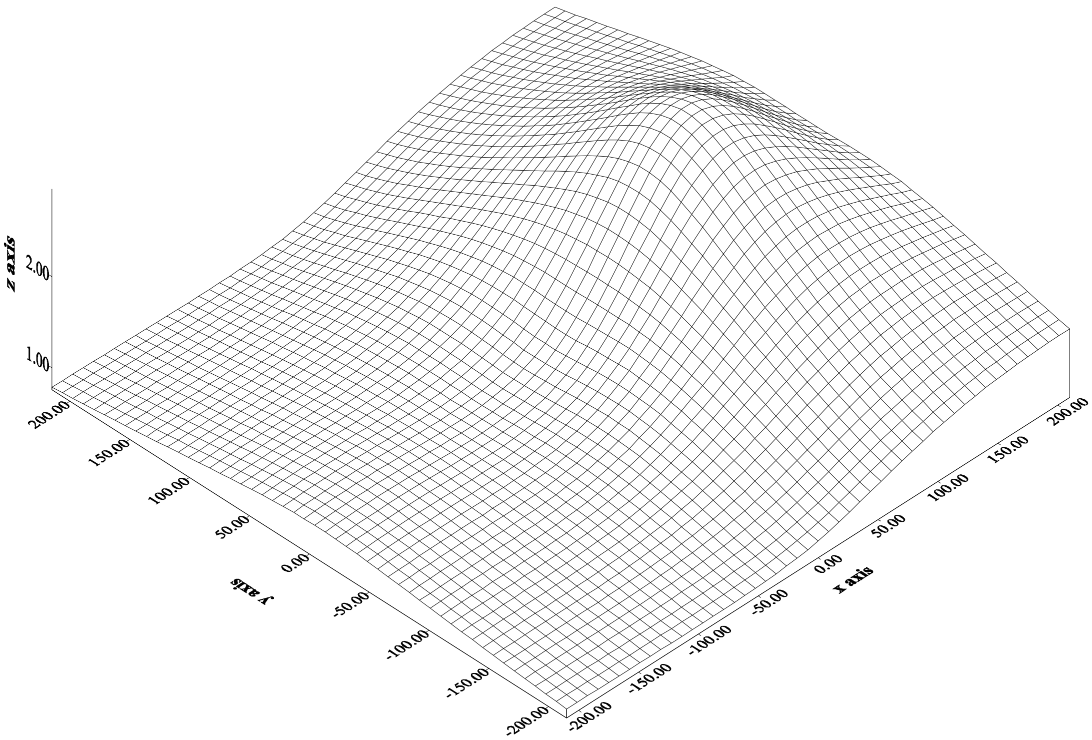

Figure 3: The surface plot of mass transfer coefficients (×10^{-5} m/s) near the cone region of the bath at a gas flow rate of 0.010 m^3/s

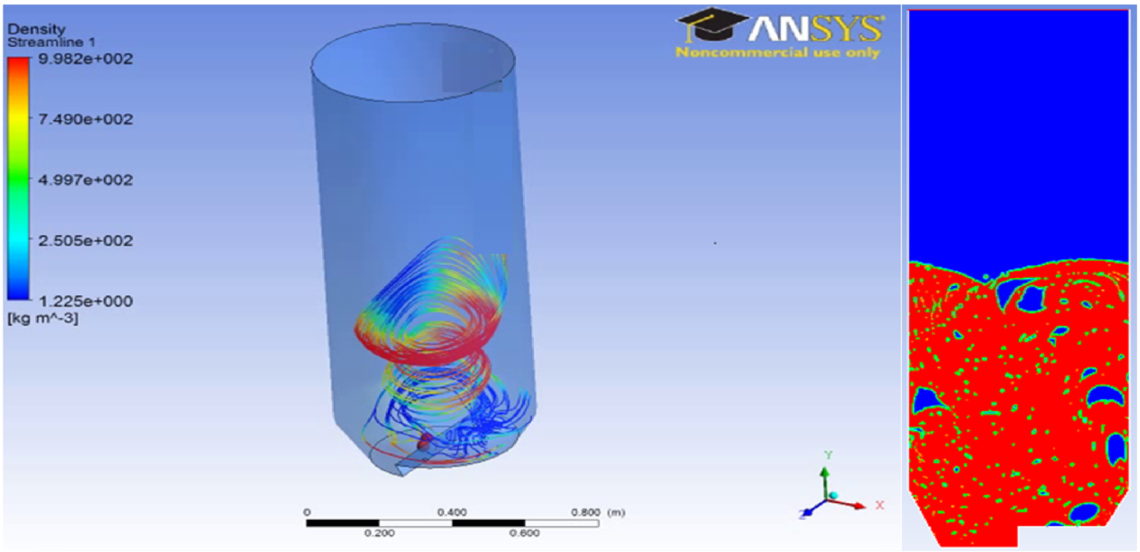

Figure 4: The plume zone and turbulent flow behaviour in the CLU vessel as computed in CFD modelling

Similar and comprehensive experimental and modelling work, which included CFD, was also undertaken for a stainless steel making AOD vessel (Haas *et al*., 2016), the results of which are substantial, but are not presented here in the interests of keeping this paper short.

The fundamental knowledge generated in the examples given can well be used to improve the efficiency of the operation of the specific processes through modelling, simulation, and optimization with a view to developing strategies for better process control. This will lead to satisfying BAT targets and can give clues for conversion to circular economy, all of which will be the first stage in approaching sustainability and industrial ecology on the way to circular economy. Further research and an understanding of the fundamentals in a similar way on other related processes that can potentially be integrated will eventually lead to our achieving circular economy.

Is this enough? In certain cases and processes the answer may be yes. However, whatever we do — *i.e.*, in reaching BAT targets on the way to circular economy – we still may not be able to reduce waste significantly especially in the form of carbon dioxide emissions and to reduce energy intensity beyond certain levels, both of which are governed by the thermodynamics of the existing processes. In such cases, we have to consider designing new and novel alternatives with different and lower thermodynamic limits. The example quoted here for consideration and debate is to use natural gas for reduction of ferro-alloy ores almost completely in the solid state at temperatures even lower than ordinary solid-state carbothermic reductions (Eric, Fabritius and Taskinen, 2014). From a thermodynamic point of view the behaviour of methane shows promise. It can decrease significantly the temperature of the solid-state reduction of oxides, resulting in significantly lower temperatures of operation and hence lower CO_2 emissions and lower consumption of energy. Obviously, this is an opportunity to make a step change, to adopt new and potentially more sustainable technologies that can meet the principles of circular economy with a considerably smaller carbon footprint and lower energy consumption.

Methane tends to crack/decompose into hydrogen gas and solid carbon at about 550°C, especially when there is a solid phase in the system acting as a catalyst:

$$CH_4(g) = C(s) + 2H_2(g) \qquad [3]$$

This seems to be a blessing providing two potential reductants for high-temperature processes. The thermodynamic activity of carbon here is much greater than one (unit activity). Moreover, the reaction is exothermic (Petteri, 2015). The thermodynamic potential of methane is shown in Figure 5. The high activity of carbon will reduce significantly the reduction temperature while hydrogen gas will assist the process by reducing less stable iron oxides. Thus metal processing could involve a relatively low temperature solid-state reduction operation followed by a simple melting (and final reduction if and when necessary) operation.

In ferrochromium manufacture, for example, submerged-arc furnaces may not be required. A rotary kiln or a fluidized-bed reactor combined with an open-arc furnace could do the job, thereby reducing energy and CO_2 emissions significantly.

It is clear that the thermodynamics of reduction of metal oxides by methane looks favourable, and by monitoring the methane/hydrogen ratio in the gas phase the thermodynamic activity of carbon precipitating as micro-sized particles can be controlled/manipulated.

What about transient phenomena? The rate and mechanism of reduction are important fundamentals that should be determined. Thus, there is a need for more fundamental experimental research.

Chromite ore from the Kemi deposit in Finland was reduced in CH_4-H_2 atmosphere (Leikola, 2015). The reduction temperatures were 1100, 1200, 1300 and 1350°C and the reduction times 10, 20, 30, 60, 90 and 120 minutes. Three methane contents were used, 10, 20 and 30 vol% with H_2. At 1350°C, all of the chromium was reduced within 30 minutes, resulting in residual aluminium and magnesium oxides with varying amounts of silica being left of the original Kemi chromite. The mechanism and kinetics of this process were also established. Figure 6 shows a chromite particle almost fully reduced within 20 minutes at 1350ºC in a gas mixture of 30% CH_4-H_2. Ordinary carbothermic reduction of Kemi Chromite to about 95% metallization required 1500°C and approximately 120 minutes as determined by thermogravimetry with 20% excess carbon under a flow of argon gas. It is again clear through laboratory experiments that transient phenomena are also favourable, but a will to change is required to pursue this approach through test work on a larger scale if we are to reach a sustainable process within the concept of a circular economy . This is just an example of a clean start in changing the process paradigm.

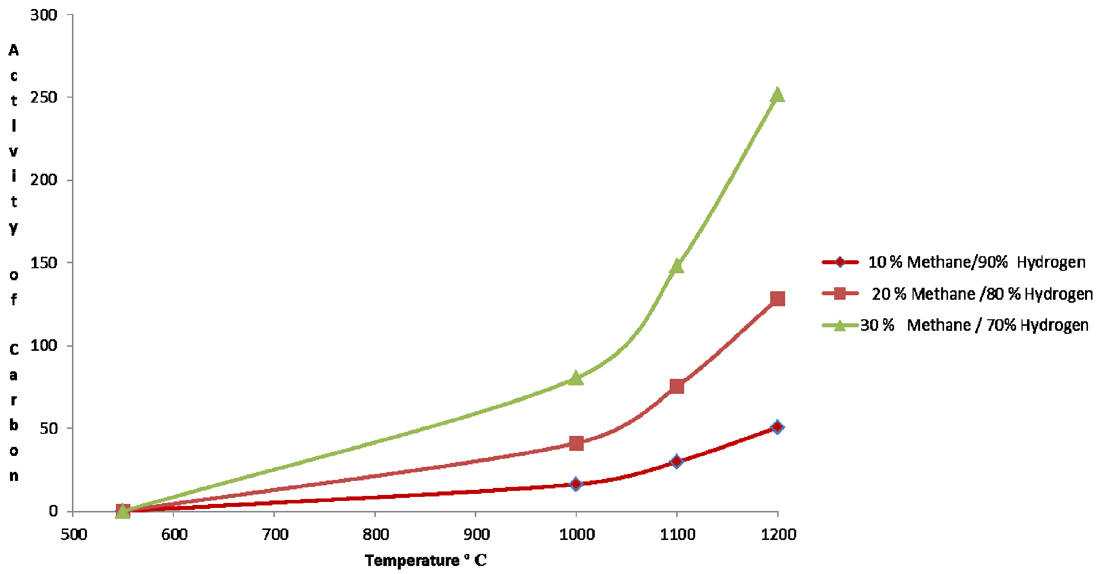

Figure 5: Thermodynamic activity of carbon (graphite as the standard state) as a function of temperature and methane content of the CH_4-H_2 gas mixture

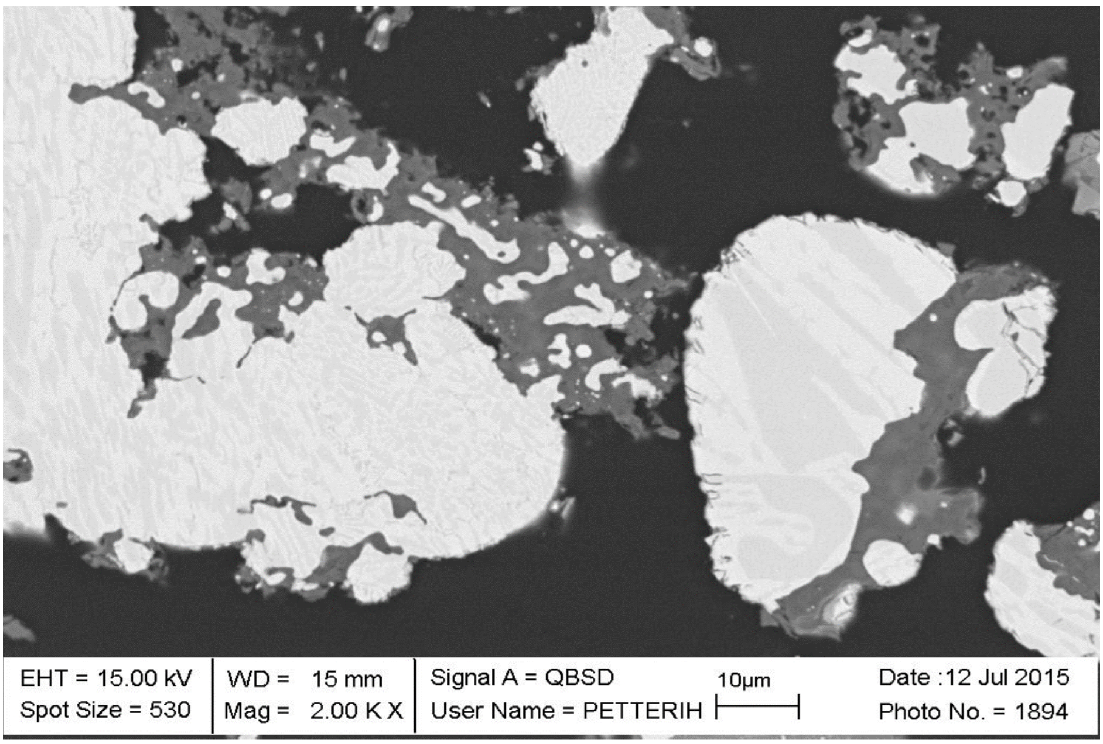

Figure 6: SEM micrograph (backscattered-electron image) of a sample reduced at 1350ºC for 20 minutes in a gas mixture of 30%CH_4-H_2 (Leikola, 2015)

From my experience in reduction reactions with methane I illustrate a conceptual flow sheet, for approaching circular economy, for the integration of ferro-alloy and steelmaking with energy recovery, carbon recovery and usage, CO_2 capture and flux generation, and slag valorization (see Figure 7). It must be emphasized that what is shown is just a mental exercise/idea and by no means complete or comprehensive. It requires a lot more – matching capacities of the processes, a mass balance, and an energy balance are just three. However, it can be considered as a start on a clean slate.

Ferro-alloys are intermediate products that can be considered as feedback streams to mainly steel and stainless steel making processes; hence from a circular economy point of view, just as steels and stainless steels (except certain stainless steel products such as kitchenware), they are not direct products for the final user/consumer. Hence the inner circles of circular economy – maintenance, reuse, re-manufacturing, and even recycling (except in-house plant recycling) – do not apply directly to ferro-alloys, but apply to the final products manufactured from steels and stainless steels containing ferro-alloys. The main target of the ferro-alloy industry, as mentioned, should therefore be an *integration* (along with substantial process improvements and/or process changes) with steel and stainless steel making while achieving absolute waste minimization, lowering energy and CO_2 emissions, recovering and reusing carbon, regenerating flux and valorizing slag. Obviously the final products made from steels and stainless steels containing the ferro-alloys should be designed in such a way that the circles of circular economy are achieved along with integration.

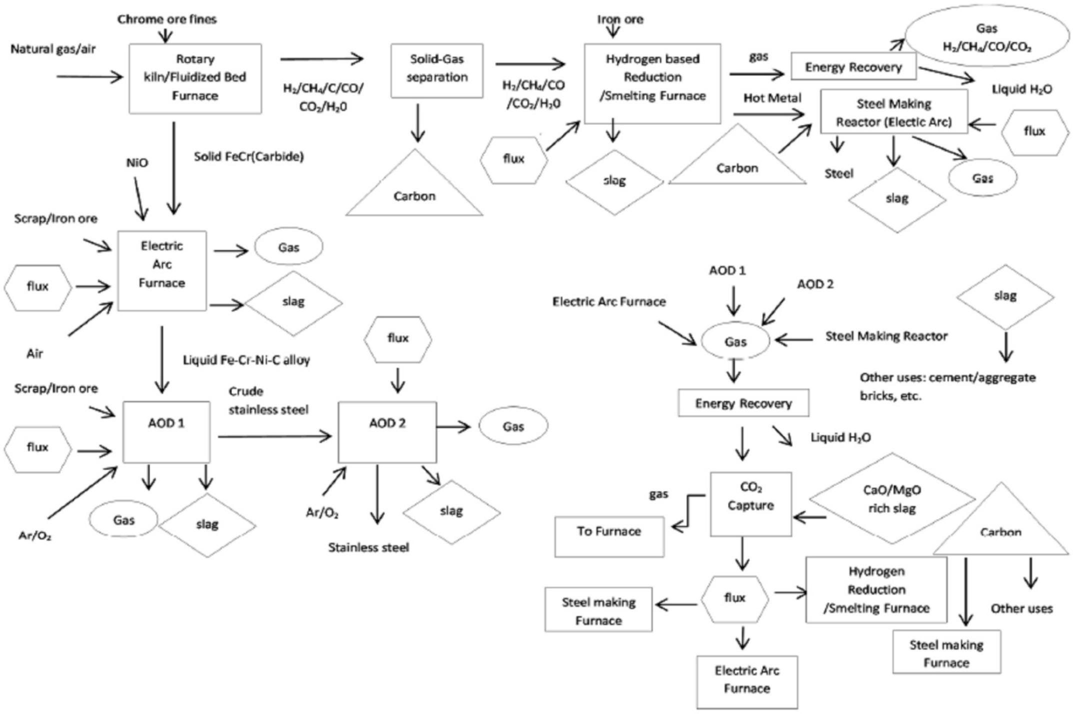

Figure 7: Flow sheet for the conceptual integration of ferro-alloy and steelmaking with energy recovery, carbon recovery and usage, CO_2 capture and flux generation, and slag valorization

Other related and important issues

By 2050 world steel production, as mentioned, is expected to reach 3 230 Mt. Even with BAT practice achieving about 30% reduction in emissions this will mean 4 552 Mt of CO_2 added to the atmosphere just in the year 2050, which is absolutely unacceptable and intolerable. The terrible, adverse changes to climate already happening is a clear sign of what can happen. Currently the world output of steel is about 1 500 Mt/y emitting around 1.8 to 2.0 tons of CO_2/ton of hot metal during the process (World Steel

Association, 2014). This is almost 3 000 Mt of CO_2 added to the atmosphere each year. It is claimed that this accounts for up to 10% (probably a pessimistic value) of total CO_2 emissions excluding the amount emitted during energy generation consumed by this industry (Eric, Fabritius and Taskinen, 2014).

When the thermodynamics of the reduction of oxides is examined carefully, one can easily conclude that the oxides of Ni, Pb, Cu, Co, Sn, W and most importantly Fe can be reduced to metallic form by hydrogen gas. ZnO is questionable**.** Oxides of Mg, Al, Ti, Si, V, Mn and Cr cannot be reduced by hydrogen and thus require carbon as the reductant. Te reduction of the first group of oxides, therefore, especially the most important one, Fe oxide, should switch to hydrogen for iron and steelmaking while pursuing sustainability and the principles of circular economy if we are serious about continuing to live on this planet. A source of hydrogen, at least initially, is natural gas, which is currently abundant.

These issues in reduction are nothing other than the need for a change in process paradigm; and it requires not only a will to change, but also a will to invest in research, in particular fundamental research – to be able to design new technologies without repeating the mistakes of the past. Luckily, this seems to have started. When iron and steelmaking is hopefully out of the picture from a carbothermic-reduction point of view, metal process engineering will be in a better position to use carbothermic reduction for other important oxides, especially those in ferrochromium and other ferro-alloy processes, reduction potentially based on methane – *i.e.*, natural gas and biomass carbon. The CO_2 released from these methane- and/or bio-carbon-based operations will be lower than 200 Mt (less than 4.5% of the emissions from carbon-based iron and steel making, if it were to remain) in the year 2050.

Over and above the discussions and research needs outlined, to be able to reach circular economy with absolutely minimum or no waste generation through integration, product design, re-manufacturing and minimized recycling, other things have to change as well. The pathway has to involve fundamental changes in governance structures, economic frameworks, and business and human behaviour. These are considered necessary to achieving the transition, to be feasible, and to provide business opportunities for companies that put sustainability principles into practice.

Here are a few examples. In 2016, 77.7 million passenger cars and 18.4 million light commercial vehicles were manufactured, which required approximately +100 million tons of steel-based products (Passenger Car World, 2016). It is estimated that in 2017 the vehicle population in use in the world had already reached 1 335 670 000 – 1 vehicle per 5.2 people. These numbers exclude heavy commercial, passenger vehicles, and obviously trains, planes, ships, *etc*. How many patients per doctors exist in the world? Conservatively, the average CO_2 emission is 250g/km-vehicle **(**neglecting NO_xs and particulates) and the average distance travelled is 20000 km/year**.** This results in 6.68 billion tons of CO_2 emitted to the atmosphere just from light vehicles in only 2017, more than double the amount emitted from iron and steel-making (approximately 3 billion tons)**.** *One vehicle per 5.2 people in the world* – is this right and acceptable?

Most of the chromite mined is converted to ferrochromium, 80% of which is used to make stainless steel and the rest to make low-alloy steels such as tool steels. Some of the chromite is used to make Cr-Mag or Mag-Cr refractories and a much smaller portion is converted to sodium chromate, mainly for the tanning industry (Cr^{6+}?). Uses of stainless steel are mostly domestic: *67% kitchenware (?)*, 7% process industries, *8% architecture/construction (?), 5% transportation(?),* 6% engineering/electro-mechanical, and 7% other (Gopal, 2008). Do we really need that much stainless steel (~30 million tons produced in 2016) and hence that much chromium based on the above?

CONCLUSION

"A planet of around nine billion people, all living well with enough food, clean water, sanitation, shelter, mobility, education and health to make for wellness within the limits of what this small, fragile planet can supply and renew, every day." The Target Year 2050. Will it then be possible to reach the vision?

This is only possible if human endeavour – in contrast to what it has done up to now – starts to show respect to this planet, to its environment and resources, to itself and to all the other living creatures and organisms (obviously including plants), all of which have the same, an equal right to live. Circular economy is just the tool to an end. As a final conclusion and for the way forward I should like to quote the great humanist and leader Nelson Mandela: *It is always impossible until it is done***.**

ACKNOWLEDGEMENTS

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