REDUCTION OF CO_2 EMISSIONS IN THE STEEL INDUSTRY BASED ON LCA METHODOLOGY

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Abstract

Integrating environmental considerations into the product traditional process design is now the major challenge for steel industry. Life Cycle Assessment (LCA) is nowadays considered as an appropriate method for assessing environmental impact and selecting new technologies to reduce CO_2 emissions for steel industry.

In this paper we propose a new methodological concept which combines LCA thinking with process simulation software in order to carry out the life cycle inventory of classical steelmaking process.
Using Aspen Plus™ software, a physicochemical model has been developed for the integrated steelmaking route. This model gives the possibility to carry out life cycle inventories for different operational practices in order to optimise the use of energy, to calculate CO_2 and other emissions and to control the mass and the heat balances of processes.

It is also shown that such approach can be used to design and assess new technologies for steelmaking without large industrial application.

Introduction

During recent years, it was recognised that CO_2 emissions are the major factor of the global warming effect. In order to meet Kyoto requirements, the steel industry is embracing the challenge of sustainable development by improving its competitiveness and economic success while reducing its environmental impacts. Integrating environmental considerations into the traditional product design process, for powerful eco-efficiency, is now one of the major priorities for steelmakers.
The European Steel Industry has measured up to this challenge by creating ULCOS (Ultra Low CO_2 Steelmaking) consortium that has taken up the mission to develop breakthrough steelmaking process with the potential to reduce CO_2 emissions (Eurofer, 2005).
In order to develop technologies to reduce emissions, it is necessary to assess the environmental impact of the classical steelmaking route (coke plant, sinter plant, blast furnace, basic oxygen furnace, continuous casting and hot rolling).
Life Cycle Assessment (LCA) method has been undertaken in ULCOS as the most holistic approach of assessing environmental impact and selecting new technologies. Previous to the impact assessment, it is essential to carry out the Life Cycle Inventory (LCI) of the process which is the core part of LCA methodology. According to the current LCA standards (ISO 14040, 1997), the quality of the data used for carrying out this inventory is one of the most important limiting factors. The LCI analysis involves data collection, calculation and procedures

to quantify the relevant inputs and outputs of the product system. The data collection should correspond to some conditions: precision, completeness, representativeness, consistency and reproducibility (ISO 14040, 1997). It is obvious that such conditions are not easy to respect. The environmental performance of complex steelmaking processes such as iron ore sintering are strongly dependent on operational conditions and can change significantly when different types of fuels and recycled wastes are used in the process.

Moreover, data used for inventory calculation should respect also exigencies such are the age, the geographical and technological coverage. In many cases, the environmental data related to the steelmaking industry cannot be used due to the lack of measurement of certain pollutants or because the information is much too summarized. It is clear that LCA practitioners are confronted with serious difficulties in respecting these conditions when the LCI is based only on data coming from literature and/or industrial practice. Also, it is generally recognized that the classical approach of assessing LCI takes time, and usually it cannot guarantee the mass and energy balances of flow rates which are considered in the system boundaries.

That's why it is important to improve the way of assessing the LCI of the steelmaking industry in order to guarantee the quality of the data and to predict the change of the environmental performances with respect to the operational conditions.

New methodological framework proposal

The objective of the current study was to develop a new way of carrying out the LCI of the classical steelmaking route so that the quality of data and the mass and energy balances are guaranteed. The classical route of steel production is based on the production of hot metal from iron ore, and its conversion to steel in a converter.
The proposed methodological framework is based on the interconnection between the environmental tool (LCA) and the process simulation software Aspen Plus™ (Advanced System for Process Engineering) as shown in figure 1.

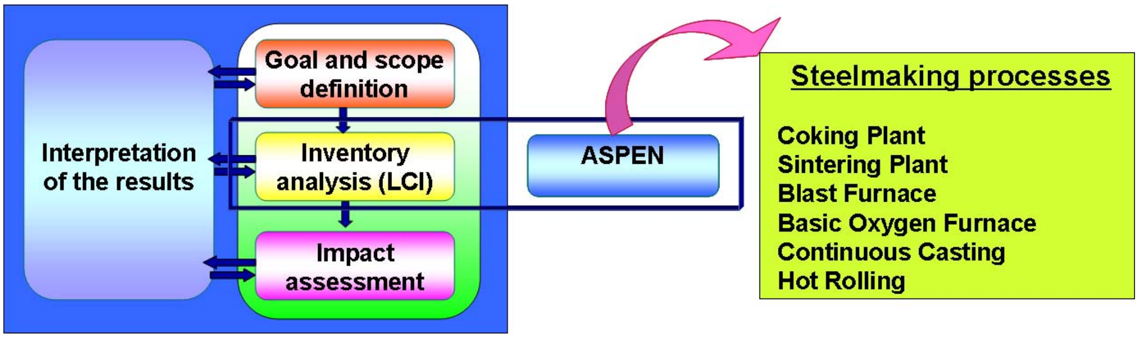

Figure 1. New methodological framework for LCI analysis.

The concept of life cycle assessment originated in the late 1960's when it became clear that the only sensible way to examine industrial systems was to examine their performance, starting with the extraction of raw materials from the earth and tracing all operations until the final disposal of these materials as wastes back into the earth (cradle to grave). The LCA concentrated on energy, raw materials, air emissions, water emissions and solid waste calculations has four main stages as shown in figure 1.
Aspen Plus™ is a process engineering software package that is used to simulate processes based on the thermodynamic models, properties of materials and several ready-made unit operation models.

Based on the proposed approach, the LCI has been carried out for the classical route of steel production. Hence, simplified physicochemical model has been developed for each process of the integrated steelmaking plant as defined by the system boundaries.
In terms of system boundaries, the study covers the foreground processes: coking plant, sintering plant, blast furnace, converter (or basic oxygen furnace) and hot rolling plant. The interconnections of these processes is given in figure 2.

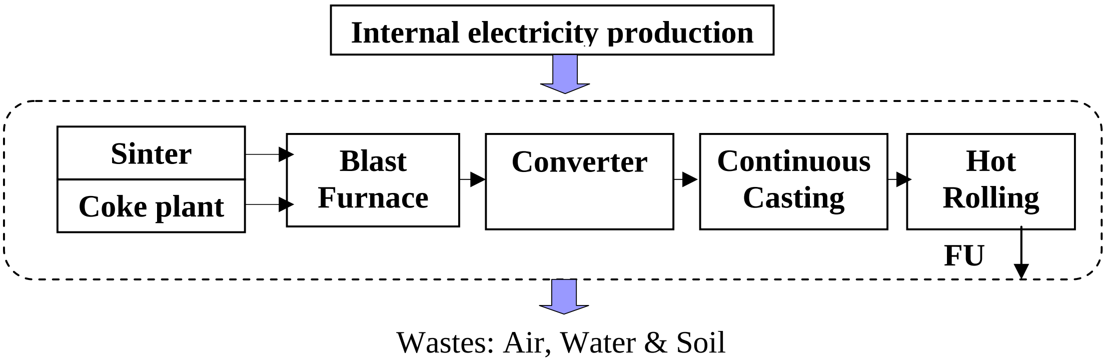

Figure 2: Steelmaking system boundaries.

The continuous casting was excluded from our study because this system is not adapted to Aspen simulation. Actually, the continuous casting process is more characterized by thermal phenomena than by physicochemical mechanisms.
The electricity required to operate the process was also considered in the system boundaries. It was assumed that the electricity requested by the integrated process is supplied by an internal power generation plant which uses steelworks gases (namely blast furnace gas, coke oven gas and converter gas). For the first stage of our study, the system considered does not include the extraction of raw materials, their transportation to the plant and the waste storage.
In order to ensure the comparability of LCA results, the selected functional unit (FU) for the current study is one ton of hot rolled coil produced in a classical integrated steelmaking plant.

Modelling of integrated steelmaking plant

The five main processes characterizing the production of steel have been modeled using Aspen Plus™ commercial simulation software equipped with a thermodynamic database, which is used to design process flow sheets and to calculate mass and energy balances, emissions, and the chemical compositions of products and by-products simultaneously. Finally, the association of the five separately developed modules builds the complete flow sheet of the integrated steelmaking plant. For clarity reasons, the steelmaking process modelling is briefly described in this paper.

Modelling of cokemaking plant

Metallurgical coke is one of the raw materials used in blast furnaces for pig iron production. The main process which characterises coke production is the thermal decomposition of coal in a closed reactor (heating in the absence of air). Coke manufacturing includes the following stages: coal grinding and blending; heating of the coke oven; carbonisation of coal; coke quenching; cleaning the coke oven gas and finally wastewater treatment. During the pyrolysis process, the primary gas leaving the coke oven contains a great amount of tarry matter, considerable moisture and various hydrocarbons compounds.

In the case of cokemaking plant, the facilities considered in the model are: coke oven heating facility, coke oven batteries, coke quenching and coke gas cleaning units.
For simplicity sake and because of their low environmental burden, some facilities were not considered in the frame of the model.

Full presentation of cokemaking model is available in (Iosif et al., 2008[a]). The main physicochemical phenomena involved in the process have been modelled as shown in figure 4.

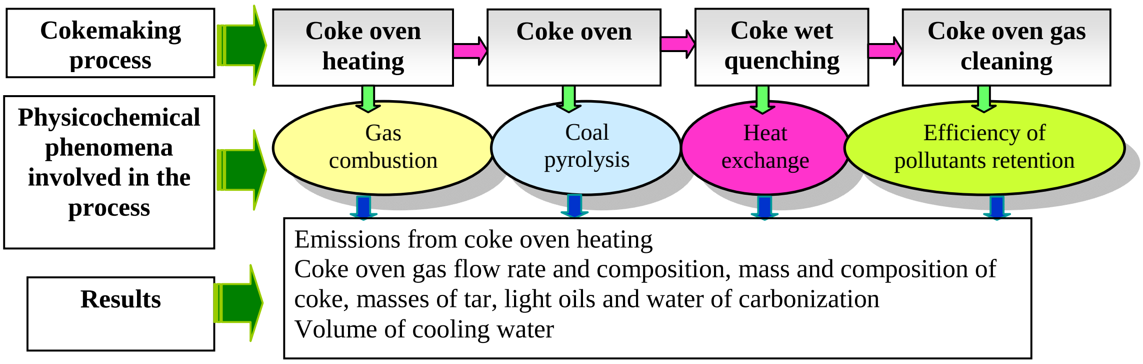

Figure 4. Schematic representation of coke plant modelling.

The input data requested are: the energy supplied for the coke oven heating, the coal mass flow and its elementary composition. Some other parameters are imposed such are the tar average composition, the partition of input of sulfur between the gas phase and solid phase the final temperature of products, etc.
The model provides with good precision the volume and the final composition of the coke oven gas (CO, CO_2, CH_4, C_2H_4, C_2H_6, H_2, N_2, NH_3, H_2S), the mass and the elementary composition of coke (C, H, S, N) and the mass of by-products (tar, light oils and ammonium sulphate). Also the model allows the calculation of CO_2, CO and SO_2 emissions realised during the operation of coke oven heating by the combustion of steelmaking gases (coke oven and blast furnace gases).
Thanks to available industrial data, the model was validated through simulations carried out for various mixtures of coals with different characteristics in terms of chemical composition. Comparison of some results with industrial data are given in figure 5.
Good results have been also obtained concerning the coke oven gas composition. Finally, it was proved that the model is mature enough to be undertaken in a complete Aspen flowsheet developed for the integrated steelmaking plant.

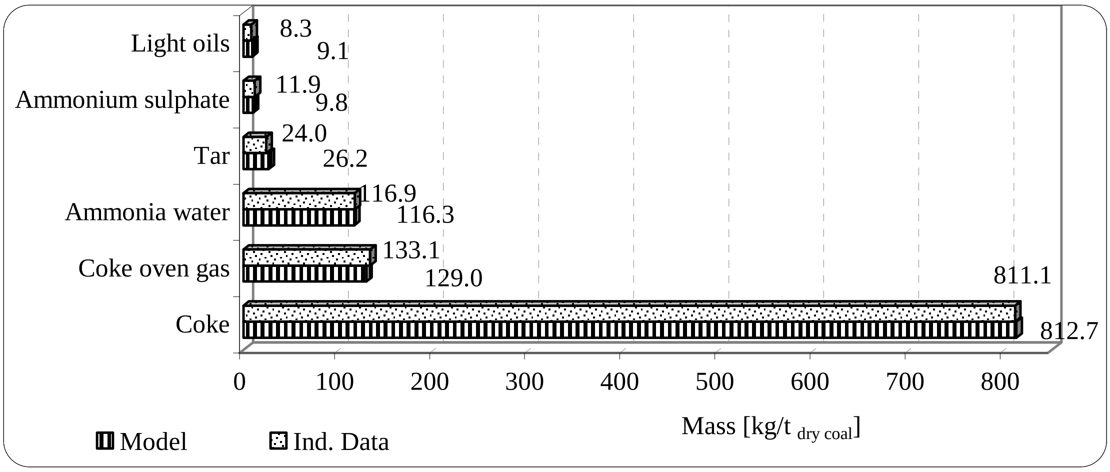

Figure 5. Comparison between coking products calculated by the model and industrial data.

<u>Modelling of sinter plant</u>

The iron ore sintering is the process which allows the preparation of iron ores into the sinter before charging into the blast furnace. Before the agglomeration, the iron ores are first mixed with various substances such as solid fuels, dolomite and lime. The iron ores are agglomerated on conveyor sinter installations thanks to the combustion of a solid fuel.

The sinter plant is considered the most polluting unit among all the steel works and the modelling of this facility is the most complex in comparison to the others. Details about the modelling of this process are available in (Iosif et al., 2008[b]). The processes considered into the module boundary are: the ignition process, the agglomeration of iron ores on the sinter strand, the exhaust gas cleaning and the sinter cooling.

The model has been built as a mathematical matrix, based on chemical reactions and correlations between emissions and different parameters of the process in order to allow an accurate simulation of various mechanisms.

The main pollutants evolved by the system, namely CO, CO_2, NOx, SOx, VOC ($CH_{4\ equ.}$), HCl, heavy metals and dust are the most important outcomes of the model. Also, the mass and the chemical composition of the sinter have been calculated and the energy balance has been attentively checked.

After the model building, simulations of different European industrial configurations have been carried out and the results were successfully compared with industrial data. Some of emissions calculated by the mode are plotted out in figure 6. The other constituents of sintering fumes calculated by the model are: 7.1% CO_2, 1.3% CO, 10.8% H_2O, 77% N_2 and 14.6% O_2.

Using a similar approach, the other processes defined for the integrated steelmaking plant: the blast furnace, the basic oxygen furnace and hot rolling have been modelled with Aspen software. Each module has been validated with industrial data and finally connected together in order to build the integrated steelmaking model. Full details on modelling these processes are given elsewhere (Iosif, 2006).

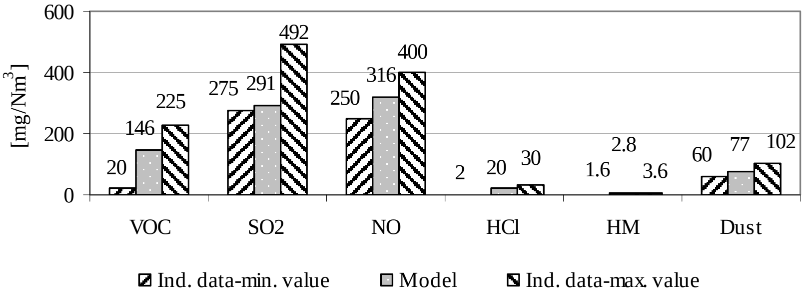

Figure 6: Emissions within the sinter waste gas downstream from electrostatic precipitator.

Life Cycle Inventory assessment using Aspen model

Using the global model and industrial data, the LCI of an existing European integrated steelmaking plant has been successfully calculated. The inventory calculated by the model has been inserted into GaBi software in order to assess the environmental impacts for the analysed case. GaBi allows us to quantify emissions which are not calculated by the model (i.e. uncontrolled emissions). As illustration, a part of the LCI calculated with the model for the given European integrated plant is summarized in table 1.

Table 1. Summary of the integrated steelmaking plant inventory calculated by the model.

Flux	**Identification**	**Unit [a]**	**Quantity**
Materials inputs	Iron ore	kg/FU	1321
	Coal for cokemaking	kg/FU	430
	BF injection coal	kg/FU	154
	Scraps	kg/FU	127
	Pellets	kg/FU	139
	Lime	kg/FU	40
Energy inputs	Internal electricity	MJe/FU	884
Intermediates products	Sinter	kg/FU	1403
	Coke	kg/FU	336
	Hot metal	kg/FU	1020
	Liquid steel	kg/FU	1077
	Slabs/ Blooms	kg/FU	1027
	Coke oven gas	Nm^3/FU	132
	Blast furnace gas	Nm^3/FU	1478
	Converter gas	Nm^3/FU	82
Material outputs (by-products)	Slag	kg/FU	423
	Tar	kg/FU	10
	Ammonium sulphate	kg/FU	4
Product	Hot rolled coil	kg/FU	1000
Emissions to air	CO_2 [b]	kg/FU	1587
Emissions to land	Sintering dust	kg/FU	1

[a] FU: one ton of hot rolled coil ; [b] "gate to gate" system boundaries according to figure 2.

Validation of the new approach for LCI assessment

In order to check the maturity of the developed approach, two Aspen simulations have been carried out using:

a) industrial data supplied by a European integrated steelmaking plant,
b) "benchmark" data supplied by the ULCOS project.

In the frame of the ULCOS project, the "benchmark" data defined an integrated steelmaking plant characterised by the best available technologies.
The inventories calculated by the model for both cases have been compared between them and to one another, considered as a "reference LCI". This reference LCI has been developed by the International Iron and Steel Institute (IISI) to quantify the use of resources, energy and environmental emissions associated with the processing of fourteen worldwide steel plants (IISI, 1998). For all three cases, LCI are reported at the same functional unit derived via the blast furnace/basic oxygen furnace route. The comparison between these three "gate to gate" LCI has been possible thanks to GaBi software. The objective of this comparison was to demonstrate the maturity of the model for given reliable inventories of real cases such as the integrated European plant but also of "virtual" cases such as the ULCOS benchmark. As illustration, in the current paper is showing only the comparison of CO_2 emissions between the three scenarios. This comparison is outlined in figure 7.

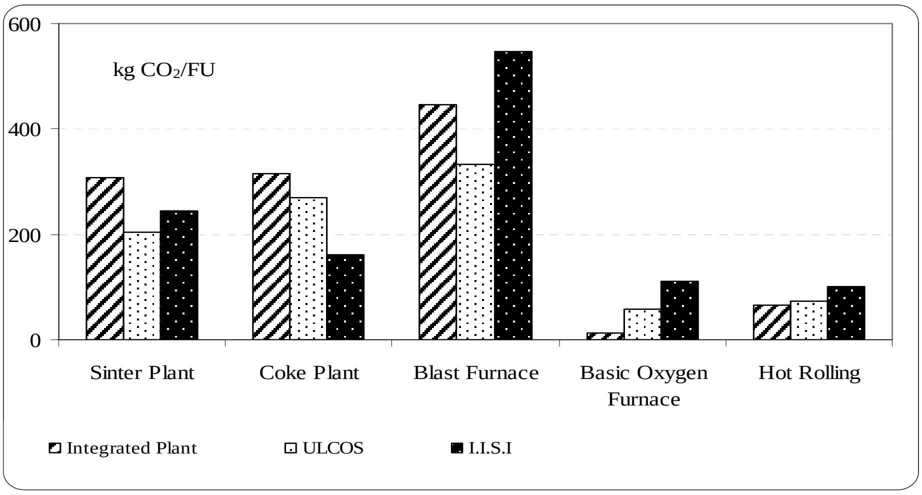

Figure 7. Inventory of CO_2 emissions for each process included in the analysed system.

According to this figure, the total CO_2 emission released by the defined processes is: 1147 kg/FU (European integrated plant); 937 kg/FU (ULCOS benchmark) and 1165 kg/FU (IISI reference case). The CO_2 emissions are calculated for each process without taking into consideration the consumption of electricity. CO_2 variance between the analysed cases is basically linked to the difference masses of raw and intermediate materials (coke, sinter, hot metal…) used in the process. Moreover, the use of various types of fuels for heat supply: blast furnace, coke oven, converter and natural gases, can also contribute to the variation of emission due to the chemical composition and the heat capacity of these gases. As mentioned, the system electricity is supplied by internal production using steelworks gases, namely blast furnace gas, coke oven gas and converter gas, which are considered as by-products of coke, hot metal and steel plants. It is important to stress that the entire amount of steelworks gases produced in the system is not consumed only for electricity generation. In reality, prior to electricity production, some of the gases are used in the system as heat supply for coke oven heating, hot rolling stoves, and blast stoves as indicated in figure 8.

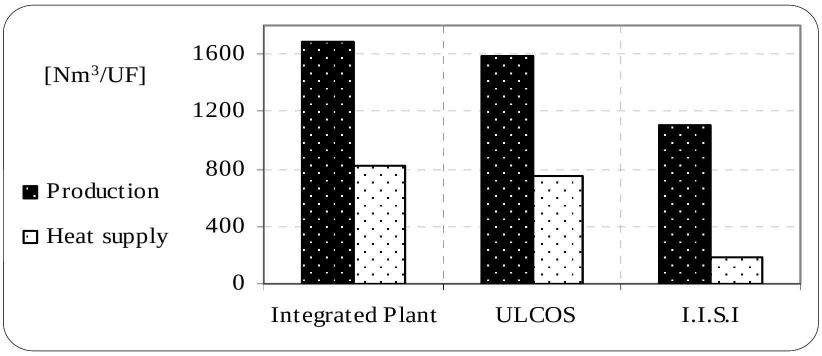

Figure 8. Steelworks gases production and internal consumption as heat supply.

A schematic representation of the steelworks gases used in an integrated plant is given in figure 9.

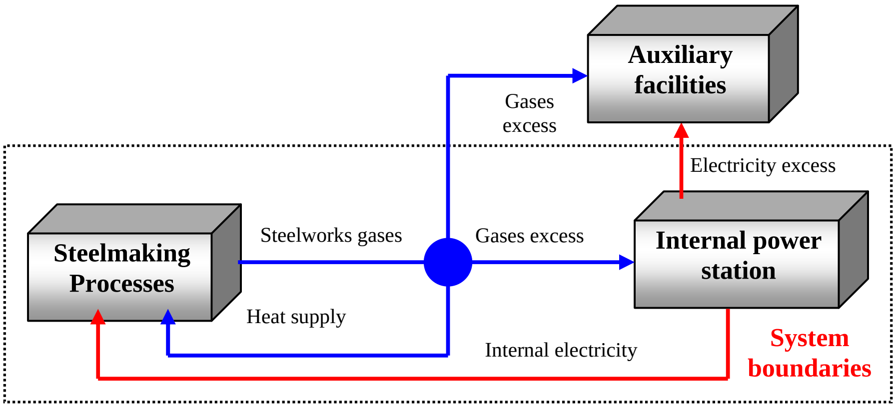

Figure 9. Internal electricity production.

The difference between the production of these gases and their consumption as heat supply was called "excess of steelworks gases". This excess is used mainly for internal electricity production but also as an energy supply for auxiliary facilities such as raw materials preparation, lime production and steam production. For the current LCA study these facilities are not considered in the system boundaries. The production of electricity using steelworks gases was also simulated with a simplified Aspen module developed for an internal power station. The CO_2 emissions calculated with this module for the production of electricity required by the system are given in table 2.

Table 2. CO_2 emissions involved in the integrated steelmaking plant.

CO_2 emission [kg/FU]	**Integrated Plant**	**ULCOS**	**IISI**
Steelmaking Processes	1147	937	1165
Electricity production	440	510	499
System total emissions	**1587**	**1447**	**1664**
Auxiliary facilities	362	293	344
Total	**1949**	**1740**	**2007**

Table 2 also sums the amount of CO_2 released by the production of one ton of hot rolled coil as defined by the system boundaries and all the CO_2 emissions are summarized in figure 10. CO_2 emissions for the ULCOS benchmark are significantly lower than the other scenarios. This can be explained by the fact that ULCOS scenario is based on the consumption of a large amount of pellets in the blast furnace. The environmental burden of pellet production is lower than the burden of sinter production. In addition, in the ULCOS scenario, the coal injection in the blast furnace reaches the maximum rate and consequently the consumption of coke is reduced. Indeed, the decrease of coke demand leads to lower environmental burden for the system. The CO_2 emissions calculated by the model for the European steelmaking plant were successfully compared to the average value of fourteen plants derived from the IISI inventory. This result emphasizes the maturity of the model and fortifies the reliability of the proposed approach.

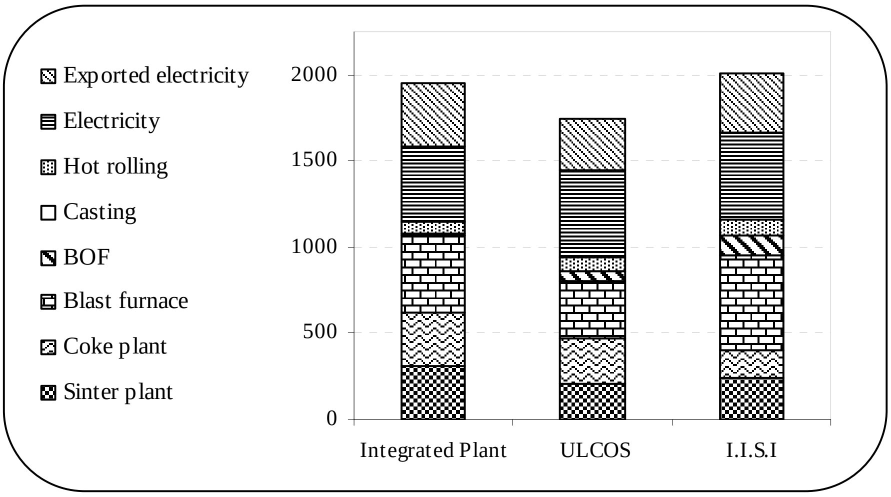

Figure 10. Summary of all the CO_2 emissions.

According to the steel people (Iosif, 2006), the industrial experience shows that there is no excess of energy when all the auxiliary facilities (raw materials preparation, lime production, steam production) are part of integrated plant. If the system boundaries are extended towards auxiliary facilities, the environmental burden involved in the total consumption of steelworks gases in the frame of the system should be integrated into the LCA study (see table 2 for CO_2 emissions). Thanks to the current approach, it has been shown that by using the best available techniques and optimizing the use of resources, the environmental burden can be notably reduced. To exemplify, the CO_2 emissions can be reduced by 200 kg of CO_2/FU for the ULCOS benchmark case. Finally, it is important to stress that the agreement between results obtained for the ULCOS benchmark and the European plant cases validates the current approach.

Modelling of new steelmaking processes

The integrated steelmaking plant constitutes the actual reference for the classic steelmaking route. The modules developed to simulate the different processes of this integrated steelmaking plant were all validated on the basis of industrial data and proved their ability to generate accurate life cycle inventories. Once this method has proved its maturity it can be extended to other systems, which have the ability to be modelled with Aspen Plus^{TM}. In this framework, models for the Direct Reduction route are currently elaborated, on the basis of MIDREX^{TM} process, in order to draw a comparison with the blast furnace route, in terms of CO_2 emissions.

But the main feature of this methodological coupling between flowsheeting and Life Cycle Analysis, lays in the ability to study processes that do not exist yet.
Indeed for processes that do not exist yet, the establishment of the life cycle inventory with the classical data collection is not possible. The most relevant way to produce an accurate life cycle inventory with such processes is to go through a physicochemical modelling step that ensure mass and energy balance, and verify fundamentals laws of physics and chemistry.
In this way, flowsheeting has to be considered as a powerful way to generate LCI and thus allows relevant prospective LCA.
In the framework of ULCOS, several breakthrough processes were imagined and designed to produce iron with limited CO_2 emissions. Those processes are currently being modelled via simplified physicochemical models and integrated into complete ASPEN flowsheets to generate LCI of those new routes.
Once done, a relevant comparison between the classical reference route and the breakthrough routes proposed in the framework of ULCOS will be possible. Such a comparison may help to assess the different possibilities that are offered and to choose the less burdensome for the environment.
In addition the flowsheeting models developed in this framework allows to test easily different configurations of the flowsheet (repartition of gases, production of steam, electricity, …) and in this way, they can be considered as helpful tools to establish an optimal design of the process flowsheet.
Study of the different ULCOS processes will be published later, in dedicated papers.

Conclusions

In the present paper we have proposed and developed a new methodological framework which combines a physicochemical modelling approach with LCA thinking, in order to carry out the LCI of steelmaking processes.
The integrated classical steelmaking route (via blast furnace/converter) has been modelled with Aspen software and the results were successfully compared with industrial data. It was shown that the validated model is a powerful tool in order to provide a rigorous “gate to gate” inventory. Moreover, the model allows the calculation of the chemical compositions of products and by-products such as the steelworks gases. This information is very important because the steelworks gases are used as fuels by all of the steelmaking processes. Hence, the contribution of these gases to the total environmental burden of the system can be easily estimated. Also, the developed model helps different companies rapidly assess their environmental impacts with respect to their own industrial configuration.
The main advantages offered by this new methodology framework for LCI assessment are the ability to predict emissions for different flowsheets, and to control the mass and the heat balances of the analysed process. Consequently, the quality of data used in LCI is improved remarkably. Moreover, the environmental burden for special conditions such as gas and waste recycling can be rapidly calculated, and the best scenario for each processing route can be easily selected. These attributes give a strong credibility to the calculated inventory and allow LCI analysis to proceed more quickly.
In addition this methodology can be extended to processes that do not exist yet. This allows to carry out the prospective LCA of those processes, in order to be able to chose the less burdensome for the environment. Such a methodology is currently applied for the breakthrough processes which are investigated under the ULCOS umbrella.

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