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Life Cycle Assessment of Steel Produced in an Italian Integrated Steel Mill

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Abstract: The purpose of this work is to carry out an accurate and extensive environmental analysis of the steel production occurring in in the largest integrated EU steel mill, located in the city of Taranto in southern Italy. The end goal is that of highlighting the steelworks' main hot spots and identifying potential options for environmental improvement. The development for such an analysis is based on a Life Cycle Assessment (LCA) of steel production with a cradle to casting plant gate approach that covers the stages from raw material extraction to solid steel slab production. The inventory results have highlighted the large solid waste production, especially in terms of slag, which could be reused in other industries as secondary raw materials. Other reuses, in accordance with the circular economy paradigm, could encompass the energy waste involved in the steelmaking process. The most burdening lifecycle phases are the ones linked to blast furnace and coke oven operations. Specifically, the impact categories are influenced by the energy consumption and also by the toxicity of the emissions associated with the lifecycle of steel production. A detailed analysis of the toxicity impacts indicates that LCA is still not perfectly suitable for toxicity assessments and should be coupled with other more site specific studies in order to understand such aspects fully. Overall, the results represent a first step to understanding the current levels of sustainability of the steelworks, which should be used as a starting point for the development both of pollution control measures and of symbiotic waste reutilization scenarios needed to maintain the competitiveness of the industrial plant.

Keywords: steel production; integrated steel mill; Life Cycle Thinking; LCA; LCI; industrial symbiosis; waste reuse

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1. Introduction

The steel industry is the second biggest in the world after oil and gas with an estimated global turnover of 900 billion USD [1]. Steel is used in many sectors ranging from building and construction, to packaging, to the transportation industry, to the renewable energy sector. Crude Steel production has more than doubled, over the last three decades, with the 2014 production amounting to 1665 Mtons. This productivity inevitably makes the steel making sector responsible for environmental burdens. For example, in countries like China, this industry responsible for 12% of the national CO_2 emissions [2]. Thus, it is imperative to analyse the steelmaking processes in order to give a clear picture of the main environmental impacts together with possible solutions involving the implementation of a circular economy paradigm.

The Italian crude steel production in 2014 totalled 23.7 Mtons [3]. Over 27% of this quantity is produced in the integrated steel mill in Taranto [4], of the Ilva industrial group, which is the largest steelworks of its kind in the EU. At present, the mill is suffering from the economic crisis and also from several environmental issues that have forced the steelwork's managers to reduce its productive capacity by nearly 50% over the last four years. As a consequence, the industrial complex is currently striving for innovation, both at technical and managerial levels, in order to reduce the environmental impacts to acceptable levels.

The first step in trying to “close the loop” of product life cycles (including that of steel) through greater recycling and re-use [5] is that of effectively and systematically analysing, in environmental terms, such product systems via methods such as Life Cycle Assessment (LCA) [6]. Such an approach has been developed and in some cases adopted as a fundamental tool for specific policies such as the case of the Integrated Product Policy of the EU [7]. Specifically, LCA allows a product system to be assessed from an environmental point of view by holistically considering all life cycle stages of the product, ranging from raw material extraction to the final disposal of the product. Such a tool has been used in the past to evaluate the environmental performance of steel product systems. The World Steel Association [8] has, over the last decades, commissioned three Life Cycle Inventory (LCI) studies concerning the production of 15 steel products such as plates, coils, rods and pipes. The most recent study dates back to 2010 and the data are typically cradle-to-gate including end-of-life recycling. The production process considered are those of the classic integrated steel mill, the more modern ones using direct reduction and electric arc furnaces implemented in 16 steelmaking facilities around the world. The results also include some partial impact assessment data provided for illustrative purposes concerning the lifecycle of sections, hot-rolled coil and hot-dip galvanized steel. The above-mentioned Ilva facility is not among the ones participating in this project. The Eurofer [9] association has carried out an LCI study concerning 18 sheet products, manufactured in seven European countries (including Italy, but not the Ilva plant which only produces carbon steel and low alloy non stainless steel), made with different types of stainless steel with different surface finishes. The study considers all the lifecycle phases from raw material extraction to the gate of the mill but it excludes the waste sent to landfill. The purpose of the study is that of allowing stainless steel producers to perform an environmental benchmarking of their process stages as well as their products. The International Stainless Steel Forum [10] has also carried out a cradle-to-gate LCI study, concerning stainless steel products, which stems from the above-mentioned European study, as a means of providing global data for further case studies. The collected data, from European, North America, Korean and Japanese producers, concern long and flat products (austenitic and ferritic grades) produced from ore and scrap steel. Prior to the above-mentioned international LCI initiatives, at the beginning of the 1990s, a cradle-to-gate LCI study was carried out concerning Canadian integrated and scrap based steel mills [11]. In the following decade, the study was updated and combined with data from US steel plants. In order to represent an average condition of the characteristics of the electric arc furnaces and integrated mills in the US and Canada, reference plant inventories were simulated by using the specific plant data. Whenever data was not directly retrievable from the plants considered for this study, statistical data was used to model the processes and estimate the inventory inputs and outputs such as the one concerning the emissions to air.

LCA has also been used to obtain several Environmental Product Declarations for steel products [12] produced in steelworks around the world, but none specifically concern the Ilva steelworks products. Furthermore, the ULCOS (Ultra-Low Carbon dioxide Steelmaking) consortium [13], composed of European steelmaking companies, energy and engineering partners, research institutes and universities, is currently trying to develop technologies for reducing steel production CO_2 emissions and uses LCA as one of its main environmental evaluation tools. The initiative is funded by the consortium partners and by the EU via specific programmes set up to promote industrial research and technological development within Europe. The research has so far investigated over 80 technologies for CO_2 reduction and has shortlisted some of these and is now evaluating, among other aspects, their environmental characteristics via the use of the life cycle paradigm. Specifically, an LCI of the integrated classical steelmaking route has been combined with process simulation software to model the CO_2 emissions of potentially more sustainable processes [14] involving new technologies, reductants and methods for capturing and storing CO_2. Overall, the project is still at a feasibility evaluation stage and aims to reach the large-scale industrial production conditions within the next decade. Similarly, Huang et al. [15] have built the total CO_2 emission model of a Chinese integrated steel mill on the basis of an LCI. The model was then used to analyse the variation of the greenhouse gas production, via specific software, by varying the inputs to the inventory model. This allowed the authors to identify factors that influence CO_2 emissions from steelworks, and has also allowed them to propose measures to reduce CO_2 emissions.

The scientific literature also contains nation specific steel LCAs such as that of Bieda [16,17] that has used data from the ArcelorMittal steel mill in Poland, together with that of other studies, to create an inventory of Polish pig iron and steel production. Buchart-Korol's study [18] also entails the LCA of Polish steel by using averaged data originating from a group of mills. The cradle-to-gate assessment regards steel production through the integrated mill and electric arc furnace routes.

Comparative studies, also found in literature, concern complete LCAs of national metal production, including that of steel, which are performed with averaged data from various scientific sources. For example, Norgate et al. [19] carried out a cradle-to-gate environmental evaluation (in terms of global warming, acidification potential, energy requirement and waste production) of a number of metal production processes (copper, nickel, aluminium, lead, zinc, steel, stainless steel and titanium) practised either currently or potentially in Australia.

Similarly, the present study, intended as starting point for innovative change, represents an accurate and extensive environmental analysis of the steel production in the Taranto district, with the aim of highlighting its main hot spots. Specifically, this work entails the LCA of steel production occurring in the Ilva steelworks, carried out with specific foreground data collected on site.

The paper is organised as follows: the next section illustrates the main LCA method and its assumptions. Section 3 describes the results of the inventory phase. Section 4 illustrates the results of the environmental impact assessment. In the final sections, the results are discussed and some conclusions are drawn.

2. Materials and Methods

The present study is intended as a holistic environmental assessment of the integrated steel mill, located in Taranto, via the LCA methodology. The LCA was conducted following the requirements of the ISO 14040 (2006) International Standards [20]. The four stages of the LCA applied in this work included determination of the goal, scope and system boundary; inventory analysis of inputs and outputs; assessment of environmental impact; and interpretation of results.

The primary objective is that of identifying the use of materials and energy together with the quantities and qualities of the emissions during the lifecycle in order to identify critical features, phases and whenever possible options for improvement.

The foreground data for the LCA, gathered onsite, does not concern current production levels. In fact, the data were collected before the aforementioned environmental crisis, when the production levels of the steelworks were nearly up to the levels of the maximum production capacity of 12 Mt of steel per year [21]. Whenever data was not available, it was estimated via the Best Available Techniques Reference documents (BREF) for steel [22]. Data on Emissions was partially obtained from the local environmental protection agency [23]. Background data was obtained from commercial LCA databases. The software used for the assessment is SimaPro (version 8.2, PRé Consultants bv, Amersfoort, The Netherlands).

LCA Approach and Assumptions

The system boundaries include the raw material extraction, the sintering operations, the coke production and the pig iron and steel production (Figure 1).

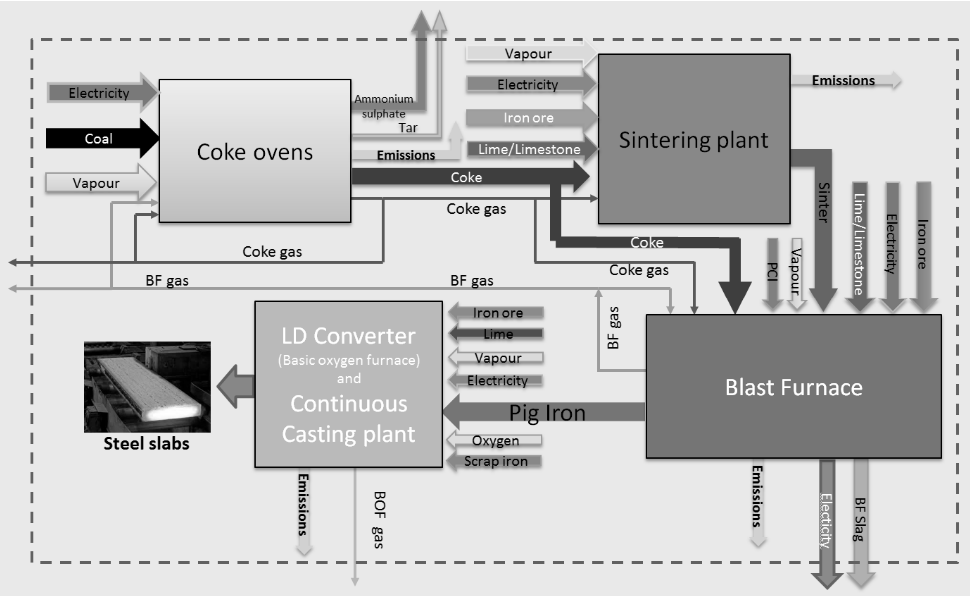


Figure 1. The system boundaries. The by-products cross the boundaries (dashed line) and have part of the environmental impacts allocated to them. (BOF: Basic Oxygen Furnace (also known as LD converter), BF: Blast Furnace, PCI: Pulverised Coal Injection.)

The functional unit (FU) is defined as the production of 1,000,000 t of solid steel slabs. Transport of semi-finished products occurring between the various parts of the industrial plant was not considered in the assessment. The transport distances of waste was hypothesized by contemplating the layout of the steelworks and assumed to use 16 t trucks. The amount of steelworks gases (gas from coke production, blast furnace gas and converter gas), collected and stored after purification, were also estimated. Final disposal is assumed to occur in a dump for which specific data was used. The Ecoinvent (versions 2 and 3, Ecoinvent, Zurich, Switzerland) [24] and the ELCD (European reference Life Cycle Database) [25] databases were used for the inventories of limestone, lime, oxygen, argon, iron oxide pellets, coal and iron ore.

By products, intended as other marketable products other than steel, arising from the steel production process, are tar, ammonium sulphate, gases and blast furnace (BF) slag (see Figure 1). The allocation of the environmental impacts between the primary product (steel) and the by-products, considers both the mass and the economic value of the by-products. Specifically, the allocation is carried out with a weighting between the by-products' mass and economic value in order to balance their quantities with their low economic value. The prices of the by-products were obtained from the Chamber of Commerce in Milan, Italy.

The production residues, intended as those materials arising from the production process that are not considered waste or by-products (e.g., coke dusts, fine particles of sintered material, mill scale, etc.), are assumed to be recycled in the production cycle. In the present study, waste is intended as the undesired or unusable materials, arising from the steel production process, which is disposed of.

The environmental impact categories used for this study is described in the documentation of the International Reference Life Cycle Data System (ILCD) [26], which recommends a set of 16 midpoint categories [27], namely:

- Global warming: caused by greenhouse gasses emitted in atmosphere;
- Ozone depletion: caused the emission of ozone-depleting substances (e.g., CFCs) in the atmosphere which then reach the stratosphere;
- Human toxicity cancer effect: carcinogenic effect on human health due to the emission of toxic substances;

- Human toxicity non cancer effect: negative effect (excluding carcinogenic one) on human health due to the emission of toxic substances;
- Particulate matter: microscopic solid or liquid matter suspended in the atmosphere, which can have negative effects on climate, human health and vegetation;
- Ionizing radiation: high-energy electromagnetic waves and subatomic particles, ions or atoms that can have negative effects on health;
- Photochemical ozone formation: formation occurs when nitrogen oxides carbon monoxide and volatile organic compounds react in the atmosphere in the presence of sunlight, and has negative effects on health;
- Acidification: formation of acid rain which can have effects on soil, plants, water, fish and wildlife and materials;
- Terrestrial eutrophication: oversupply of nutrients which induces explosive growth of certain plants whilst hindering others;
- Freshwater and Marine eutrophication: oversupply of nutrients which induces explosive growth of plants and algae which disrupts the normal functioning of the aquatic ecosystem;
- Freshwater eco-toxicity: a result of emissions of toxic substances to air, water and soil which end up in freshwater systems;
- Land use: the amount of land occupied/used for the activities related to the product system under assessment;
- Water resource depletion: decline of quantity or quality of water resources;
- Mineral fossil and renewable depletion: reduction/increase in scarcity of available mineral fossil and renewable resources.

3. Inventory Analysis

Raw materials (coal, pulverised coal and iron ore) are imported mainly from overseas (Australia, South Africa, USA, Canada, Venezuela, Brazil and Mauritania). Small amounts of coal also are imported from Poland whilst the limestone is produced locally in the quarries located near the steelmaking site. Distances were calculated for all modes and types of transport of the raw materials and modelled using the above-mentioned Ecoinvent inventories.

The mill consumes approximately 4600 GWh of electrical energy per year. Approximately 4% of this is produced on site, principally via the turbo-expanders that use the exhaust gases of the blast furnace to drive an alternator. The neighbouring thermo-electric power plant provides 3300 GWh per year of electrical energy. The rest of the necessary electricity is purchased from national grid providers. As already mentioned, the mill produces gas during coke production and in the pig iron and steel furnaces. Such gas is collected, purified and used as fuel. Specifically, the mill produces approximately 7850 TJ of energy in terms of gases and consumes approximately 3700 TJ of this gas directly during the steelmaking processes. The rest is sold to the above-mentioned power plant that uses the gas to produce electricity. The final energy balance for the production of 1 ton of solid steel is 19.8 GJ. This is subdivided in the following manner: 3.7 GJ used during the coke making process, 1.9 GJ used during the sintering process, 13.4 GJ in the blast furnace operation and 0.8 GJ in the LD steel converter—Basic Oxygen Furnace (Table 1).

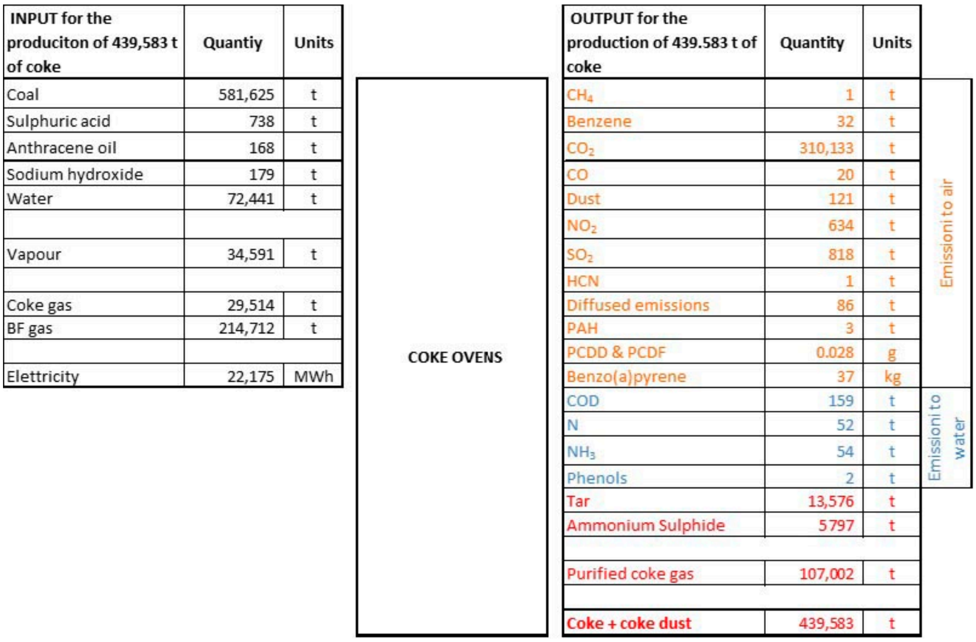
For the production of 1,000,000 t of steel (FU), the required inputs and respective outputs are illustrated in Figures 2–5, subdivided per phase.

The inputs and outputs of the production, via the coke ovens, of 439,583 t of the coke necessary for the production of the 1,000,000 t of steel are illustrated in Figure 2. The most significant emissions to air are CO_2, SO_2 and NO_2. This process also produces 107,002 t of coke oven gas, 13,576 t of tar and 5797 t of ammonium sulphate. This phase is also responsible for the creation of dioxins and polychlorinated dibenzofurans (PCDDs and PCDFs) and polycyclic aromatic hydrocarbons (PAHs). PCDDs and PCDFs, which are classified as persistent organic pollutants, are particularly toxic and can have effects on human and animal health. Similarly PAHs, composed of multiple aromatic rings and primarily produced from the incomplete combustion of organic matter, have negative effects on human health (including cancer). The lifecycle phase related to the coke oven activities is also responsible for the production of benzo(a)pyrene (BaP), a mutagenic and highly carcinogenic polycyclic aromatic hydrocarbon.

Table 1. Energy balance of the production of 1 t of steel.

	Input	Energy Input (MJ)	Output	Energy Output (MJ)	GJ/t Steel
Coke ovens	Electric energy	79,830,000	Coke	12,845,384,530	**3.7**
	Fossil fuels	19,050,124,247	Coke gas	4,348,146,647	
	BF gas	565,821,301	Tar	138,475,200	
	Coke gas	1,199,334,593			
	Vapour	103,773,000			
	Total	20,998,883,141		17,332,006,377	
Sintering Plant	Electric energy	174,801,600			**1.9**
	Coke gas	95,616,802			
	Coke	1,614,852,349			
	Vapour	54,618,000			
	Total	1,939,888,751		-	
Blast Furnace	Electric energy	179,460,000	Pig iron	1,471,761,225	**13.4**
	Fossil PCI	5,002,995,703	BF gas	3,857,363,340	
	Coke	11,230,532,182			
	Coke gas	867,784,449			
	BF gas	1,060,867,505			
	Vapour	365,931,000			
	Total	18,707,570,839		5,329,124,565	
Basic Oxygen Furnace	Electric energy	290,037,600	BOF gas	969,152,322	**0.8**
	Pig Iron	1,471,761,225	Steel	29,700,000	
	Vapour	21,846,000			
	Total	1,783,644,825		998,852,322	
	(Data referred to the production of 1 Mt of steel)				**19.8**

BOF: Basic Oxygen Furnace; BF: Blast Furnace; PCI: Pulverised Coal Injection.

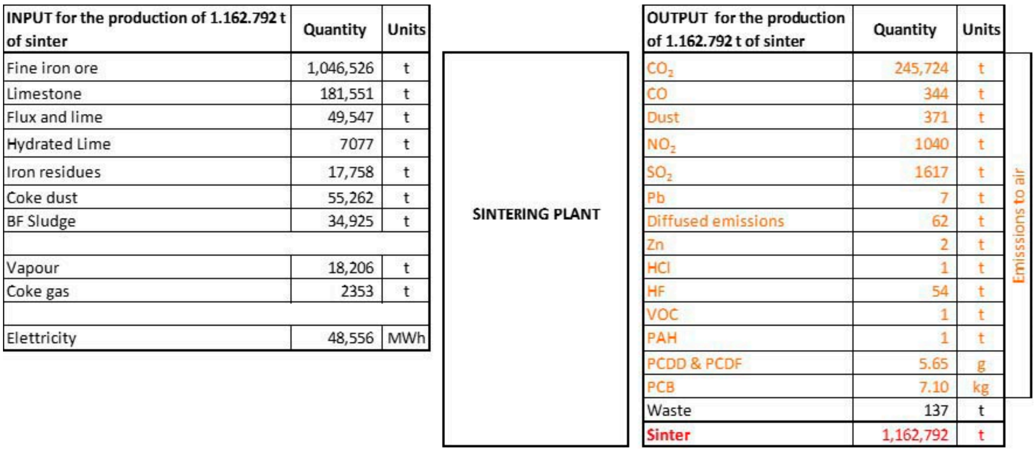


INPUT for the produciton of 439,583 t of coke	Quantiy	Units
Coal	581,625	t
Sulphuric acid	738	t
Anthracene oil	168	t
Sodium hydroxide	179	t
Water	72,441	t
Vapour	34,591	t
Coke gas	29,514	t
BF gas	214,712	t
Elettricity	22,175	MWh

OUTPUT for the production of 439.583 t of coke	Quantity	Units
CH_4	1	t
Benzene	32	t
CO_2	310,133	t
CO	20	t
Dust	121	t
NO_2	634	t
SO_2	818	t
HCN	1	t
Diffused emissions	86	t
PAH	3	t
PCDD & PCDF	0.028	g
Benzo(a)pyrene	37	kg
COD	159	t
N	52	t
NH_3	54	t
Phenols	2	t
Tar	13,576	t
Ammonium Sulphide	5797	t
Purified coke gas	107,002	t
Coke + coke dust	439,583	t

Figure 2. Input to the coke ovens for the production the coke necessary for the production of 1 Mt of steel. BF: Blast Furnace; COD: Chemical Oxygen Demand; PCDD: Polychlorinated Dibenzodioxin; PCDF: Polychlorinated Dibenzofuran; PAH: Polycyclic Aromatic Hydrocarbon. In orange: emissions to air; in blue: emissions to water; in red: products and by-products.

The inputs and outputs of the production, via the sintering furnace, of 1,162,792 t of the sintered ore, necessary for the production of the 1,000,000 t of steel, are illustrated in Figure 3. The most significant emissions to air are CO_2 and NO_2 and SO_2. Dioxins, PAHs and PCBs are also generated in this lifecycle phase. PCB, an organic chlorine compound, also classified as a persistent organic pollutant, is particularly impacting on human health (carcinogenic effects).

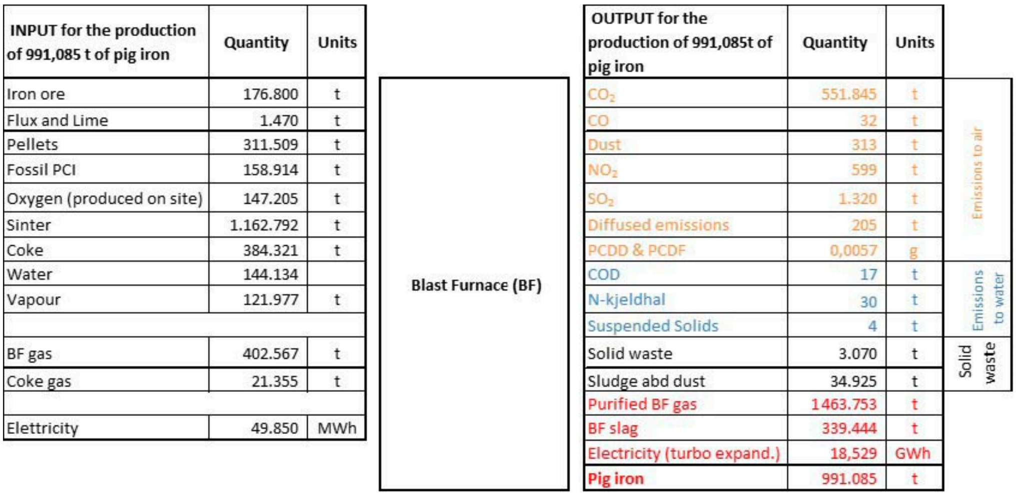


INPUT for the production of 1.162.792 t of sinter	Quantity	Units
Fine iron ore	1,046,526	t
Limestone	181,551	t
Flux and lime	49,547	t
Hydrated Lime	7077	t
Iron residues	17,758	t
Coke dust	55,262	t
BF Sludge	34,925	t
Vapour	18,206	t
Coke gas	2353	t
Elettricity	48,556	MWh

OUTPUT for the production of 1.162.792 t of sinter	Quantity	Units
CO_2	245,724	t
CO	344	t
Dust	371	t
NO_2	1040	t
SO_2	1617	t
Pb	7	t
Diffused emissions	62	t
Zn	2	t
HCl	1	t
HF	54	t
VOC	1	t
PAH	1	t
PCDD & PCDF	5.65	g
PCB	7.10	kg
Waste	137	t
Sinter	1,162,792	t

Figure 3. Input to the sintering furnace for the production the sintered ore necessary for the production of 1 Mt of steel. BF: Blast Furnace; PCB: Polychlorinated Biphenyl; COD: Chemical Oxygen Demand; PCDD: Polychlorinated Dibenzodioxin; PCDF: Polychlorinated Dibenzofuran; PAH: Polycyclic Aromatic Hydrocarbon. In orange: emissions to air; in black (on the output side): emissions to land; in red: products and by-products.

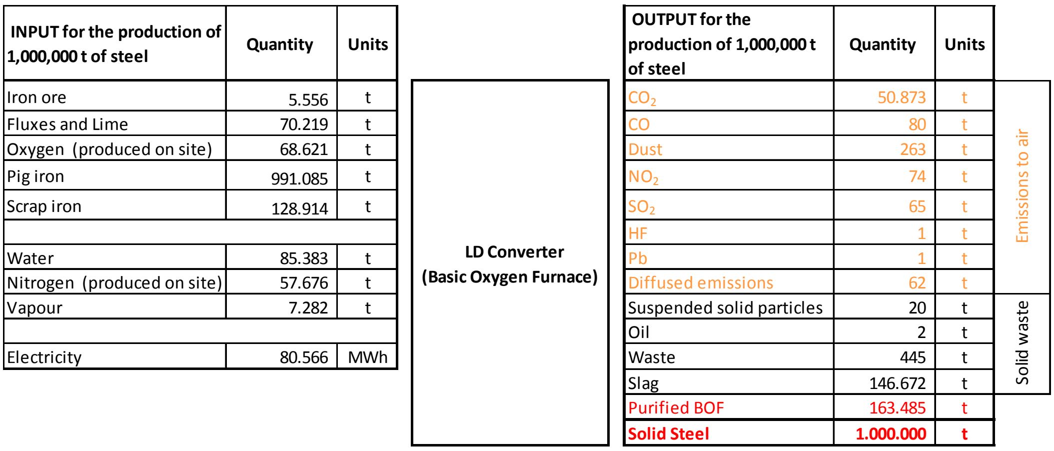
The inputs and outputs for the production, via the blast furnace, of 991,085 t of the pig iron necessary for the production of the 1,000,000 t of steel, are illustrated in Figure 4. The emissions to air are numerous and the most significant are CO_2 and SO_2. This process also produces 1,463,753 t of BF gas, 339,444 t of slag and 34,925 t of dust and sludge. Small amounts of PCDDs and PCDFs emission are also associated to blast furnace operations.



INPUT for the production of 991,085 t of pig iron	Quantity	Units
Iron ore	176.800	t
Flux and Lime	1.470	t
Pellets	311.509	t
Fossil PCI	158.914	t
Oxygen (produced on site)	147.205	t
Sinter	1.162.792	t
Coke	384.321	t
Water	144.134	
Vapour	121.977	t
BF gas	402.567	t
Coke gas	21.355	t
Elettricity	49.850	MWh

OUTPUT for the production of 991,085t of pig iron	Quantity	Units
CO_2	551.845	t
CO	32	t
Dust	313	t
NO_2	599	t
SO_2	1.320	t
Diffused emissions	205	t
PCDD & PCDF	0,0057	g
COD	17	t
N-kjeldhal	30	t
Suspended Solids	4	t
Solid waste	3.070	t
Sludge abd dust	34.925	t
Purified BF gas	1463.753	t
BF slag	339.444	t
Electricity (turbo expand.)	18,529	GWh
Pig iron	991.085	t

Figure 4. Input to the blast furnace for the production the pig iron required for the production of 1 Mt of steel. BF: Blast Furnace; PCI: Pulverised Coal Injection; COD: Chemical Oxygen Demand; PCDD: Polychlorinated Dibenzodioxin; PCDF: Polychlorinated Dibenzofuran. In orange: emissions to air; in blue: emissions to water; in black (on the output side): emissions to land; in red: products and by-products.



INPUT for the production of 1,000,000 t of steel	Quantity	Units
Iron ore	5.556	t
Fluxes and Lime	70.219	t
Oxygen (produced on site)	68.621	t
Pig iron	991.085	t
Scrap iron	128.914	t
Water	85.383	t
Nitrogen (produced on site)	57.676	t
Vapour	7.282	t
Electricity	80.566	MWh

LD Converter (Basic Oxygen Furnace)

OUTPUT for the production of 1,000,000 t of steel	Quantity	Units	
CO_2	50.873	t	Emissions to air
CO	80	t	
Dust	263	t	
NO_2	74	t	
SO_2	65	t	
HF	1	t	
Pb	1	t	
Diffused emissions	62	t	
Suspended solid particles	20	t	Solid waste
Oil	2	t	
Waste	445	t	
Slag	146.672	t	
Purified BOF	163.485	t	
Solid Steel	**1.000.000**	**t**	

Figure 5. Input to the LD converter for the production of 1 Mt of steel. BOF: Basic Oxygen Furnace. In orange: emissions to air; in black (on the output side): emissions to land; in red: products and by-products.

Figure 5 illustrates the inputs and outputs for the LD converter (also known as Basic Oxygen furnace). The most significant emissions to air are CO_2 and vapour. This process also produces 163,485 t of BOF gas and 146,672 t of slag.

4. Impact Assessment, Results and Implications

The environmental impact results were calculated by following the ISO 14040 norm procedure up to the characterisation step; hence the results are not normalised. Table 2 illustrates the absolute values, for each lifecycle phase, of the impact of each category resulting from the classification and characterisation steps of the impact analysis per FU.

Table 2. Characterisation of the impact assessment results—Absolute values of the burden for each impact category for each production phase per FU (1 Mt of steel).

Impact Category	Unit	Coke Ovens	Sintering Plant	Blast Furnace	Basic Oxygen Furnace	Total
Climate change	kg CO_2 eq	3.57×10^8	3.27×10^8	6.63×10^8	2.42×10^8	1.59×10^9
Ozone depletion	kg CFC-11 eq	6.34×10^0	8.86×10^0	1.77×10^1	1.58×10^1	4.87×10^1
Human toxicity, cancer effects	CTUh	8.21×10^1	4.10×10^0	3.45×10^1	5.10×10^0	1.26×10^2
Human toxicity, non-cancer effects	CTUh	2.37×10^2	8.26×10^1	1.42×10^2	3.35×10^1	4.95×10^2
Particulate matter	kg PM2.5 eq	1.44×10^5	2.49×10^5	2.85×10^5	6.12×10^4	7.40×10^5
Ionizing radiation HH	kBq U235 eq	1.08×10^7	1.55×10^7	2.63×10^7	2.20×10^7	7.45×10^7
Ionizing radiation E (interim)	CTUe	3.70×10^1	5.04×10^1	7.48×10^1	5.09×10^1	2.13×10^2
Photochemical ozone formation	kg NMVOC eq	1.97×10^6	2.21×10^6	2.53×10^6	5.11×10^5	7.23×10^6
Acidification	molc H^+ eq	3.33×10^6	4.26×10^6	4.94×10^6	9.04×10^5	1.34×10^7
Terrestrial eutrophication	molc N eq	7.93×10^6	8.43×10^6	9.57×10^6	1.68×10^6	2.76×10^7
Freshwater eutrophication	kg P eq	9.97×10^5	1.95×10^4	3.84×10^5	2.76×10^4	1.43×10^6
Marine eutrophication	kg N eq	8.93×10^5	7.43×10^5	9.10×10^5	1.57×10^5	2.70×10^6
Freshwater ecotoxicity	CTUe	7.21×10^9	4.08×10^8	3.81×10^9	1.11×10^9	1.25×10^{10}
Land use	kg C deficit	4.45×10^8	1.09×10^8	6.52×10^8	1.48×10^8	1.35×10^9
Water resource depletion	m^3 water eq	8.75×10^7	1.47×10^8	3.63×10^8	4.12×10^8	1.01×10^9
Mineral, fossil & ren resource depletion	kg Sb eq	1.27×10^3	2.05×10^3	3.48×10^3	4.88×10^3	1.17×10^4

Figure 6 illustrates the contribution, in terms of percentages, of the various production phases to each of the impact categories.

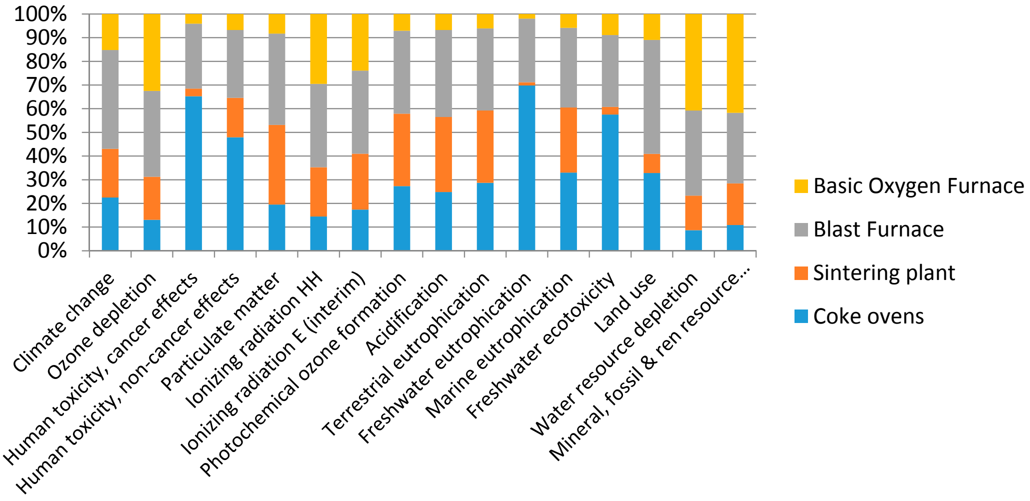


Figure 6. Characterisation of the impact assessment results—contribution analysis of the different production phases to each of the impact categories.

Figure 6 indicates that, in general, the lifecycle activities associated with the BF operations contribute substantially to all the impact categories. In particular, over 40% of the potential Climate Change is due to the transport of the raw materials used in the BF and to the actual operation of the furnace. Similarly, the transport of the materials used in the BF is also responsible for a large share of the Ozone Depletion potential. The extraction of the same raw materials is responsible for nearly 50% of the overall Land Use indicator value and 40% of the potential Particulate Matter emission. Overall, the activities related to the BOF operations make the smallest contribution to the impact categories with the exception of the Water Resource Depletion and the Mineral Fossil and Renewable Resource Depletion (40% of the overall indicator values), which is mainly due to the use of electric energy. The lifecycle activities associated with the sintering operations are never dominant in terms of the overall contribution to the impact categories. The same can be stated about the activities related to the coke production, with the exception of the impact categories regarding Toxicity and Freshwater Eutrophication, where such activities contribute to over 50% of the overall indicator values.

5. Discussion

What emerges from the results is that many of the environmental impacts are related to the energy consumption and also to the toxicity of the emissions associated with the lifecycle of steel production. As far as energy use is concerned, for the present study, the above calculated energy balance for the production of 1 ton of solid steel, amounting to 19.8 GJ, corresponds to a primary energy demand of 23.2 GJ. This last value is in slightly higher than the one calculated by Pardo et al. [28] in their study, concerning European steel, which estimates an energy use of 22.5 GJ/ton. Similarly, in the study by Norgate [29], concerning the life cycle energy assessment of steel, the primary energy demand amounts to 22 GJ/ton of steel. In the above-mentioned inventory study of the World Steel Association [8], involving data from fifteen worldwide steel companies, the primary energy demand amounts to 16.4 GJ/ton of steel. Most of these energy values found in literature also include the energy used for rolling the steel sections, which is not included in the present study. What this implies is that, for the Ilva steelworks, there is a potential for saving energy via the implementation of more efficient production processes. In other words, energy losses should be reduced by improving currently implemented technologies or investment should be made in newer innovative steelmaking approaches such the use of larger amounts of direct injected coal or the injection of other types of fuel [30] into the blast furnace that may reduce by 50% the use of coke and by 30% the use of energy. Furthermore, waste energy reuse practices could be implemented such as those that exploit low grade waste energy for heating offices and other working spaces [31] or for the generation of mechanical energy by using Organic Rankine Cycle systems [32].

As mentioned previously, the Ilva steelworks is currently undergoing an environmental crisis, which was sparked off, among other events, by the review of the Integrated Environmental Authorisation (EU Directive 2010/75/EU on industrial emissions) following the high emissions levels of the carcinogenic polycyclic aromatic hydrocarbon benzo(a)pyrene. What follows is a focus on the aspects regarding toxicity impact indicators related to the lifecycle of steel production in Taranto.

Among the many midpoint indicators implementable in LCA, the USEtox [33] method includes characterisation factors for benzo(a)pyrene whilst others do not (including the ReCipe [34] method, which is also recommended in the ILCD documentation). As a consequence, in the present study, the characterisation factors of such a method were used for modelling Human Toxicity and Freshwater Ecotoxicity potential impacts.

As mentioned above, the lifecycle processes related to the coke ovens seem to influence substantially the indicator values and the impact categories associated with toxicity (Human Toxicity—cancer and non-cancer effect—and Freshwater Ecotoxicity). This generally appears in line with the results of the study, carried out by the regional environmental protection agency, of the evaluation of the damage to human health associated with the steelworks [23]. Such a study has a different nature from that of an LCA since it considers site specific information, such as population distribution, climatic conditions and epidemiological studies to establish the existence and quantify the risk of damage to human health. The study has highlighted the fact that, for the local population of the city of Taranto, the highest impacts on human morbidity and mortality, in terms of cancer, are due to the coke oven emissions of benzo(a)pyrene.

However, a more in-depth analysis of the impact assessment results of the present study reveals that such correlation, reported by the regional environmental protection agency, of health damage (to the local population) to the emissions benzo(a)pyrene, does not emerge. In fact, by analysing the potential direct effect (i.e., the effects due to lifecycle activities occurring in the steelworks and around the city of Taranto) on the local population of the town of Taranto of the Human Toxicity Cancer Effect impact category, the major contribution to such indicator (in terms of direct effects) is due to the sintering operations (Figure 7). This major contribution is due in particular to the emissions of heavy metals, dioxins and polychlorinated dibenzofurans emitted from the sintering plant.

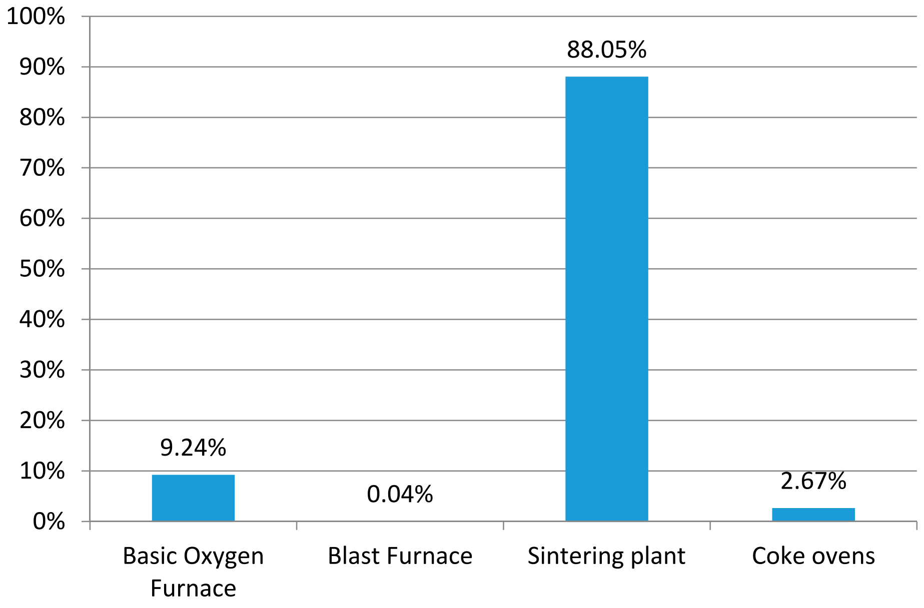
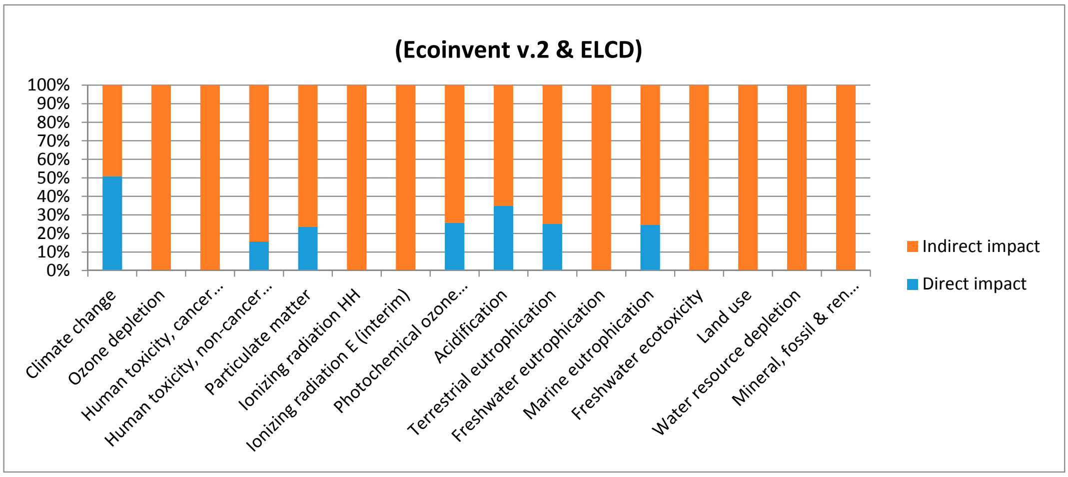
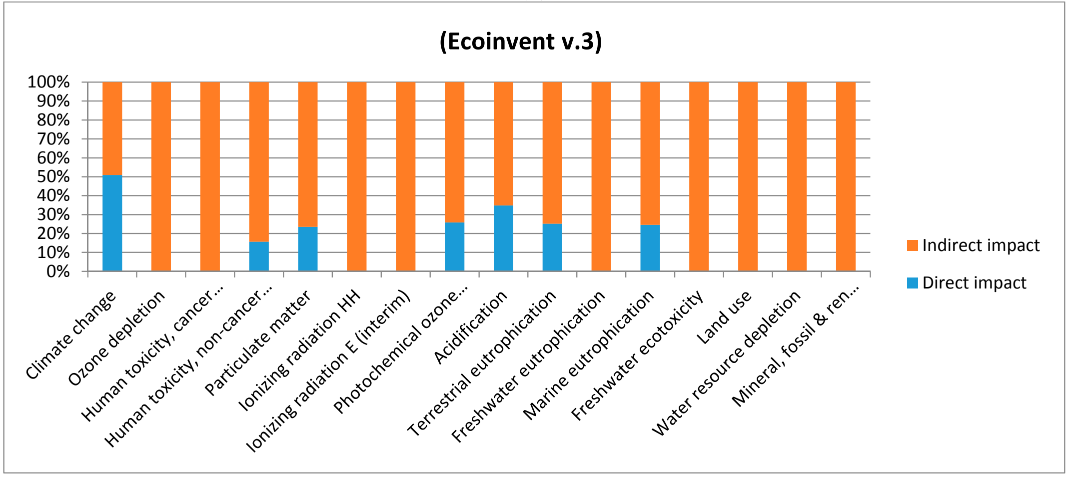


Figure 7. Contribution to the impact (Human Toxicity Cancer Effect) potentially occurring directly in the area around Taranto—subdivided per production process.

Furthermore, according to the LCA results, the direct potential effects on Taranto in terms of the impact category Human Toxicity Cancer Effects are only 10% of the overall effect that potentially could occur during all the lifecycle (i.e., not only in Taranto but also during the raw material extraction, transport, etc.). This percentage falls to 0.23% when the results are calculated with the Ecoinvent v.3 database (as opposed to a combination of data from the Ecoinvent v.2 and ELCD). Such variability is also present for all of the categories involving toxicity aspects (Figure 8).



(**a**)



(**b**)

Figure 8. Share of the potential direct effect (occurring in and around the area of the steelworks) of each impact category with respect to the potential indirect effect (occurring elsewhere). (**a**) the results are calculated using a combination of Ecoinvent v.2 and ELCD data; (**b**) the results are calculated using of Ecoinvent v.3 data only.

All of this highlights several aspects concerning the toxicity modelling of the present study, namely:

- there is a discrepancy, in terms of results, when assessing the same system, between toxicity modelling with site specific approaches such as the above-mentioned one and site independent approaches like LCA. This has often been highlighted as a critical issue of LCA [35], and it is demonstrated by the fact that many impact assessment models do not include characterisation factors (CFs) for all toxic substances, and, in many cases, one CF of one method may give very different results for the same CF of another method;

- the calculated impact resulting from LCA studies is not necessarily that which actually occurs in specific areas due to the "potential" and site independent nature of the LCA indicator values. Hence, a large potential Human Toxicity impact, which is attributable to areas where iron ore mining and overseas transport activities occur, does not translate in an effective damage to humans due to the small presence of human beings in these areas. Vice versa, a small potential human toxicity impact can turn out to effectively cause widespread damage to human health, as in the case of Taranto, due to the high population density around the steelworks;
- independently of the characterisation factor used to model an LCA potential impact, the results of the study have highlighted how shifting from an LCA database to another can, in some cases, give different results.

Finally, the inventory phase of the present LCA study has also highlighted the large production of material waste, especially in terms of BOF slag, which amounts to over 140 kt per million ton of steel produced. Such slag, produced in the LD converter, is all used to fill a quarry located in the steelworks area. Even though such filling is harmless in environmental terms, since the slag is used a substitute of other natural inert materials, the scientific literature has often highlighted many more productive options for the reuse of this type of slag in other productive contexts. For example, Notarnicola et al. [5] have highlighted how BOF slag can be used as a fertiliser, a concrete aggregate or simply for road paving. If all the BOF slag were to be used for such applications, by using process data concerning "crushed stone" from the ELCD 2.0 database, it is possible to estimate an avoided production of 1.96 Mtons of CO_2 eq per each 1,000,000 t of steel (FU) produced. Similarly, in terms of energy, the above-mentioned virtuous reuse of the BOF slag would imply an avoided energy use of 885 toe/FU. Furthermore, the slag generated in the BF is only partially reused in the nearby cement factory. Eighty-five percent of the BF slag is shipped to South America for re-use. Even though such a practice is consistent with the paradigm of a circular economy, a local reuse of such by-product would avoid the impacts related to the overseas transport of the slag.

6. Conclusions

The inventory phase of the present LCA study has highlighted the large production of waste for which the scientific literature has often highlighted many productive options for the reuse. The results indicate that the reuse of BOF slag, for infrastructures or agricultural purposes and the local reuse of BF slag, currently shipped abroad, represent a large potential for reducing the environmental impacts and increasing the sustainability of the steel production. The energy demand associated with the lifecycle of the steel production is higher than that found in other studies. Hence, there is potential for energy saving, in terms of reducing energy losses of the currently implemented technologies, and also in terms of implementing innovative, more efficient steel making technologies. This last option would obviously be capital intensive and would have to be developed in the long term with careful planning in order to maintain the steelworks' economic integrity.

The impact assessment has highlighted that the BF and coke oven related activities occurring along the whole lifecycle of the steel production are among the most impacting phases. These results, in a certain manner, are in line with the environmental restrictions currently imposed on the mill that has been accused of damaging the health of the workers and local population through its production processes. Concerning human toxicity aspects, the results indicate that the coke oven phase is responsible for the main potential toxicity related impacts. The detailed analysis of such impacts potentially occurring in the area around the steelworks is inconsistent with the results of more site-specific studies concerning the damage to human health associated with the steelworks activities. This indicates that, as far as toxicity impact related aspects are concerned, LCA is still not perfectly suited to such assessments and should be coupled with other more site-specific studies in order to fully understand such aspects.

Overall, the results represent a first step to understanding the current levels of sustainability of the steelworks, which should be used as a starting point for the development both pollution control measures and symbiotic waste reutilization scenarios needed to maintain the competitiveness of the industrial plant. In the future, the current LCA could be extended to include the production process of other semi-finished products, such as billets, and the interaction of the mill with the neighbouring power plant in order to extend the picture of the environmental sustainability issues of the steelworks.

This study is limited to only a part of the overall steel production cycle. In the future, the current LCA could be extended to include the final steel product rolling operations and the production process of all semi-finished products in order to extend fully the picture of the environmental sustainability issues of the steelworks. Furthermore, the exchange of fuel (BOF, BF and coke gas) and of energy between the mill and the neighbouring power plant could also be modelled with the purpose of evaluating the environmental advantages of such exchanges and also with the intent of quantifying energy losses and other potential reuses of waste energy.

Author Contributions: The work illustrated in this paper was coordinated by Giuseppe Tassielli and Bruno Notarnicola. The literature review contained in this paper was carried out by Pietro A. Renzulli, Gabriella Arcese and Rosa Di Capua. The inventory data was collected by Giuseppe Tassielli and Pietro A. Renzulli. The impact assessment was carried out by Giuseppe Tassielli and Pietro A. Renzulli. All of the authors contributed in equal parts to the writing of the paper.

Conflicts of Interest: The authors have no conflict of interest to declare.

Abbreviations

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
ULCOS	Ultra-Low CO_2 Steelmaking
BOF	Basic Oxygen Furnace
LD converter	Linz–Donawitz converter
BF	Blast Furnace
PCI	Pulverised Coal Injection
FU	Functional Unit
BREFs	Best Available Techniques reference documents
ELCD	European Reference Life Cycle Database
ILCD	International Reference Life Cycle Data System
CFs	Characterisation Factors
PAHs	Polycyclic Aromatic Hydrocarbons
PCDDs	Polychlorinated Dibenzodioxins
PCDFs	Polychlorinated Dibenzofurans
PCB	Polychlorinated Biphenyl
VOC	Volatile Organic Compounds
COD	Chemical Oxygen Demand

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