Journal of Materials and Environmental Sciences
ISSN : 2028-2508
CODEN : JMESCN

J. Mater. Environ. Sci., 2018, Volume 9, Issue 6, Page 1630-1635

https://doi.org/10.26872/jmes.2018.9.6.181

http://www.jmaterenvironsci.com

Survey on environmental impact and circular economy aspects related to steel production in Europe

A. Di Schino

Dipartimento di Ingegneria, Università degli Studi di Perugia, Perugia, Italy

Received 29 Aug 2017,
Revised 01 Oct 2017,
Accepted 11 Oct 2017

Keywords
- ✓ *Steel*
- ✓ *Environenment*
- ✓ *Slag*
- ✓ *Emission*
- ✓ *Energy*

andrea.dischino@unipg.it
Phone: +39 3283311875

Abstract

The iron and steel industry is the world's biggest manufacturing energy consuming industry with the largest share in the world's economy. In the iron and steel production over world, China takes the first place, and Japan and U.S. follow it. Turkey, with a 34.7 million tonnes production has a share of 2.1% of the total world production in 2016 [1]. In Europe there are declared targets of the European Community aimed to protect the environment and to improve its quality, to serve the protection of the human health and to guarantee a cautious and efficient use of the natural resources. In this framework, steel companies are becoming increasingly aware about the sustainability challenges, in order to satisfy such requirements and to increase their competitiveness through an adequate management of resource and energy. Steel production is in fact characterized by an energy intensive activity, since the largest part of the production process takes place at high temperatures. Besides, iron ore is converted in metallic iron by using carbon as reducing agent. As global warming due to CO_2 emissions, steel production is considered one of today's main environmental problem and environmental impact of steel production mainly focus on reduction of energy use. This reduction of energy use is mainly achieved by important process measures, the reduction of material losses in the different production steps (also by looking at the use of steel slag as an opportunity to save natural resources) as well as of good housekeeping practices. Next to CO_2 large industrial steelworks also emit pollutant to be faced.

1. Introduction

Steel is a metal which combines a strong set of properties able to satisfy a large variety of applications with a fairly "cheap" price. It is one of the most important structural material in the world. It is virtually used in all sectors, from automotive, construction, mechanical engineering and shipbuilding to household appliances, computers and consumer electronics. Infrastructure projects such as road, bridge or rail construction would be impossible without steel. When an industrial manufactured component does not include steel as a major component (such as smart phones, computers or aircraft), it is made of parts which were produced with machines made of steel. In other words, steel is essential for the high standard of living in the developed world and for the growth of emerging economies. Steel firstly appeared in History at the end of the Neolithic, when villagers first learned how to smelt iron from earths [1]. Iron was initially used as a sign of wealth and power, but it soon became the favoured material to manufacture weapons, pots and pans and eventually ploughs (Brue and Rubin 2008): from a symbol of aristocracy, which was a new social paradigm of the settlers who had replaced the hunters-gatherers of the Mesolithic [2] it turned into a structural material, used to give shape, strength, elasticity, toughness and in some cases engineering audacity to the exploding number of small and large artefacts designed and produced by humankind around the time of the industrial revolution. Steel originates from earths concentrated into ores, coming from energy resources and from reducing agents and other fluxes (all from the geosphere) and it enters the techno-sphere to become metallic and alloyed, while the "gangue" is separated out of the major element (iron) to become a by-product, solid, gaseous, sometimes liquid or mixtures of these. While steel moves further into becoming a material embedded in artefacts, which are used for short or long lives and then eventually get discarded, the by-products are either used in other sectors in an industrial ecology synergy or landfilled. All may be dissipated to the environment to a small extent. Steel itself can be reused or recycled and, indeed, steel is the most recycled material [3]. The complexity of this scheme is obvious but is compounded by the fact that steel is not simply iron: it contains other elements, either originating from the initial raw materials, or added as alloying. These have a different fate in the recycling loop from iron: some are also recycled, often co-recycled with iron, while others are simply lost. From the above considerations it appears that the robustness of steel to serve as a core structural material of society and a key part of its evolving technology has been constantly at work in these changing times of demographic and economic explosion. Other materials, like wood and concrete, show similar features, but only steel exhibits such universality. This role of steel is expected to continue in the future. What is truly remarkable is that this trend continued across centuries and that production has been multiplied almost one hundred times since the beginning of the 20th century. In the iron and steel production over world, China takes today the first place, and Japan and U.S. follow it. Turkey, with a 34.7 million tonnes production has a share of 2.1% of the total world production in 2016. Currently, two processes dominate the global steel production: a) the integrated steel mill in which steel is made by reducing iron ore in a blast furnace and subsequently processing in an oxy-steel plant (BOF); b) the mini-mill in which steel is made by melting scrap or scrap substitutes in an electric arc furnace (EAF). Other processes that are in use are either outdated (e.g. the open-hearth furnace, OHF) or so new that their share in the world steel production is still small (e.g. direct reduction and smelt reduction processes). In this framework it has to be anyway taken into account that both the above processes are energy intensive, with a significant environmental impact [4]. In Europe there are declared targets of the European Community aimed to protect the environment and to improve its quality, to serve the protection of the human health and to guarantee a cautious and efficient use of the natural resources and steel companies are becoming increasingly aware about the sustainability challenges. In order to become a responsible corporate citizen, the industry has responded to these challenges through adoption of pillars of sustainability and identifying sustainability indicators specific for steel industry. In order to satisfy such requirements steelworks, need to increase their competitiveness through an adequate management of resource and energy. Steel production is in fact characterized by an energy (hence CO_2) intensive activity, as much of the production process takes place at high temperatures. Besides, iron ore is converted in metallic iron by using carbon as reducing agent. As global warming due to CO_2 emissions, steel production is considered one of today's main environmental problem and publications about the environmental impact of steel production mainly focus on reduction of energy use. This reduction of energy use is mainly achieved by important process measures, the reduction of material losses in the different production steps (also by looking at the use of steel slag as an opportunity to save natural resources) as well as of good housekeeping practices.

2. Raw material utilization in the "circular economy" framework

Raw materials for steel production are neither rare nor scarce, except for a very few alloying and reactant elements. This is why main steel elements are iron and carbon and iron is the most abundant element in the Earth (quite common also in the Earth crust). This does not mean, however, that we will be able to use them without limitations in the future; in fact, steel is today already recycled to a high level (83% and 36 years of average life) [3] and, when peak steel production will be reached (probably towards the end of this century) a full circular economy will take over, except, possibly at the margin for a small number of niche applications. Steel is not only iron and carbon of course, and many alloying and micro-alloying elements are added to make it a "material" responding to the strength, elasticity, toughness requirements of the different applications [4-12]. In the case of electrical steel production, when steel is recycled, also alloying elements are recycled: while some will be oxidized out of the steel at steelmaking and incorporated into EAF slag (silicon, half of the manganese, part of the chromium, most of sulphur and phosphorous, molybdenum, rare earths, aluminium and other deoxidizing agents), or vaporized (zinc from coatings, some sulphur), others will be diluted into the steel matrix and thus either dissipated (tin) or co-recycled (part of the manganese, most of the chromium, nickel). Only the non-recycled steel will be dissipated or absorbed in urban sites (ships sunk at sea, landfilled material, hidden scrap piles, deep foundations of buildings, etc.). A quantitative and exhaustive mass balance of all items involved in the steel value chain is not readily available, although the main orders of magnitude are not in doubt. The iron ore used today has skimmed the best deposits of high-grade ore that can be shipped directly to the steel industry, either as natural ore or after beneficiation. Even with such a favourable scheme, the mining industry discards between half and two thirds of the material removed from the mine, usually as tailings, in addition to the overburden of rocks inside which the iron- rich deposit is geologically enclosed. Tailings constitute a slurry, which is difficult to dry and therefore is stored in natural valleys, behind dams. The tailings also concentrate heavy metals in the slime and in discharged water, which has to be treated accordingly. Tailings and the conditions under which they are stored constitute one of the major environmental burdens carried by the steel value chain. The issue will disappear, when the recycling economy fully takes over towards the end of the century. pure ores will be called upon and therefore the energy needs for steel production will increase, while its purity will decrease [13]. The same will eventually be true for the secondary raw material route (scrap), which will become enriched in non- ferrous elements.

3. Sources and emissions from the steel industry

Steel plants have usually been associated with the terms air pollution even if nowadays most problems had found solutions. In fact, during the steel making process, some of the elements separated from iron leave the reactors as dust or volatiles. Dust, also known as particulate matter, comes from ore piles, sinter plants, coke ovens, blast furnaces, steel shops, roughly 10 to 20 kg per major reactor. Most of the dust is collected and either or marginally landfilled. Air pollution issues related to dust were handled in the second half of the 20th century, especially since many steel mills were quickly enclosed in cities subject to urbanization growth. Volatiles emissions are related to heavy metals (cadmium, mercury, nickel, copper, zinc, lead, etc.), inorganic (H_2S, CO, SOx, NO_x, O_3) and organic compounds. Air pollution has been brought under control at the best-run steel mills of the world, following very active research and abatement technology development. Moreover, lists of technologies to guarantee conformity to present standards have been compiled, for example by the European Commission. Besides these "elite" mills, however, there are still air pollution issues in parts of the world. Moreover, the standards are very likely to be raised to much tougher limits by the middle of the century, due to increased urbanization, to the fact that locating production plants away from cities will no longer be an option and to several air pollution issues stepping up from local to global scale (Figure 1) [1].

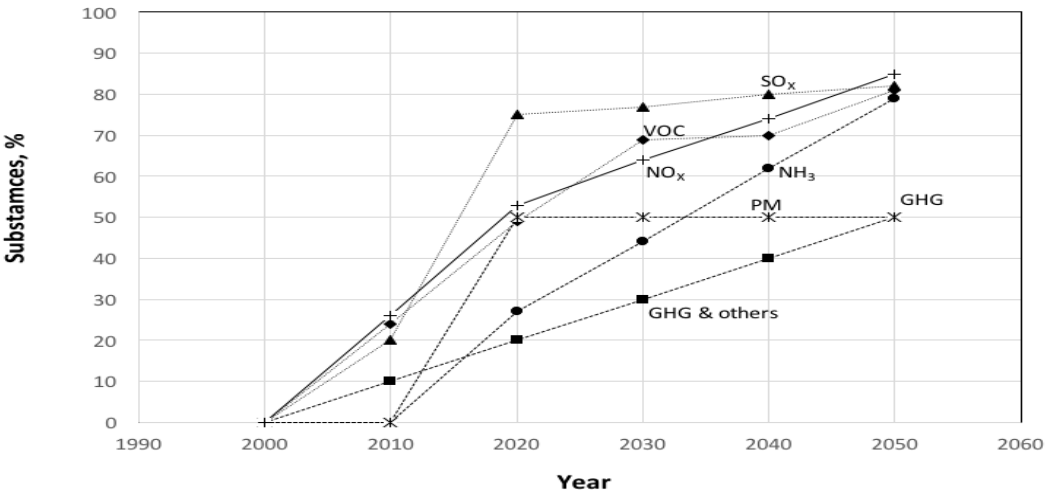

Figure 1. Emission targets evolution for main indicators (data from [1]).

Main green house gas (GHG) emitted by steel industry is carbon dioxide (CO2). The CO2 emission associated to steel production is estimated to be 1425 Mt. The CO2 emission associated with the production of 1 tonne of steel varies depending on the adopted process (Table 1) [14].

In an open hearth furnace, the process emissions of the open hearth furnace consist of particulates and heavy metals. Also main pollutants such as NO_x, CO and SO_x are emitted but these are considered to originate mainly from the combustion. In an open hearth furnace, dust generation depends on three basic processes: combustion, mechanical impact of furnace atmosphere and charge, and the chemical processes. The flow of gases in the furnace working chamber results in entrainment of fine particles of charge in the initial process of heating and in the refining process. The chemical processes taking place in fluid metal actively increase dust generation in the furnace gases. Especially in the process of intensive refining, rising CO bubbles throw particles to the surface of the melt which are then entrained by furnace gases, thereby increasing the dust load. Introduction of ore materials into the furnace as well as of dolomite and limestone affects slag generation and results also in an increase in furnace gas dust generation. Moreover, a considerable increase of furnace gas dust generation is observed during oxygen application for intensification of combustion and refining processes.

The concentration of dust in furnace gas heating changes during the process. Moreover, the concentration in individual periods depends on a whole range of factors, of which the following are the most important:

- type of charge material;
- type of process used;
- technical condition of the furnace;
- type of fuel;
- application of oxygen during the melting and refining processes.

The amount and temperature of furnace gases depends also on many factors including: furnace capacity, type of fuel, type of roof lining, furnace construction (stationary or tilting), type of heads and technical condition of a furnace. The SO_2 content in furnace gas is relatively low, even in the case of using residual oil as a fuel.

Table 1. CO_2 emissions for different production processes**.**

Process	CO_2 emissions (tonnes per tonne/product)
Integrated steel mill	1.8-2.0
Scrap base production	0.6-0.8
Scrap substitues in a minimill	1.6-1.8

In an integrated steel mill, the majority of CO_2 emissions (70%) comes from iron production in the blast furnace. Small but still significant CO_2 emissions arises from rolling. Moreover, for a blast oxygen furnace, the primary dust abatement produces, in addition to CO and CO_2, mainly dust emissions. When the converter is provided with a fire resistant coating, this coating has to be preheated, producing polycyclic aromatic hydrocarbons (PAH). The amount of PAH is usually below the detection limit of the measuring technique. The dust contains a small amount of heavy metals. The secondary dust abatement produces dust with higher heavy metal content than the primary dust. The same applies to the unabated dust emissions from ventilation through the roof. The main part of the dust emissions consists of particles with a size smaller than 10 microns. For the dust emitted through the roof this is more than 50%.

In scrap based mini-mills main GHG emissions are from electric furnace (45%), finishing and rolling (36%) and oxygen/power production (16%). In an electric arc furnace plant, besides carbon monoxide and carbon dioxide, dust is the main emission. Sixty percent of the dust particles are smaller than ten microns. Because polluted scrap is used, the dust contains heavy metals such as lead and zinc. Also copper, chromium, nickel, arsenic, cadmium, and mercury (Hg) are present. Small amounts of hex chlorobenzene, dioxins and furans are also emitted. Emissions of PAH depend on the coating material used, e.g. in the Netherlands PAH are not emitted, because tar-free materials are used for the coating. The total energy input for this process is between 2 300 and 2 700 MJ per Mg of steel produced, of which 1 250–1 800 MJ/Mg is from electricity. The oxygen demand is 24–47 m^3/Mg steel. Hot-rolling of slabs and non-flat products (billets) produces hydrocarbon emissions from lubricating oils. Preheating of material and annealing after rolling results in emissions of nitrogen oxides and carbon monoxide. When volatile halogenated organic (VHO) gas is used some sulphur dioxide will also be emitted. Pickling before cold rolling produces emissions of hydrochloric acid. Cold rolling gives emissions of hydrocarbons and decomposition products of lubricant oil. Gradual heating and cooling gives emissions of nitrogen oxides and carbon monoxide. Protection gas contains polycyclic aromatic hydrocarbons. In general, it can be said that emissions from rolling mills are small compared to the other emissions from the (integrated) steel plant.

There also large differences between CO_2 emission factors of steel making between world regions. This is due to differences in efficiency of the processes and fuel input and due to a different pace of penetration of new technologies [15].

The options to reduce CO_2 emissions have been identified in the following:

1. Shift from primary to secondary steel. The CO_2 emission factor of secondary steel is about 35% of that of primary steel. During recent decades the usage of secondary steel has been stagnated. This was due to the technological development in smelting, casting and processing that led to a decline of the amount of plants and circulating scrap. Primary steel is likely to remain the preferred material for many high quality products due to its lower content of undesirable residual metals. Furthermore, a shortage of high grade scraps may limit further growth of the mini-mill capacity. Plants that produce primary iron scrap-substitutes (e.g. direct reduced iron) are partly filling this gap while exhibiting CO_2 emission factors similar to the conventional blast furnace route. Due to the complexity of steel product categories and different scrap qualities the reduction potential of a shift from primary to secondary steel is hard to project.
2. Carbon dioxide recovery from blast furnace gas. Decarbonising blast furnace gas before use can be done at cost of US$35/tonne CO_2. Transportation and storage of CO_2 will add US$8-20/tonne CO_2 (at transportation distance of 100 km). in 2020 this could contribute 290 Mtonnes to the CO_2 emission abatement.
3. Improvement of energy efficiency by the introduction of new and emerging techniques. The main techniques in this category are smelt reduction and near net shape casting technologies. The specific energy consumption of an integrated steel mill incorporating all these new technologies can be 45% lower than current world average. Large efforts in the study of new techniques are being carried out in Europe in the framework of ULCOS [16]. ULCOS stands for Ultra-Low Carbon dioxide (CO_2) Steelmaking and is a consortium of 48 European companies and organisations from 15 European countries that have launched a cooperative research & development initiative to enable drastic reduction in CO_2 emissions from steel production. The consortium consists of all major EU steel companies, of energy and engineering partners, research institutes and universities and is supported by the European commission. The aim of the ULCOS programme is to reduce the CO_2 emissions of today's best routes by at least 50 percent. ULCOS proposed two new processes which

can play an important role in a grid fed by a large proportion of renewables: ULCOWIN process, also called electro winning, and iron ore ULCOLYSIS. Both technologies have already been shown possible at small scale and through the research carried out in ULCOS. In the ULCOLYSIS process, iron ore is dissolved in a molten oxide mixture at 1600°C. This unusual electrolyte medium is chosen in order to operate at a temperature high enough to be above the melting point of iron metal. The anode, made of a material inert towards the oxide mixture, is dipped in this solution. The electrical current is flown between this anode and a liquid iron pool connected to the circuit as the cathode. Oxygen (O_2) evolves as a gas at the anode and iron is produced as a liquid metal at the cathode. ULCOWIN is at a more advanced stage of development. A proposal has been made to further test this technology through additional scaling up of the process. The envisaged pilot plant would be able to produce a capacity of 5kg/day.

Four scenarios have been proposed in 2010 to assess the possible CO2 emissions in 2020. The scenarios are called: Frozen Technology, Moderate Change, Accelerated Change, Wonderful World. The scenarios differ in the development of energy efficiency per world region. This reflects differences in assumed diffusion of technologies over world regions. The CO_2 emissions projected according to these four scenarios are reported in Figure 2.

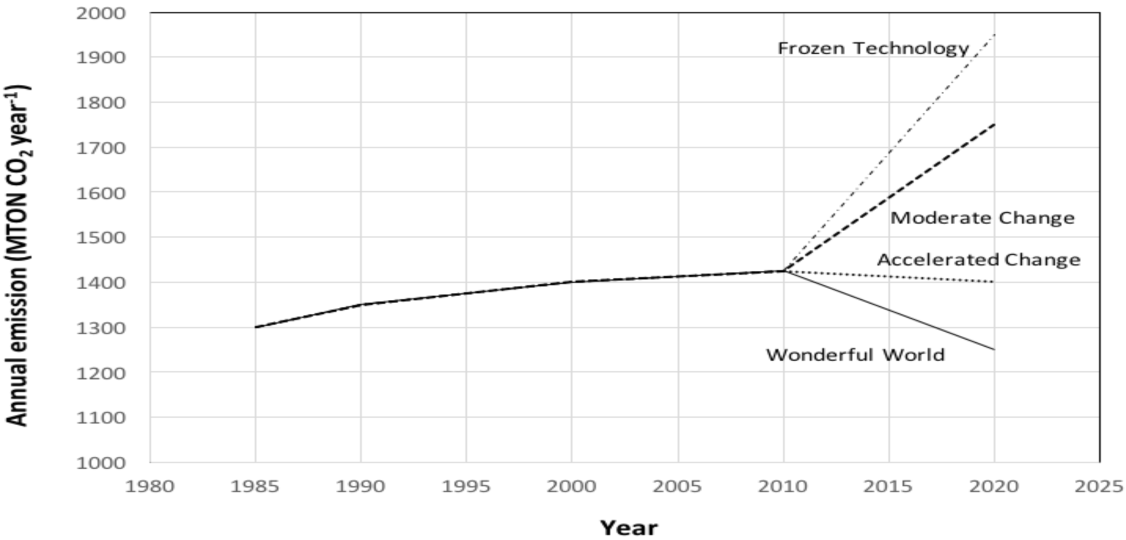

Figure 2. Projected global emissions for the four scenarios (data from [3])

The discussion should now address emissions to water and emissions to soil, but it will be kept very short. These issues have also been scrutinized at the end of the 20th century, regulated and carefully monitored, for example in Europe, so that problems have dwindled. Some European steel producers like to state that the water they discharge is cleaner than the water they take in and, anyway, recycling water internally in the steel mill has become the norm and, in the EU, the specific consumption of water of the steel industry is negligible compared to some other parts of the worldSoil pollution is mostly a legacy of the past, an archaeological signature of steel mills long shut down. As a matter of fact, soil and water table pollution went hand in hand at that time, but this has been long past [2].

4. Reduction of emissions in the steel industry

In the case of purifying furnace gases from open-hearth furnaces the effectiveness of dust removal units should not be lower than 99 %. That is why wet scrubbers, electrostatic precipitators or fabric filters are used for furnace gas dust removal. The wet scrubbers were the earliest to be applied for furnace gas dust removal from open hearth furnaces. They usually consist of two elements: dust coagulator and basic dust removal unit. The dust removal systems most often used in the case of open hearth furnaces are electrostatic precipitators. Their efficiency is very high and usually exceeds 99 %. Only in a few cases lower efficiencies (i.e. 94–98 %) are observed. However, obsolete equipment reduces cleaning efficiency to about 85 %. For flue gas cleaning at double-bath furnaces both wet and dry cleaning systems are applied. Dry systems are more widely used where gases are cooled and cleaned first in the waste heat boiler and in the scrubber and then in an electrostatic precipitator (Kakareka et al., 1998). Recently, fabric filters have been applied to the purification of furnace gas from open hearth furnaces. They allow an efficiency of 99 % or even higher, regardless of the dust contents in furnace gas. Nonetheless, they require an especially precise design and proper selection of technical parameters. For a basic oxygen furnace, primary dust abatement consists of a vapour cooler for separation of coarse dust and a washer for fine dust abatement. The secondary dust abatement is usually a fabric filter.

In an electric arc furnace, reduction of the emissions can be achieved by technological process changes as well as by abatement equipment. Varying the operating conditions or the design of the furnace may lead to a reduction in the amount of dust produced. Use of an 'after burner' reduces the amount of CO emitted. Use of equipment to capture the emitted particles, e.g. fabric filter or electrostatic precipitators (ESP), reduces the amount of dust emitted. Fugitive emissions can be reduced by placing the furnace in a doghouse (a 'hall') and using abatement equipment to clean the effluent from the doghouse. Table 2 lists the overall efficiency of several abatement technologies.

Table 2. Abatement technologies and their efficiencies for complete electric furnace steel plants (assuming good housekeeping).

Abatement technology	**Efficiency (%)**
Fabric filter	95
Electrostatic precipitators (ESP)	>95
Doghouse, suction hood and fabric filter	>99.5
Fibrous filter and post-combustion	>95

In rolling mills, hydrochloric acid from pickling is removed by a washing tower. Hydrocarbon vapours from rolling are captured by lamella filters. Production gas containing PAHs can be burned in afterburners.

Conclusions

In Europe there are declared targets of the European Community aimed to protect the environment and to improve its quality, to serve the protection of the human health and to guarantee a cautious and efficient use of the natural resources and steel companies are becoming increasingly aware about the sustainability challenges. In order to become a responsible corporate citizen, the industry has responded to these challenges through adoption of pillars of sustainability and identifying sustainability indicators specific for steel industry. In order to satisfy such requirements steelworks, need to increase their competitiveness through an adequate management of resource and energy. Steel production is in fact characterized by an energy (hence CO_2) intensive activity, as much of the production process takes place at high temperatures. Besides, iron ore is converted in metallic iron by using carbon as reducing agent. As global warming due to CO_2 emissions, steel production is considered one of today's main environmental problem and publications about the environmental impact of steel production mainly focus on reduction of energy use. This reduction of energy use is mainly achieved by important process measures, the reduction of material losses in the different production steps (also by looking at the use of steel slag as an opportunity to save natural resources) as well as of good housekeeping practices

References

1. J.P. Birat, *La Revue de Métallurgie*, (2004) 937-944.
2. J.P. Birat, *Metall. Res. Technol.* 112 (2015) 206-212.
3. J.P. Birat, *Metall. Res. Technol.* 113 (2016) 201-207.
4. A. Di Schino, P. Di Nunzio, *Mat. Lett.* 186 (2017) 86-89.
5. G. Napoli, S. Mengaroni, M. Rallini, L. Torre, A. Di Schino, *Metalurgija* (2017) 56 337-340.
6. C. Zitelli, S. Mengaroni, A. Di Schino, *Metalurgija*, 56 (2017) 326-328.
7. A. Di Schino, L. Valentini, J.M. Kenny, Y. Gerbig, I. Ahmed, H. Haefke, *Surf. and Coat. Tech*., 161 (2002) 224-231
8. A. Di Schino, M. Barteri, J.M. Kenny, *J. Mat. Sci. Lett*., 22 (2003) 1511-1513.
9. A. Di Schino, C. Guarnascelli, *Mat. Sci. Forum* 638-642 (2010) 3188-3193.
10. S. Mengaroni, F. Cianetti, M. Calderini, E. Evangelista, A. Di Schino, H. Mc Queen, *Acta Physica Polonica*, 128 (2015) 629-632.
11. A. Di Schino, J.M. Kenny, M. Barteri, *J. Mat. Sci. Lett*., 22 (2003) 691-693.
12. A. Di Schino, P.E. Di Nunzio, *Acta metallurgica slovaca*, 23 (2017) 62-71.
13. World Steel Association, *Raw Materials Improvement Report*, ISBN: 978-2- 930069-72-2, 2014.
14. R. Ceccolini, U. Martini, S. Rinaldi S. Mengaroni, S. Neri, A. Di Schino, *J. Mat. and Environmental Science*, 8 (2017) 2403-2408.
15. A. Hasanbeigi, M. Arens, L. Price, Renew. Sustain. Energy, 33 (2014) 245-248.
16. www.ulcos.org

(2018) ; http://www.jmaterenvironsci.com