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Process integration analysis and some economic-environmental implications for an innovative environmentally friendly recovery and pre-treatment of steel scrap

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HIGHLIGHTS

- A method combining preheating and surface rinsing of coated steel scrap is explained.
- The recovery of valuable raw material (e.g. Zinc) is one of the main objective.
- Energy and chlorine containing plastic waste such as PVC is used as a resource.
- A flowsheet simulation and optimization of the involved processes have been realized.
- The method has been analyzed also from an environmental and economic perspective.

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ABSTRACT

The use of Zinc-coated steel (e.g. galvanized steel) in melting cycles based on Electric Arc Furnaces can increase the production of harmful dust and hazardous air emissions. This article describes a novel process to simultaneously preheat and remove the coating from the scrap surface before the melting phase. The zinc in coating is removed in the gas phase by chloride containing syngas combustion and collected in a dedicated recovery system. Two possible innovative process routes are described, which involve plastic waste pre-treatment, shredded plastic gasification/pyrolysis, steel scrap preheating and zinc recovery processes. The routes have been modeled in an integrated flowsheet, in order to allow a comprehensive simulation and optimization of the pretreatment processes. The process optimization results in possible energy savings of over 300 MJ/t of preheated scrap charged in the Electric Arc Furnace for steel production. Moreover, a comparison among different scenarios according to economic and environmental criteria has been carried out.

1. Introduction

Steel scrap is a valuable raw material for the steel industry, especially for the electric steelmaking route: its recycling reduces the need for iron ore extraction, significantly reducing CO_2 emissions, energy and water consumption as well as air pollution [1]. In 2013 the percentage of the crude steel produced in the EU-27 through Electric Arc Furnace (EAF) is 39.8% with a production of about 66 Mt steel [2]. In order to increase its resistance to corrosion, steel is sometimes subjected to a galvanization process, resulting in the creation of a Zinc coating on its surface. At the end of its life cycle, when it is recycled as scrap into the EAF, galvanized steel is contaminated by Zinc and organics creating harmful or toxic elements that contaminate the EAF dust (EAFD) which is therefore considered as hazardous waste. Originally, the EAFD was landfilled as a waste from EAF process and no metals were recovered: in recent years, following regulations on waste management and an increasing cost for landfilled wastes due to a shortage of landfill areas, the percentage of dust put into landfill has been reduced [3]. An alternative to the landfill process is to further process the EAFD in order to recover and recycle metals. In the literature, there are some studies where the EAFD has been used for cement and concrete industry and, recently, EAFD has been

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Nomenclature

Abbreviations

AP	acidification potential
ASR	automotive shredder residues
BF/BOF	blast furnace and basic oxygen furnace
COSS	Continuous Optimized Shaft System
CO_2	carbon dioxide
EAF	Electric Arc Furnace
EAFD	Electric Arc Furnace Dust
EP	Eutrophication Potential
FAT	Freshwater Aquatic Ecotoxicity
GOB	Good Ordinary Brand
GWP	Global Warming Potential
HCl	hydrochloric acid
HU	Human Toxicity Potential
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LHV	Lower Heating Value
MAT	Marine Aquatic Ecotoxicity
PE	Polyethylene
PI	Process Integration
PlastSep	Plastics Pre-treatment process developed by Stena Metall A/S
POCP	Photochemical Ozone Creation Potential
PVC	Polyvinylchloride
SHG	Special High Grade
SLF	Shredder Light Fractions
TE	Terrestrial Ecotoxicity Potential
TSCRAP	Ton of Steel Scrap
VW-SiCon	Plastics Pre-treatment process developed by SiCon Gmbh

Symbols

C_O	operating cost
C_E	energy cost
C_{RM}	raw material Cost
C_{LB}	labor cost
C_{LD}	waste landfill cost
C_{INT}	interest cost
C_{INS}	insurance cost
C_{inv}	investment cost
C_{MAINT}	maintenance cost
C_s	savings and revenues
C_t	net total cost
r	discounting rate

Subscript

LS	liquid steel
n	time
t	ton
tot	total

evaluated as a filler material into a polymer matrix, in order to obtain a heavyweight sheet useful as acoustic insulation supplement in building envelopes [4,5]. By the way, currently, different pyro-metallurgical processes such as Waelz Kiln, Rotary Hearth (RH) or Shaft Furnace are the mostly applied technologies for the recycling of dusty steel mill residues. In [6], the Waelz Kiln and the RH have been compared by an exergy analysis, taking into consideration different operational modes of the processes and where the amount of Zn (wt%) in the treated dust, different product qualities for the RHF process and the inclusion of the Waelz Slag as a useful product were considered as the most important variables. The most common treatment process of EAFD today is the Waelz Kiln, which represents 80% of the global capacity in the EU-27 [7]. The significant inconvenience of the Waelz process is that the Fe content (and the valuable Ni) of the residues cannot be re-used in the steel industry. In the best case the Waelz slag is usable in road construction or cement production [8]. Pre-treatment of scrap prior to its melting in the EAF is another way to handle the problem with the coated scrap [9]. In literature several pre-treatment methods are reported, such as electrochemically aided caustic leaching, but few concepts have reached industrial scale [10]. In this article an innovative stand-alone method which combines scrap preheating and surface cleaning is presented. Its basic principle consists in removing Zinc from the steel scrap prior to the steel recovery process (through EAF or BF/BOF), so that the formation of Zinc ferrites in the EAF is avoided. The energy and chlorine containing plastic waste such as PVC and SLF is used as a resource. The plastic is converted to a chlorine containing syngas which is burnt in a dedicated preheating shaft. Such a concept has been suggested and developed firstly in Sweden at Swerea MEFOS. The pre-treated and cleaned scrap is charged hot into the steelmaking furnaces giving direct savings of energy [9] and improving the energy efficiency of the scrap melting process [11]. European manufacturing industries, e.g. the steel industries, are nowadays facing such issues in order to maintain their competitiveness in the international panorama [12]. In such context, in order to achieve a fundamental understanding and a total insight of the processes, especially in complex industrial plants such as those ones which are commonly found in the steel sector, thanks to its holistic approach to process design, retrofitting and operation, Process Integration (PI) can be very helpful by providing also a practical support to decision makers [13]. PI represents a family of methodologies in which several parts of processes or whole processes are combined in order to face complex tasks such as resource conservation, pollution prevention and waste management [14]. The International Energy Agency has adopted the following definition for the PI: "Process Integration is the common term used for the application of methodologies developed for system-oriented and integrated approaches to industrial process plant design for both new and retrofit applications. Such methodologies can be mathematical, thermodynamic and economic models, methods and techniques" [15,16]. El-Halwaigi in [17] explains the activities involved in PI: task identification (the goal to be reached should be an actionable task), targeting, generation of alternatives (process synthesis), selection of the alternatives (mathematical optimization techniques can be used for select the optimum alternatives) and, finally, the analysis of the selected alternatives. Process analysis, process techniques and optimization are in fact the three key elements to obtain a comprehensive PI. Systematic methods based on mathematical programming and pinch analysis have been applied over more than 40 years in order to achieve improved energy and water integration [18]. Also advanced optimization techniques, combining flow-sheeting models and artificial intelligence [12] are very helpful in order to achieve both reduction of total energy [19] and natural resources conservation [20].

In the steel industry, process integration techniques have been applied several times. For instance, a PI approach based on mathematical programming, i.e. mixed integer linear programming (MILP) has been applied to illustrate the investment strategies for a typical European integrated steel plant toward positive energy and environmental effects [21]. Lundkvist et al. [22] use the PI in order to investigate the possibilities for recovering the materials by developing a system optimization model of the steel plants and integrating a dedicated material upgrading process in the system. In the management of industrial water systems some problems have been tackled by means of PI techniques, such as the water pinch analysis which has been extensively investigated by Wang and Smith [23]. Based on the PI, Thevendiraraj et al. [24] enhanced the water network of a citrus plant by minimizing the water consumption and wastewater generation and a reduction in the freshwater consumption and wastewater generation up to 30% has been demonstrated. Latest results in literature demonstrate that in some industrial applications the solutions extrapolated according to the PI techniques produce a significant reduction of water withdrawal by increasing the water recycle [25,26]. Recently, some developments in PI-based approaches have been carried out also by Klemes et al. which couples standard methodologies like Pinch Analysis with new ones, like heat and power integration or mathematical programming [27]. According to [28], the PI remains one of the keys to reach a sustainable use of resources.

When the optimization problems require to consider multiple counteracting objectives, among which a suitable trade-off is searched, multi-objective optimization techniques can be successfully applied [29]. PI can be also used in combination with Life-Cycle Assessment (LCA) in order to evaluate the environmental benefits beyond the process itself [30]. In the area of biodiesel production, Chouinard-Dussault et al. [31] proposed a framework and a quantitative analysis combining PI with LCA in order to track the GHG emissions: a key element in such framework is to consider at the same time the process-integration scenarios (e.g. process changes to optimize energy and mass flow) with analyzing the environmental implications of these scenarios. More recently, Kalakul et al. [32] proposed a new tool that includes process simulations and LCA as well as also some economic analysis in order to help the process developer to search for more sustainable design options efficiently and reliably. In order to improve the resource efficiency in chemical industries, Denz et al. demonstrated that the integration of flowsheet simulation and LCA is a valid support on the decision making [33]. In addition, tools such Life-Cycle Costing (LCC), Key Performance Indicators (KPIs) and system analysis are also important and functional methods for analyzing overall system effects in order to be aware of efficient use of the raw materials and energy as well as environmental pollution reduction [34,35]. In particular, LCC is also used together with LCA in order to analyze the economic performance "from cradle-to-grave" of a product or activity [36]. Many studies can be found in literature where both the analysis are carried out together even in very different contexts. Some examples can be found in the waste management sector [37,38], but also in the use of fuels for cooking in developing countries [39].

In the steel industry, economic and environmental effects of using scrap preheating and surface cleaning have been analyzed by Östman et al. [40] where it has been demonstrate that implementing surface cleaning leads to increased possibilities for recycling of otherwise non-recyclable material, as ASR (automotive shredder residues). This paper presents new processing technologies investigated within the research project "Processes and technologies for environmentally friendly recovery and treatment of scrap" (PROTECT), which has received funding from the Research Fund for Coal and Steel (RFCS). Such technologies represent an example of implementation of innovative techniques to fully and profitably exploit by-materials within the integrated steelmaking route without negatively affecting the environmental impact of the production.

The analysis carried out has demonstrated the technological as well as economic/environmental feasibility of an innovative process to pre-treat steel scrap with several advantages treated in the body of the article. Such advantages are mainly related to:

- The recovery of otherwise unusable waste (ASR).
- Its conversion into energy as well as a valuable feedstock (substituting HCl).
- Full exploitation of zinc-coated scrap for steel production.
- The recovery of a valuable by-product (Zinc).
- A considerable energy saving for steel production represented by steel scrap preheating.
- Further possibilities for process integration deriving from possible future heat recovery in gasification/pyrolysis and scrap preheating.

In particular, this article presents the results of a holistic process flowsheet simulation, coupled to LCC and LCA in order to assess the potential for process integration (plastic utilization for preheating purposes is not currently implemented in electric steelmaking). The process models allowed to evaluate the feasibility of integrating different processes, already existing as standalone, with the new purpose of simultaneous steel scrap pre-heating and surface cleansing, prior to charge in the EAF – from a technical as well as an environmental and economic perspective.

The paper is organized as follows: Section 2 describes the technical aspects of the involved processes and the criteria used for the economic and environmental evaluation; Section 3 is dedicated to the description of the results of the methodology developed concerning case studies obtained in the realized process models and their optimization, economic evaluation through LCC cost analysis, and the assessment of the environmental performances through LCA technology. Finally, some concluding remarks are provided in Section 4.

2. Materials and methods

The PROTECT project aimed at a technological, economic and environmental evaluation of innovative routes for scrap preheating and simultaneous surface cleaning prior to charge in Electric Arc Furnaces (EAF) as well as an assessment of its industrial scalability. The process, which has been piloted during the PROTECT project, is composed by the following steps:

- Chlorine-containing plastic waste is separated from other automotive residues and prepared (sorted, sized, mixed) for further processing.
- A low-pH, high-LHV syngas is produced either through gasification or pyrolysis (in dedicated facilities allowing to handle acid conditions).
- The syngas flows and burns in a scrap preheating shaft where zinc-coated steel scrap (common automotive scrap) has been charged. The gas simultaneously heats and reacts with the steel surface removing its zinc coating.
- Gas is removed from the top of the shaft and evolves through a patented cleaning process (EZINEX®) that enables to recover very high grade metallic zinc from the dusts.
- Preheated, cleaned scrap leaving the shaft is charged in EAF at a temperature of around 600 °C.

An overview of the different process steps is provided in Fig. 1, which reports a set of flowsheet blocks representing different process hierarchies (different process units aggregated within a dedicated flowsheet). The project consortium includes several research institutions, commercial companies and a steel producer (SSAB). The assessment has been carried out on two levels: on one hand, a process simulation has been carried out in order to evaluate best process configuration, operating parameters and feedstock materials; on the other hand, an environmental impact assessment with the related economic implications have been

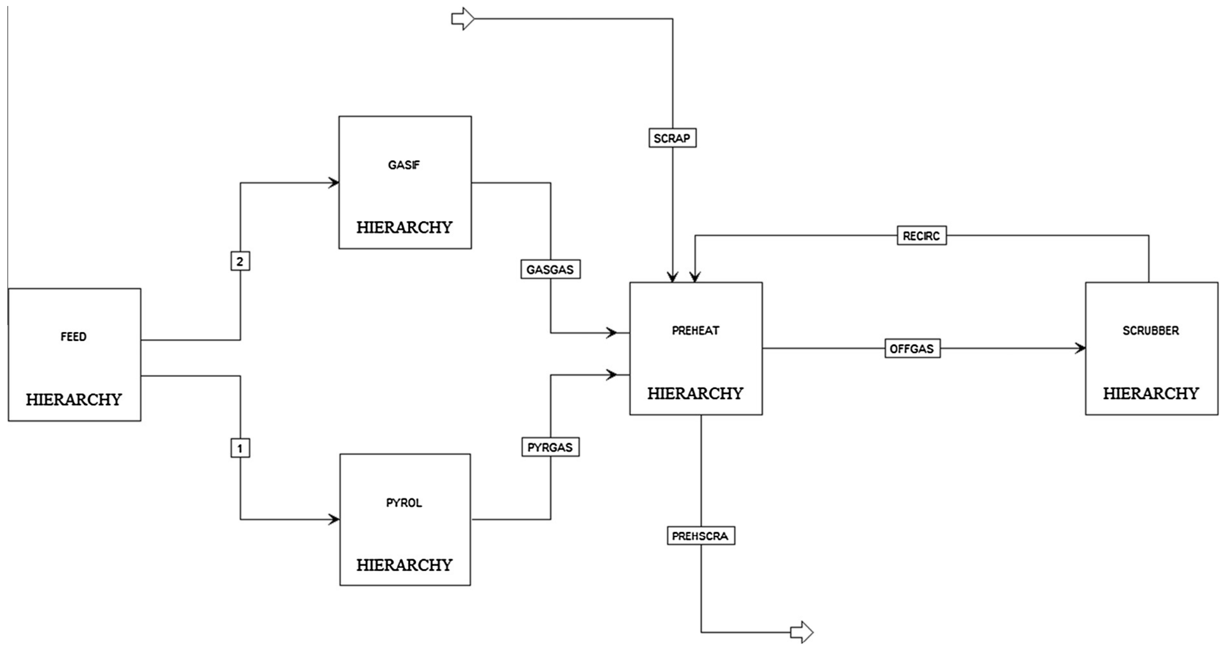

Fig. 1. Flowsheet of the overall PROTECT process modeled through Aspen plus®.

carried out. A description of the theoretical approach applied within the PROTECT project is given in the following sections.

2.1. Process models

All the involved processes have been modeled trough the software Aspen Plus®. Flowsheeting models have been realized for all the sub-processes involved in the feedstock and scrap processing, and zinc recovery from the flue gas. The models have been interconnected in a general flowsheet (shown in Fig. 1) in order to carry out simulations that enable to evaluate the processes in its completeness. The applicability of the software Aspen Plus® to the simulation of ironmaking and steelmaking processes have been demonstrated in previous literature: Schultmann et al. [41] demonstrated that flowsheeting-based simulation can support in decisions related to the recycling concepts in metal industry; Fröhling et al. [42] examined which recycling rate is optimal considering transportation planning measures and recycling rates; Porzio et al. [43] presented an approach to the realization of a software system capable to generate internal report and simulate the process plants behavior in different conditions. The software has been used also for the simulation of water treatment and biomass processes [44] and as an opportunity to evaluate different PI-based solutions and scale-up potential [45]. Moreover, as far as the work described in this article is concerned, Aspen Plus® has been used to join and combine within a same "virtual" location different technologies, which pilot plants are located in different European countries. The fundamental blocks in the flowsheet model of the PROTECT processes are: a plastic feedstock handling block, two parallel blocks reproducing plastic gasification/pyrolysis, a preheating shaft block and a block representing gas scrubbing and zinc recovery system.

2.1.1. Feedstock handling

The simulation and modeling work started from the exploitation of the laboratory analyses carried out by the industrial partners in order to feed the Aspen® simulations with a material flow that closely reproduced the actual incoming stream: different feed materials have been treated as nonconventional components (e.g. tires, shredded granules + heavies, Shredded Light Fraction – SLF), and sent to RYield blocks that are responsible for the conversion of the material flows into their constitutive chemical elements. The conversion is made based upon experimental measurements of the feedstock composition in terms of ultimate and proximate analysis, coming from SiCon GmbH that developed the feedstock preparation and handling process. A selector block then allows to choose among different feeds to be sent to syngas production through gasification/pyrolysis; the stream is duplicated in order to supply both with the same inlet composition and flowrate. The flowsheet of the feedstock handling section is shown in Fig. 2.

2.1.2. Plastic gasification

The gasification model has been realized taking as a reference the pilot plant located at Siegen University, by exploiting experimental data conducted at 700 °C, 800 °C and 900 °C with steam as gasification medium and nitrogen as inert carrier gas. The Aspen Plus® gasification flowsheet, described in detail in [46], is composed by a combination of equilibrium and separation reactors that estimate the syngas yield and composition in different operating conditions and processing different plastics. Fig. 3 shows a schematic description of the gasification model flow sheet which has been already described in [46]. Every reactor represents a different reaction zone in the gasifier, which is identified by different temperature level and reactants (e.g. steam). The results from the simulation of the plastic gasification process have been validated through comparison with experimental data from a lab-scale reactor, showing a good agreement between the simulation results and the experiments.

2.1.3. Plastic pyrolysis

The pyrolysis model has been realized by exploiting the experimental results provided by Stena Metall. In the experimental setup microwave energy has been used to supply the processes with the necessary heat for the pyrolysis reactions to take place; however, since the full-scale process is foreseen to get the

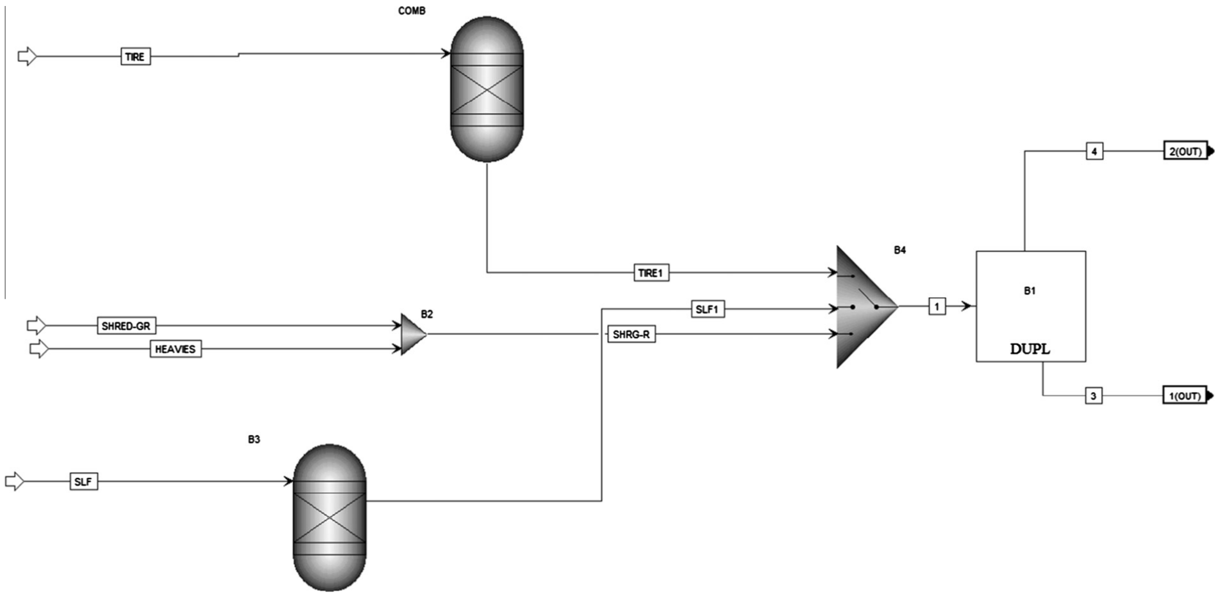

Fig. 2. Flowsheet of the PROTECT plastic feedstock processing section.

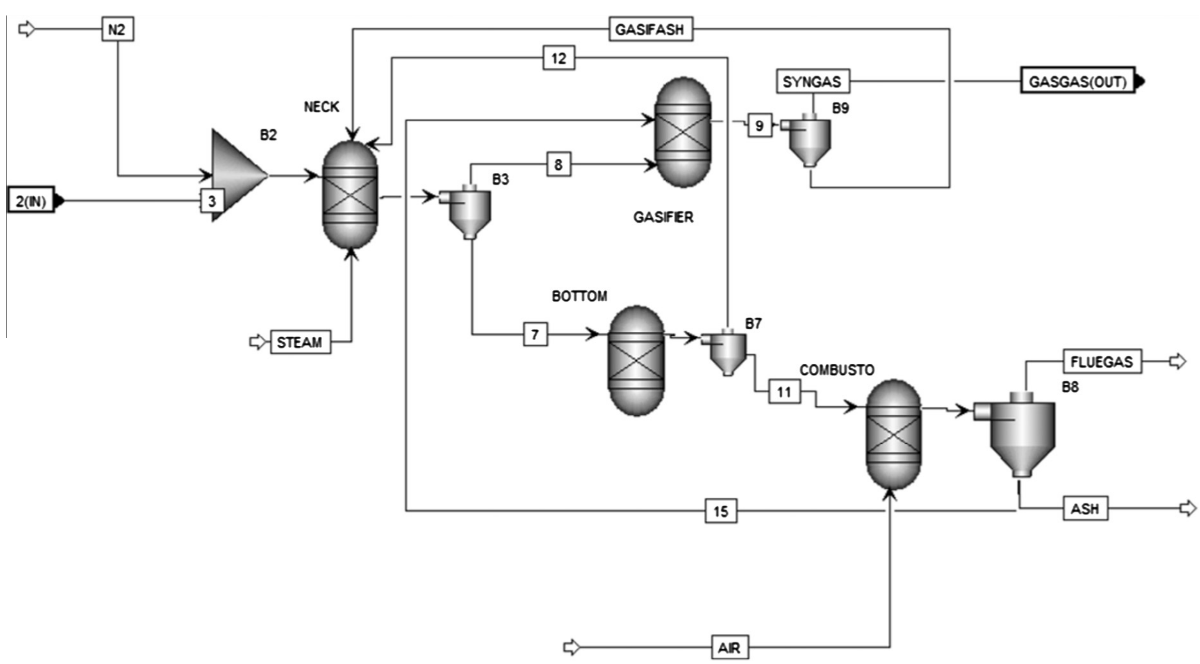

Fig. 3. Gasification model by through Aspen plus® [46].

necessary energy by burning part of the process gases, a hypothetic layout representing such a situation has been chosen for implementation in the Aspen® model (Fig. 4). In this case, an equilibrium model reactor is put in series with a stoichiometric reactor in order to simulate the isothermal conversion of the fuel into a liquid and gaseous fuel and a solid residue without addition of air. In the modeled system it is assumed that the microwave energy provided to the pyrolysis reactor is converted to heat, which is supplied to the equilibrium reactor. Products are separated in order to separate ash from fuels and recover oil from the gas stream that is sent to the preheating shaft.

2.1.4. Scrap preheating shaft

The preheating shaft model has been realized following the layout of a pilot plant by SWEREA MEFOS in Lulea, Sweden. This model section is the heart of the whole process simulation, linking all the other parts together. Propane gas (necessary to sustain the combustion reactions) is supplied to an adiabatic reactor together with oxygen, syngas from either pyrolysis or gasification and a recycled gas stream from the scrubbing section. Combustion takes place in an equilibrium reactor (where the steel scrap is brought to its preheating temperature), and the scrap preheating and simultaneous zinc removal is operated by means of the HCl content in the syngas in a stoichiometric reactor according to the reaction:

$$ZnO + 2HCl \rightarrow ZnCl_2 + H_2O \quad (1)$$

The preheated scrap is then separated from the gases, and the former is sent to the EAF, while the latter proceed to the gas scrubbing and Zinc extraction sections. A flowsheet of the preheating shaft section is shown in Fig. 5.

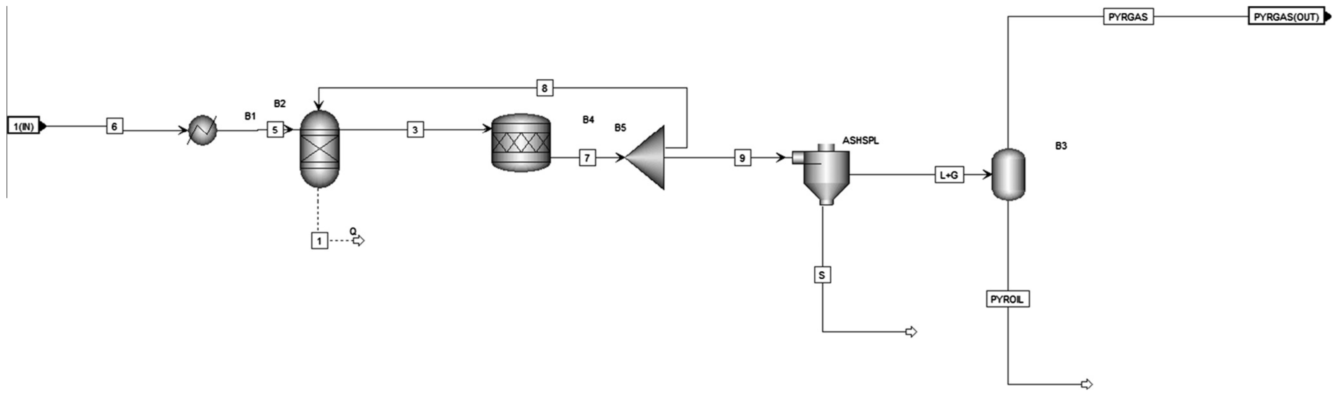

Fig. 4. Flowsheet of the PROTECT plastic pyrolysis section.

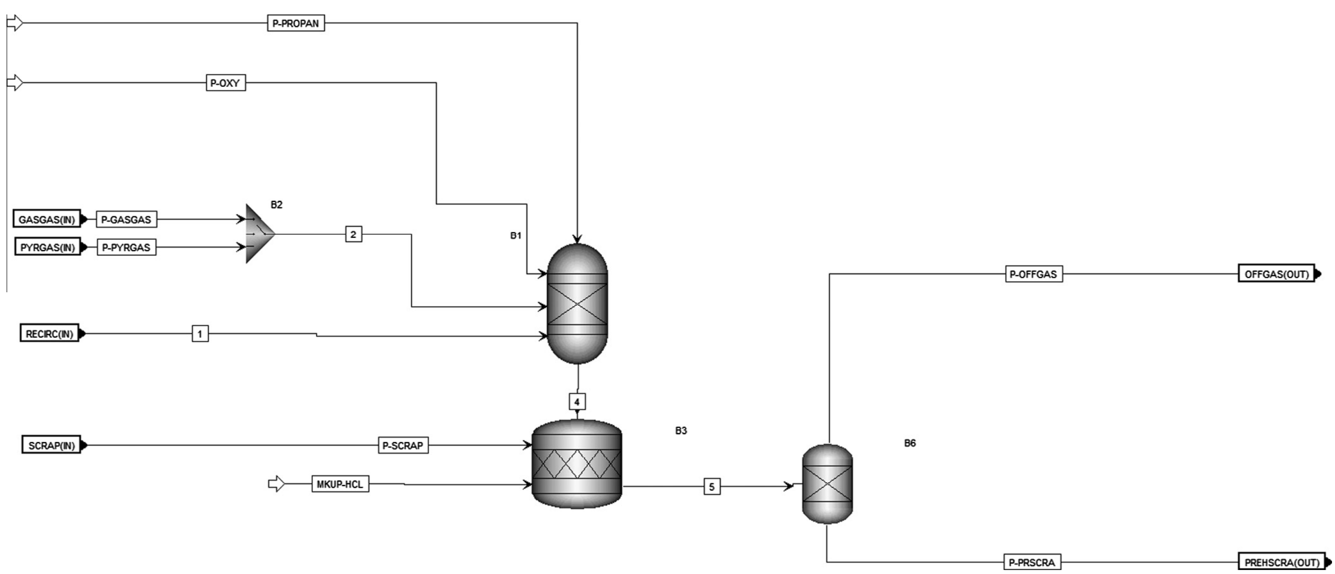

Fig. 5. Flowsheet of the PROTECT scrap surface cleansing and preheating section.

2.1.5. Scrubbing and zinc recovery section

The scrubbing process is based upon the Ezinex® technology developed by Engitec Technologies S.p.A.: its flowsheet is shown in Fig. 6. Following gas washing and solution neutralization in the scrubber, the next step is a further neutralization where Sodium Chloride (NaCl) is formed together with Zinc complex according to the reactions:

$$ZnCl_2 + 2NH_4Cl + 2NaOH \rightarrow 2H_2O + 2NaCl + Zn(NH_3)_2Cl_2 \quad (2)$$

$$4NH_3 + 2H_2O + 1/2O_2 + 2FeCl_2 \rightarrow Fe_2O_3 + 4NH_4Cl \quad (3)$$

A solid residue is then separated and the liquid flow sent to a single stage cementation reactor. The main cementation reactions can be written as:

$$PbCl_2 + Zn + 2NH_3 \rightarrow Pb + Zn(NH_3)_2Cl_2 \quad (4)$$

$$ZnO + 2NH_4Cl \rightarrow H_2O + Zn(NH_3)_2Cl_2 \quad (5)$$

Solids are washed once again in order to recover valuable by-products, while the liquid stream proceeds to the subsequent electrolysis and crystallization stages. In the electrolysis the Zinc solidification and deposition on the anode takes place, as well as some dissociation of Ammonia into gaseous Hydrogen and Nitrogen:

$$Zn(NH_3)_2Cl_2 + 2/3NH_3 \rightarrow Zn + 1/3N_2 + 2NH_4Cl \quad (6)$$

$$2NH_3 \rightarrow N_2 + 3H_2 \quad (7)$$

whereas in the crystallization step water is evaporated to produce steam and the concentrated salt sludge is sent to a centrifuge for extraction of NaCl (with about 3% residual moisture). The weak solution is circulated back into the leaching reactor and goes through the subsequent steps of the process in order to enhance the zinc recovery efficiency. The described process allows a very efficient recovery of zinc, which can be sold on the market: it has in fact been estimated that the Good Ordinary Brand (GOB) grade Zinc – or higher quality – is recoverable, with a yield of almost 100%. According to the EN 1179/2003, Special High Grade (SHG) has a 99.995% of zinc purity and GOB has a lower grade of 98.5% Zinc [47].

2.2. Cost analysis and environmental impacts

An environmental and economic evaluation has been performed in order to understand the viability and the feasibility of such new innovative stand-alone method and to compare the obtained results with the current benchmark technologies.

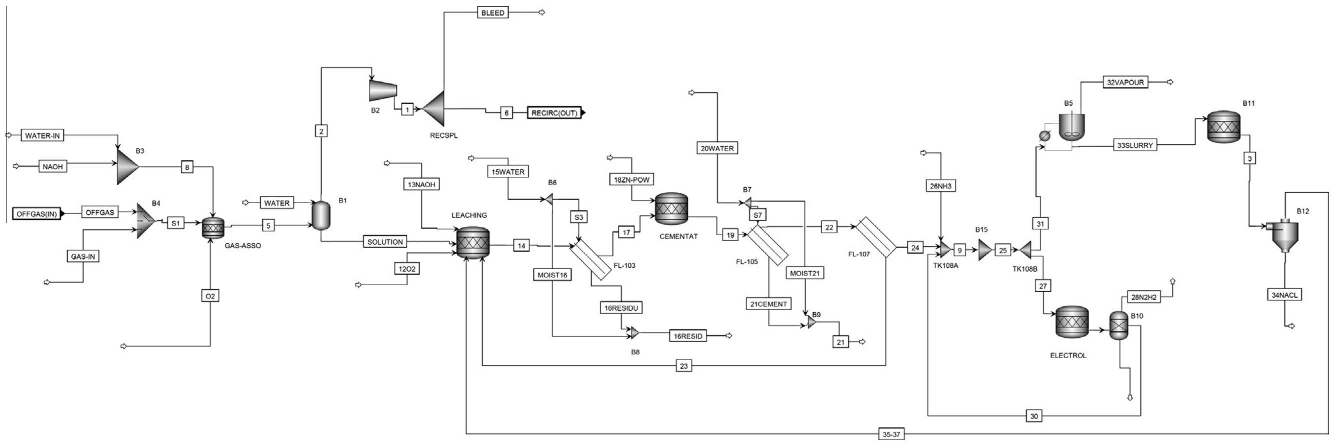

Fig. 6. Flowsheet of the PROTECT scrubbing and zinc removal section.

From an environmental point of view, the production of different products, materials, and services is often very complex and may involve many different activities in the society such as extraction of raw materials, operation of production plants, power generation and transports. Due to this complexity, it can be difficult to calculate emissions and energy consumption in a relevant way for an entire production system. The complexity may increase when various production systems are compared, or when different process changes have to be evaluated and assessed. A system is a unit that consists of different parts working together. By applying a system perspective, i.e. taking the entire system into account, one can get a better and more accurate picture of the production system and one can for example avoid sub-optimization. For example, when evaluating a process in terms of energy and environmental aspects it is important not to evaluate only the production process but also ensure that the environmental load does not increase due to e.g. increased up streams activities prior to the process or change in raw materials. Analyzing production systems rather than individual production processes make higher demands on the methodology and the implementation. A logical and structured methodology and a well thought-out analysis are required. Computer based calculations and models are also required. For this type of system analysis, the most common method is Life Cycle Assessment (LCA) exploiting a specified software called KLC-ECO [48] which allows to consider broader system boundaries. The LCA method offers a fully developed and standardized method with available computer software platforms and moreover it is a comprehensive tool comprising many different environmental aspects. In this way, a full coverage of the different process system can be achieved and the dynamics of the system can be investigated and the potential of the different process systems can be studied.

In an environmental evaluation, the different processes have been converted in a mathematical representation covering both process and environmental modeling, all in a system perspective. The models comprise the entire process from the steel scrap to the finished metallic zinc and iron products including the new generated slag and waste. The models include raw materials, energy and emission. The electric power used in the models is based on an OECD electric power production mix to reflect the market area for the process alternatives. In addition to this, several other functions are also included in the evaluation such as zinc losses and iron losses. The economic evaluation has been performed through the calculation of some financial and economic indicators as for example the Life Cycle Cost (LCC). Not only a rough estimate of the capital required for the initial investment and the installation has been carried out, but also a LCC analysis which includes the costs during a predefined time of period. In such evaluation the main important costs that have been taken into consideration can be divided into three groups: the investment cost (i.e. all cost related to the feasibility, engineering and development), the fixed costs and the operating costs (i.e. all the costs related to the production and implementation). Decommissioning costs are not considered as no data were available. The time value of money has been included and the net Present Value method has been used for the estimation of the future costs, according to the following equation [38,49,50]:

$$\mathrm{LCC_{tot}} = \sum_{t=0}^{t=n} C_t \times (1+r)^{-t} \tag{8}$$

where C_t is the estimated total costs at time t, n is the economic life of the core process facility considered in the analysis, r is the discounting rate. The present value of the estimated cost annually has then multiplied by a yearly factor as follows [38]:

$$\mathrm{LCC_{year}} = \mathrm{LCC_{tot}} \times \frac{r}{(1-(1+r)^{-n})} \tag{9}$$

where n is the economic life of the core process facility and r is the discounting rate.

The categories considered in the LCC analysis are:

- investment amount;
- fixed costs;
- operating cost.

The fixed costs are estimated to be as percentages of the initial investment as below:

- interest (1% of the Investment);
- insurance cost (1% of the Investment);
- maintenance cost (3% of the Investment).

The calculation are calculated as follows:

$$C_F = C_{\mathrm{INT}} + C_{\mathrm{INS}} + C_{\mathrm{MAINT}} \tag{10}$$

where C_F is the fixed costs, C_{INT} is the interest cost, C_{INS} is the costs of insurance, and C_{MAINT} is the cost of maintenance. The operating costs are calculated as:

$$C_O = C_E + C_{\mathrm{RM}} + C_{\mathrm{LB}} + C_{\mathrm{LD}} \tag{11}$$

where C_O is the operating costs, C_E is the cost of energy consumption, C_{RM} is the cost of raw material, C_{LB} is the labor cost, C_{LD} is the cost of waste landfill.

The net total cost is then calculated according as follows:

$$C_t = C_{\text{inv}} + C_F + C_O \tag{12}$$

where C_t is the net total costs at the time t, C_{inv} is the investment cost and C_s is the savings and revenues. The data used for the developed scenarios in the LCC calculation are the same as the ones used for LCA.

3. Results and discussion

All process models described in Section 2.1 have been validated separately through comparison with the experimental results of live experiments carried out within the PROTECT project. Validation of the gasification model results has been described in [47]. The separate process models have then been connected into an overall process flowsheet allowing to simulate the overall process. Although the process as a whole does not exist in practice, and therefore the overall simulation results cannot be validated directly, the exploitation of appropriate chemical and physical properties libraries included in the commercial flowsheet simulation software Aspen Plus® allows to consider the results of the holistic process flowsheet with a high degree of confidence. The comprehensive flowsheet simulation constitutes therefore a valid tool to evaluate process performance and scale-up potential, as described in the case studies that follow.

3.1. Case studies

Several case studies for the pre-treatment plant have been carried out based on realistic scenarios in order to assess the validity of the proposed models. The selection of such cases allowed to feed the simulation with a consistent set of input variables: all the values of the input variables for the case studies are reported in Appendix A. The resulting combinations of I/O variables from these case studies were then exploited to assess the performances of the proposed technologies. The case studies referred to the production of 50 t of hot scrap as output, mainly varying the input plastic mix (Polyethylene, PE, Polyvinylchloride, PVC, and SLF). The varied factors have been Zn in the incoming scrap, outgoing scrap temp, and ingoing plastics mixture: % PE, % SLF, and % PVC varied in fact significantly. The experiments have been first carried out considering pure PVC, then SLF, then PE, followed by different mixtures of the three plastics (note in particular that the plastics differ for their chlorine content as well as heating value, as shown in Table 1).

The preheated scrap outgoing temperature has been set in all cases to 600 °C, except for four cases where it has been increased to 700 and 800 °C. All the outputs were calculated exploiting the process model, focusing in particular on the following:

- Mass of cold scrap.
- Mass of plastics required to supply the necessary heat.
- Mass of makeup-HCl in case not enough chlorine is supplied by the plastics usage.
- Mass of CO_2 emitted from the process (gas scrubbing and zinc removal) processes.

The first result is relative to the consumption of makeup HCl in the preheating shaft. Such an addition is necessary in those cases where the hydrochloric acid carried within the syngas is enough to support the surface zinc removal reactions. In case a plastic with a high Cl content is processed (e.g. PVC, cases 1–4), there is no or little requirement for makeup HCl. The lack of Chlorine in SLF or PE (cases 5–12) is compensated by the addition of a make-up. If a mixture of the 3 plastics is considered, the high Cl-content in PVC results in an overall chlorine content of the feedstock plastic mixture that is sufficient to sustain the zinc removal reactions thus allowing not to use an additional chlorine source. The addition of makeup HCl/exploitation of the Cl incoming with the feedstock is also proportional to the Zn contained in the scrap to be processed. This behavior is visible in Fig. 7(a) (Zn in the incoming scrap and makeup HCl are both reported on the secondary axis): the calculated rate of zinc recovery from such a process shows an almost constant value for all cases (81.3% on average, min 80.2%, max 82.7%). Plastic consumption (that supplies the process with the energy required for preheating) is a function of the scrap temperature as well as feedstock heating values. From Fig. 7(b), clearly the higher the plastic heating value, the lower the requirement to reach the set scrap preheating temperature. If the scrap outgoing temperature is increased, the plastic consumption also shows an increasing trend (the set temperature has been modified to 700 °C and 800 °C).

The zinc-containing scrap is charged in batches of 50 t (the horizontal line in Fig. 8(a)), with varying amounts of zinc (and other materials) and a correspondingly variable iron content. The bars in Fig. 8(a) represents the amount of pre-treated scrap leaving the shaft, from which the Zinc has been removed and that also accounts for minor process losses. The hot scrap yield (pre-treated hot scrap mass/cold incoming scrap mass) ranges between 96.0% and 98.3%. Fig. 8(b) shows that the preheated scrap mass leaving the preheating shaft is inversely proportional to the Zinc content in the incoming scrap. A lower scrap mass for high zinc scrap (incoming Zn ranges between 0.75% and 3%) opens the possibility of pre-treating a higher amount of scrap while keeping almost constant the scrap amount that is loaded into the EAF (Fig. 2(b)).

Direct CO_2 emissions at stack from gasification reactor and preheating shaft show a complex pattern as shown in Fig. 9. Lowest CO_2 emissions are achieved in case 9 (0.65 t CO_2/batch), related to the combustion of PE as a fuel, no chlorine in the incoming plastic and the minimum amount of zinc in the incoming scrap.

The correlation between CO_2 emissions and the different input variables to the process is reported in Fig. 10, showing that the calculation of the direct CO_2 emissions at stack from gasification reactor and preheating shaft exhibit a complex pattern. A sensitivity analysis has been carried out showing that CO_2 emissions have a slight correlation with the plastic consumption as well as the plastic carbon content (~linear correlation, $R^2 = 0.55$ and $R^2 = 0.64$, respectively). In particular, the emissions show a direct proportionality with respect to the plastic consumption and an inverse proportionality with respect to the carbon content of the feedstock plastic. This latter result can be explained by the direct proportionality of the heating value with the carbon content in

Table 1
Ultimate analysis of plastics used within the case studies (all reported figures are a % of total composition unless specified differently).

	PE	SLF	PVC
C (%)	85.63	20.6	38.43
S (%)	0	0.2	0
N (%)	0	0.7	0
O (%)	0	7.6	0
Cl (%)	0	0.96	56.73
Ash (%)	0	67.14	0
H (%)	14.37	2.8	4.84
Moisture (%)	0	0	0
LHV (MJ/kg)	40	8.8	25

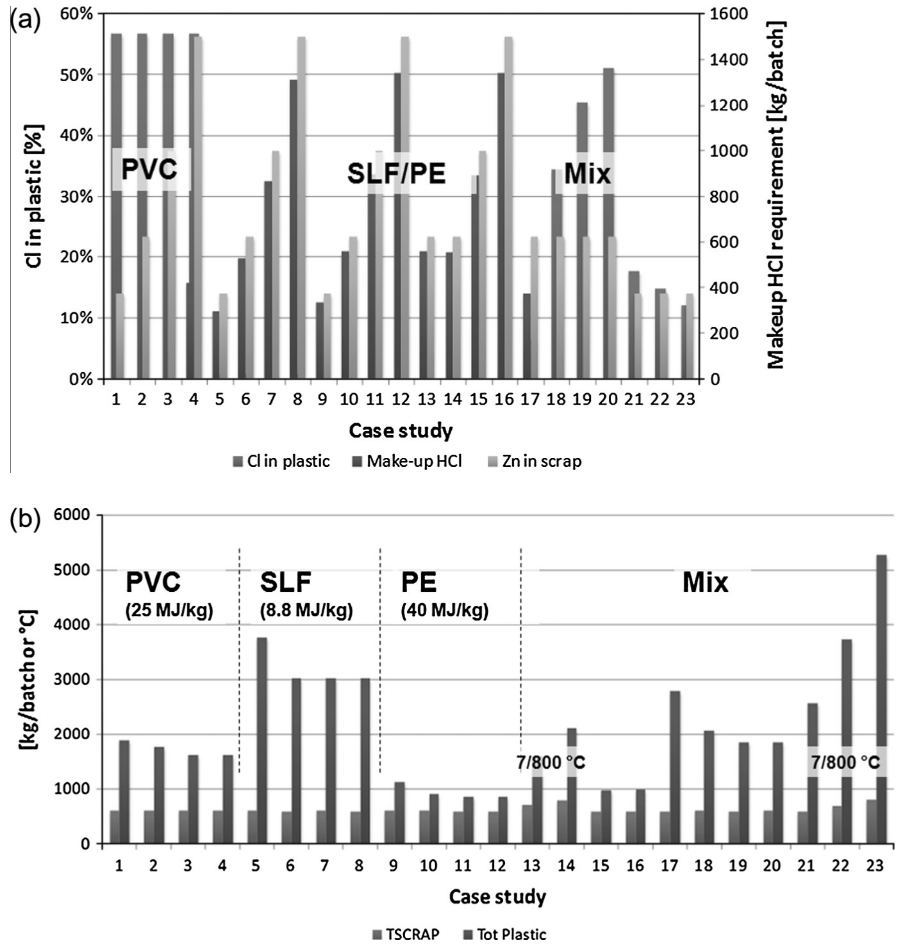

Fig. 7. Case study: Make-up HCl requirement and Cl content in plastics as a function of Zn content (a) and Plastic Consumption for the preheating process (b).

plastics, suggesting that the higher the % of C in the feedstock, the lower the amount of plastic that will have to be burnt in order to satisfy the process energy requirement.

3.2. Process optimization

Following the analysis of the case studies, a process optimization study has been carried out in order to estimate in a preliminary way the potential economic impact of a reduction in the gasification plastic feedstock on the scrap preheating temperature and makeup HCl consumption. The aim is to jointly minimize the consumption of plastic waste and the need of additional HCl, by maintaining an acceptable scrap preheating temperature level (at least 600 °C) in the case of syngas production through gasification and EAF steel production. The minimization of the production costs is in this case related to a single process alternative and is aimed at showing the process optimization capabilities of the developed simulation system. A more detailed economic analysis, taking into account different process alternatives and LCC parameters such as investment, fixed and variable costs, is reported in the following section of the paper.

The base case considered for the optimization is related to the consumption of about 49 kg/t scrap of a plastic mixture of 68% PVC and 32% SLF by weight, and already included the addition of a small amount of HCl (roughly 2.1 kg/t scrap). The temperature of the preheated scrap is around 790 °C. According to simulation results, the consumption of plastic waste can be cut down to 29 kg/t without violating the constraint on the temperature. In such a case, however, the consumption of HCl would be increased up to 9 kg/t scrap (450 kg/batch of preheating). The results in Fig. 11 also shows that in case the plastic was the only source of chlorine, an amount of at least 56 kg/t would be needed, potentially bringing the scrap to a temperature of almost 850 °C, close to the upper scrap temperature limit that has been set at 900 °C in order to avoid ignition of scrap surface. Since the model incorporated a limit at such temperature level, the calculation results for temperatures above 900 °C are not reliable (at 900 °C, the temperature stabilizes and increases for higher plastic consumption). Such an analysis is the basis for a potential economic evaluation. The variables used for the calculation of the cost function would then be the scrap preheating temperature, the plastic consumption and the makeup HCl consumption (assuming a constant yield of the Zinc recovery process). The function *f*(T, HCl, plastic) to be minimized can be written as:

$$f(\mathrm{T,HCl,plastic}) = \mathrm{HCl}\cdot\mathrm{cost_{HCl}} + \mathrm{plastic}\cdot\mathrm{cost_{plastic}} - \mathrm{energy\ saving(T)}\cdot\mathrm{cost_{energy}} \tag{13}$$

The minimization of such objective has been carried out considering a constant zinc yield and evaluating only the impact of the plastic consumption. The following assumptions were taken into account:

- Heat capacity for steel at high temperature taken [51].
- EAF heating efficiency of 95%.
- Electric energy cost of 0.01 €/MJ.
- Plastic processing cost of 0.18 €/kg (including 0.07 €/kg from plastic shredding operating costs using the SiCon process, and 0.11 €/kg for the gasification operating costs) (see Table B.1 in Appendix B).
- HCl cost of 0.15 €/kg.

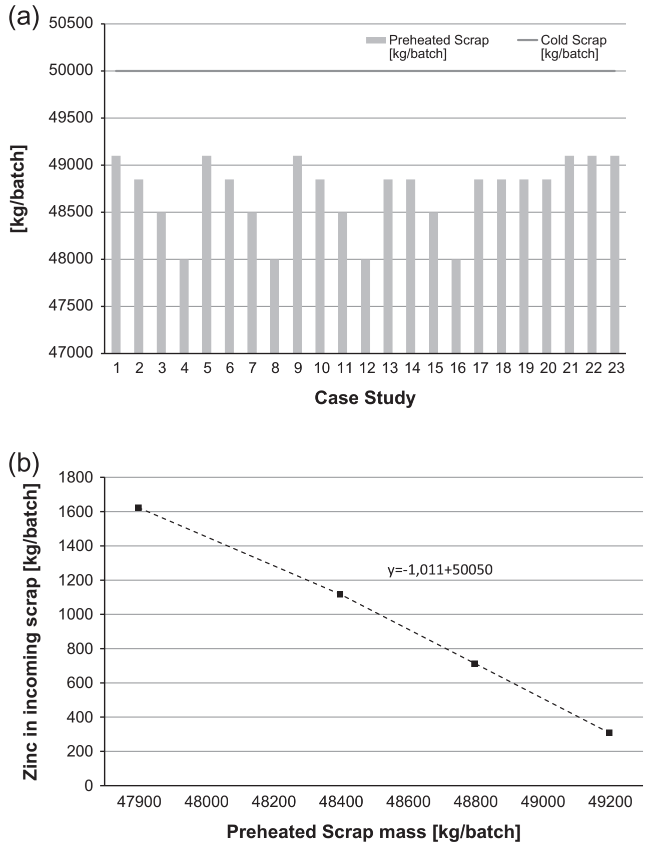

Fig. 8. Preheated scrap mass balance: preheated scrap mass balance with respect to the batch (a) and the relation between the preheated scrap mass and the Zinc incoming scrap (b).

The results from such an optimization are shown in Table 2. The achievable reduction in cost is of about 30% in relative terms, due to the combination of a 39% reduction in plastic consumption, a threefold increase in the HCl consumption and a reduction of the scrap preheating temperature by 22%. The energy saving in the EAF has been quantified for such scenario in about 320 MJ/t of preheated scrap. Such an optimization is obviously a parametric study; therefore its results strongly depend upon the cost values that are used.

3.3. Economic and environmental evaluation

The results obtained in the study of optimization have been a support to undertake economic and environmental analysis of these processes in a more wide context, that is the steelmaking sector and then applied them "theoretically" before an EAF or a BF/BOF. Decision-making of the process feasibility and viability is often based also on some economic and environmental measures and analysis [35]. In such analysis, a set of six scenarios have been investigated and compared:

- *References scenarios*:
  - Baseline 1: EAF with Waelz Kiln and sulfuric acid electrolysis (H_2SO_4) which are an example of EAF post-treatment.
  - Baseline 2: BF/BOF without Zn treatment, i.e. ordinary steel production with blast furnace.
- *Scenarios*:
  - Scenario 1: Gasification + Preheating Scrap + Scrubber (Gas Scrubbing and Zinc removal) + EAF.
  - Scenario 2: Pyrolysis + Preheating Scrap + Scrubber (Gas Scrubbing and Zinc removal) + EAF.
  - Scenario 3: Gasification + Preheating Scrap + Scrubber (Gas Scrubbing and Zinc removal) + BF/BOF.
  - Scenario 4: Pyrolysis + Preheating Scrap + Scrubber (Gas Scrubbing and Zinc removal) + BF/BOF.

As far as the baseline 1 is concerned, a sulfuric acid electrowinning has been used for Zinc metal production from Waelz oxide. The EAFD and other zinc containing materials are mixed with coal prior to the kiln. The materials travel down the kiln and are heated to reaction temperature by combustion gases from a burner at the discharge end. The Zinc ferrite is reduced to Zinc in the reduction zone of the kiln and then reoxidised to ZnO. The resulting so called Waelz oxide is rich in ZnO and can directly be sent to electrowinning of metallic Zinc. When possible and significant, a distinction between the two plastic pre-treatment processes has been made. The two plastic treatment processes are: the VW-SiCon process developed by SiCon GmbH (VW-SiCon) and the PlastSep process developed by Stena Metall AB (PlastSep). To be able to compare the different process alternatives, 1 t of liquid steel has been chosen as a functional unit that reflects the final product.

3.3.1. Economic analysis

Firstly, a comparison between the data of the current benchmark EAF and the data of the EAF applied in the Scenario 1 and Scenario 2 which exploit the scrap preheating has been performed. The estimation of the EAF savings is shown in the Table 3.

In fact, the preheated steel scrap can reduce the use of electric power for melting [3]. The higher the scrap temperature, the larger the energy saving. The above estimated reductions and the missing costs of the Waelz and H_2SO_4 processes included in the EAF baseline1 lead to a cost reduction of about 13% in the EAF steel production cost in scenarios 1 and 2 (of which 75% due to the preheating assumptions and the remaining 25% to the missing costs of the Waelz and H_2SO_4 processes). If the overall processes included in

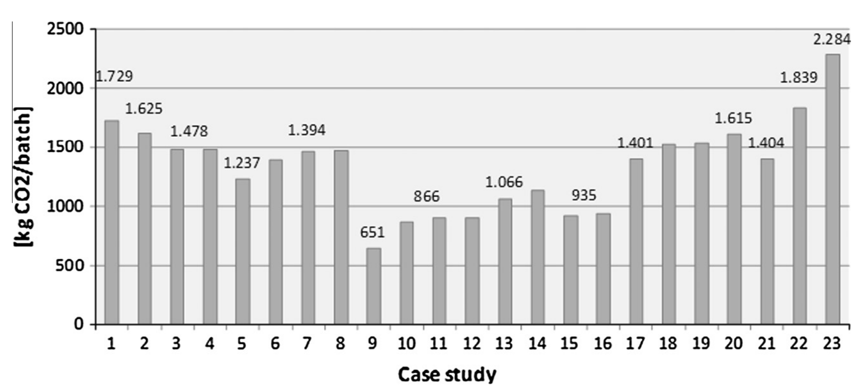

Fig. 9. Direct CO_2 emissions from the gasification + preheating.

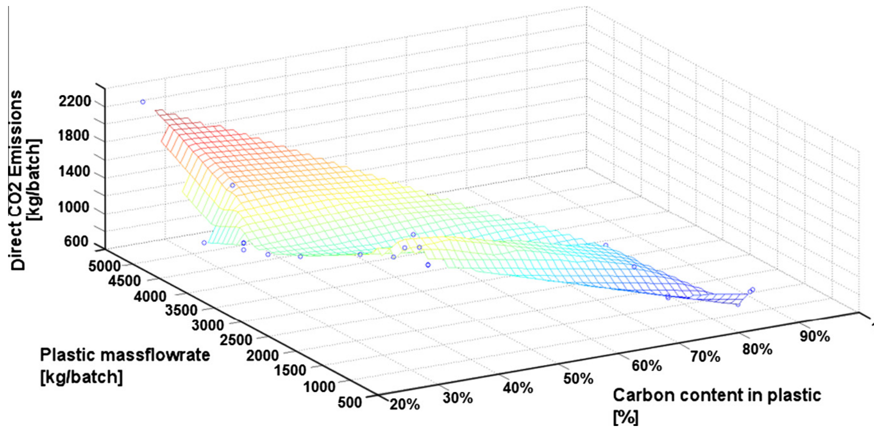

Fig. 10. CO_2 vs feed plastic flowrate and plastic carbon content.

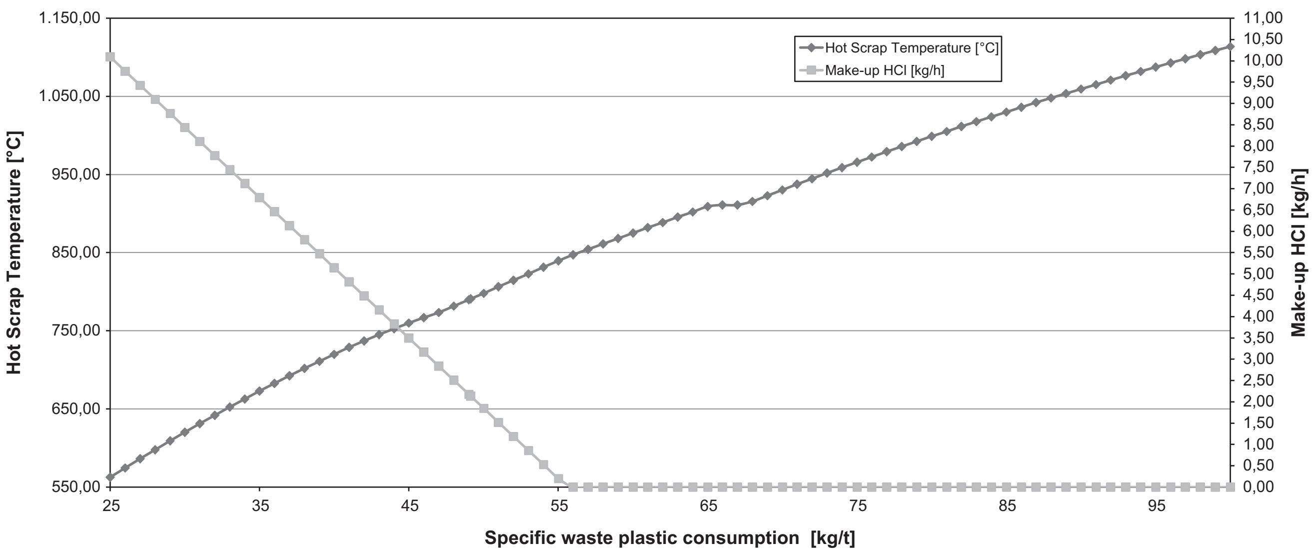

Fig. 11. Impact of waste plastic consumption on HCl makeup and scrap preheating temperature.

Table 2
Optimization results.

Variable	Unit	Case for optimization	Optimization result	Variation (%)
Final scrap temperature	°C	790.95	617.72	−22
Makeup HCl consumption	kg/t	2.13	8.50	+299
Plastic feedstock consumption	kg/t	49.14	29.80	−39.4
Incoming scrap mass flowrate	kg/t	1015.13	1015.13	–
Objective function value (cost)	(€/t)	€ 4.64	€ 3.24	−30.2

Table 3
EAF savings in Scenarios 1 and 2.

	UoM	EAF baseline 1	EAF (with scrap preheated) – Scenarios 1 and 2	Comparison and savings
Energy consumption	MJ/t_{LS}	1466	1092	−25% (an energy saving which is about 103 kW h/t_{LS})
Graphite electrodes	t/t_{LS}	0.003	0.0023	−24% (a saving of 0.72 kg/t_{LS})
Loaded scrap	kg/t_{LS}	1112	1041	−6% (a saving of 71 t/t_{LS})

the standalone method are considered, the saving of landfill cost due to the use of plastics wastes have to be accounted: such saving can be quantified in about 14% with respect to the baseline1 (by considering an average landfill cost of about 80 €/t [52]). If also the Zinc recovery is considered, such savings would further increase (up to about 20%). The comparison has been extended also to the state of the art of some scraps preheating technologies like Ecological and Economical Arc Furnace (ECOARC™) [53], Consteel® [54,55] and Continuous Optimized Shaft System (COSS) [56]. In particular, the vertical shaft scrap preheating systems are represented by ECOARC and COSS, while the only major horizontal shaft scrap preheating process today is represented by the Consteel process [57].

Consteel and Ecoarc are the most important technologies for direct heat recovery in the continuous scrap loading [58]. The ECOARC™ Technology is an Electric Arc Furnace with a scrap preheating system developed by JSP Steel Plantech Co [59]. It consists of a melting chamber and a preheating shaft, which are directly and rigidly connected together [60], thus it is possible to complete melting and at the same time a constant continuous scrap charge [61]. As a result, the efficiency is extremely high [62]. Consteel® has been developed some years ago by Tenova in Italy [57] following a different concept. Through such technology the scrap, continuously fed into the EAF, is loaded into a charge conveyor and pre-heated in a tunnel by process off-gas [54]. The Consteel® system technology allows to minimize the scrap movements as well as to keep under control bath temperature, scrap feed rate and scrap composition [56,59]. Some wider conveyors to augment the exchange surface, a different tunnel to increase the heat exchange and a new tunnel section equipped with burners are the main features of the evolution of the Consteel technology [63]. COSS technology is very similar to the ECOARC™ system [57]. This technology has been developed by Fuchs Technology AG and it combines the benefits of the CONSTEEL® process as well as the higher scrap preheating efficiency of the shaft furnace [64]. With respect to the Consteel technology, in the COSS system there is less maintenance cost as well as a reduction of the power off time and at the same time much higher scrap preheating temperature: such advantages assures very low conversion cost figures and an higher productivity [65].

For all the above listed three technologies, no technical data are available concerning the EAF, thus the hypothesis has been made that the EAF is identical to the one considered in PROTECT, which is however a quite strong assumption. The steel production cost of these three technologies have been computed according to literature results related to the estimated consumptions with respect to the EAF, as follows:

1. Consteel® technology:
- −20% of energy consumption [66];
- −20% of the amount to be put on disposal [66];
- −40% of the graphite electrodes consumption [59];
- +33% of the steel productivity [67].

2. ECOARCTM technology [66]:
- −51% of energy consumption;
- −40% of the amount to be put on disposal;
- −50% of the graphite electrodes consumption;
- +35% of the steel productivity.

3. COSS technology [68]:
- −32% of energy consumption;
- −45% of the amount to be put on disposal;
- −57% of the graphite electrodes consumption;
- −42% of the oxygen consumption;
- +20% of the steel productivity.

According to the above assumptions as well as the input data (e.g. prices of raw materials, energy, labor, etc.), the estimated cost savings are provided in Table 4:

After the comparisons among different EAF technologies, the LCC analysis for both baselines and scenarios has been developed: the reliability of the LCC analysis depends on the quality of the input data, thus variations in the input data can affect the results [69,70]. The operating basic assumptions are shown in Table 5.

As far as the BF-BOF route is concerned, the estimated assumptions are as follows:

- +25% of loaded scrap;
- +4% amount of consumption energy in case of gasification and −5% in case of pyrolysis;
- −6% of use of coal in case of gasification and pyrolysis.

Average estimates have been used for the capital expenditure necessary for the new technologies. The parameters which have been taken into consideration for an estimation of the investment cost are:

- VW-SiCon process (VW-SiCon): an average value of 5.5 M€ for about 25 kt plastic treated/year;
- Plastsep process (PlastSep): an average value of 2.5 M€ for about 10 kt plastic/year;
- Pyrolysis process: an average estimation of about 2 M€ for nearly 10 kt plastic/year [71];

Table 4
Comparison of cost savings among different EAF technologies.

Cost savings with respect to the baseline 1	Scenarios 1 and 2	Consteel	Ecoarc	Coss
(%)	−14% (−20% considering Zn recovery)	−12%	−15%	−14%

Table 5
The operating basic assumptions for the all scenarios.

	UoM	Baseline 1	Scenario 1	Scenario 2	Baseline 2	Scenario 3	Scenario 4
Annual steel production [% increase Vs benchmark]	Kt/year	600	666 [11%]	666 [11%]	2000	2000 [0%]	2000 [0%]
Operative time	h/year	8000	8000	8000	8000	8000	8000
Hourly steel production	t/h	75	83	83	250	250	250
Steel scrap consumption	kg/t_{LS}	1112	1041	1041	200	250	250
Recovered Zn [yearly production]	kg/t_{LS} [t/year]	12.06 [7200]	13.01 [8660]	13.01 [8660]	0	3.1 [6200]	3.1 [6200]
Amount of PVC (84%)	t/year [kg/t_{LS}]	0	22,171 [33.3] [68%]	18,001 [27.0]	0	15,980 [7.9] [68%]	12,980 [6.49]
Amount of SLF (16%)	t/year [kg/t_{LS}]	0	10,557 [15.8] [32%]	0	0	7620 [3.8] [32%]	0
Energy consumption	MJ/t_{LS}	1675	1484	1447	571	689	626
HCl to scrap reactor	kg/t_{LS}	0	0.00821	3.343	0	0.002	0.8027
Savings of plastics landfill cost	M€/year [$€/t_{LS}$]	0	2.6 [3.9]	1.4 [2.1]	0	1.8 [0.3]	1.0 [0.5]
Revenues from Zinc recovered	$€/t_{LS}$	20.6	22.1	22.1	0	5.6	5.6
Alkali salt cake and lead cake recovered	kg/t_{LS}	0	27.62	26.47	0	6.38	6.38

- Gasification process (without gas cleaning system, with an averaged LHV value of 25 MJ/kg, an availability of 75% and around 6600 operating hours per year): roughly 15 M€ for about 30 kt plastic/year in the EAF scenarios and 11.5 M€ for about 23.6 kt of plastics in the BF/BOF scenarios [72–74];
- Preheating Shaft process: 4 M€ for about 700 kt scrap/year;
- Gas Scrubbing and Zinc removal process: 35 M€ for about 9 kt zinc/year.

The obtained values do not include the investment costs related to the EAF and BF/BOF which are the same for every scenario. For the Waelz technology, an investment cost has been estimated to around 1 M€ [75]. The other data considered for LCC analysis are as follows:

- economic life: 20 years;
- discounting rate: 4%.

Estimated fixed and the operating costs as well as the investment costs related to the involved processes are detailed in Table 6 for the baselines and in Table 7 for the investigated scenarios. All the data are expressed in €/t_{LS}.

In the "Savings (avoided costs)" the Zn recovery, the savings for plastics landfill and the selling of alkali salt cake and lead cake recovered have been considered as shown in details in Appendix B. The obtained estimates are quite conservative. In fact the eventual recover of precious metal from the plastic treatment processes has not been taken into consideration, as these data have not been estimated, even if it could give a more detailed calculation of the revenues. The costs can further decrease, if e.g. some workers can be shared with other units. Although a distinction between the plastics processes has been made, limited differences arise in the results. Results indicated that all the EAF scenarios have a unit cost lower than the baseline 1 case (Table 7). The BF/BOF scenarios show an increase of the unit costs with respect to the baseline 2 case, even if a reduction on the consumption of the iron ore and coal can be depicted. In the cost analysis the amount of process fuel gas in output from BF/BOF has not been taken into consideration, but it could be sold to the district neighborhood with a further reduction of the costs. Such reduction obviously depends on the applied price, but with a low average price of 0.01 €/kW h and since the amount of available process fuel gas is around 1000 kW h/t LS in all the scenarios, a cost reduction can be achieved of about 5%. However, from an economic perspective it can be concluded that the EAF scenarios have the best performance, especially the Scenario 2 associated with PlastSep process.

3.3.2. Environmental impact

The LCA has been developed according to the standards EN ISO 14040:2006 and 14044:2006 [76,77]. The impact assessment is performed in consecutive steps including classification, characterization, normalization and weighting. The LCIA phase also provides information for the life cycle interpretation phase, where the final environmental interpretation is made. Only classification and characterization have been included in the impact

Table 6
LCC for baselines.

	Baseline 1 (€/t_{LS})	Baseline 2 (€/t_{LS})
Investment cost	1.9	0
Fixed cost	2.2	1.1
Operating cost	220.9	204.3
Savings and revenues[a]	−20.6	0
Net total cost	204.5	205.4

[a] Positive value means cost; negative value means savings and revenues.

Table 7
LCC for the investigated scenarios.

	EAF (€/t_{LS})				BF-BOF (€/t_{LS})			
	VW-SiCon + Scenario1	PlastSep + Scenario 1	VW-SiCon + Scenario 2	PlastSep + Scenario 2	VW-SiCon + Scenario 3	PlastSep + Scenario 3	VW-SiCon + Scenario 4	PlastSep + Scenario 4
Investment cost	6.7	6.3	5.0	5.0	1.9	1.8	1.7	1.6
Fixed cost	11.5	10.5	9.0	8.0	5.5	5.0	4.6	4.2
Operating cost	18.6	17.6	19.5	19.0	5.2	5.1	5.2	5.1
Savings and revenues[a]	−27.3	−27.3	−25.6	−25.6	−6.8	−6.8	−6.4	−6.4
EAF-BF/BOF cost with preheating savings	194.9	194.9	194.9	194.9	203	203	202	202
Net total cost	204.3	202	203	201	209	208	207	207

[a] Positive value means cost; negative value means savings and revenues.

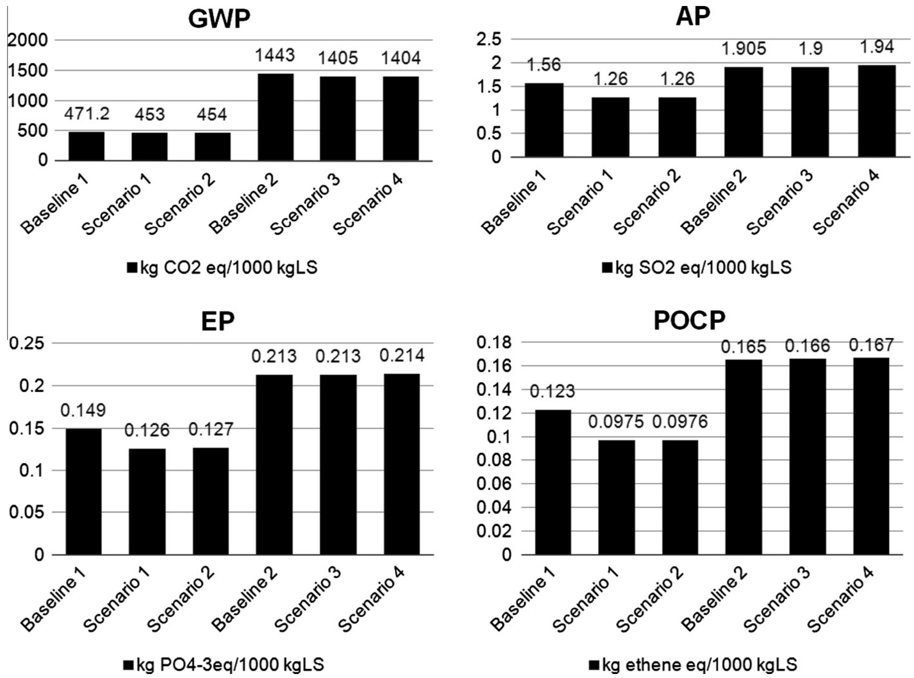

Fig. 12a. Impact assessment results of the analyzed scenarios (GWP, AP, EP, POCP).

assessment part. As far as the scenarios associated to the gasification process is considered, no additional fuels are required: the process uses only waste plastics as fuel. A part of the plastics is used as fuel for the gasification process by in situ combustion and the remaining part of the plastics will be converted to producer gas used for the steel scrap reactor. As far as the scenarios associated with the pyrolysis process is concerning, the model is equipped with three different energy sources, electric power for microwaves or electrical heating, heating with wood powder and heating with natural gas, but in the evaluation, only natural gas heating has been used. In the cases of the gasification, the overall energy efficiency from the energy in the waste plastics to the energy supplied to the steel scrap reactor is estimated to 56.4%, but for the pyrolysis cases, such efficiency has been estimated to around 70%.Truck transports have been assumed for all transports in the model. The entire process is considered to be located on the steelwork site so the recovery process generate little extra transport. The output products are also calculated to the factory gate so no transport of zinc and iron to a customer is needed. Thus, transports are only considered for supply materials to the process. The LCA model was used for the quantification of the environmental results of the benchmarks (reference cases) and the scenarios under investigation. The results of the analysis are summarized in Figs. 12a and b, where the main fol-

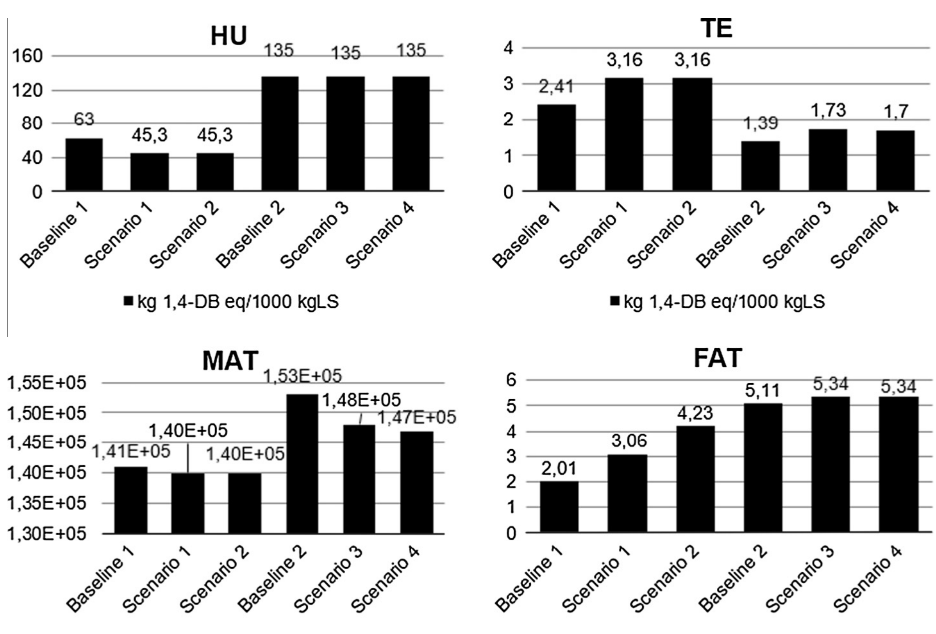

Fig. 12b. Impact assessment results of the analyzed scenarios (HU, TE, MAT, FAT).

lowing indicators are reported: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Human Toxicity Potential (HU), Terrestrial Eco-toxicity Potential (TE), Marine Aquatic Eco-toxicity (MAT), Freshwater Aquatic Eco-toxicity (FAT).

The results indicate that the new proposed Zinc recovery methods make it possible to recover the Zinc in the steel process with a small reduction or without an increase of energy and environmental load. The extra energy that the recovery process requires is recovered in the steel process and the energy and chlorides used for the Zinc recovery can be entirely obtained from waste plastics. However, the high chloride demand in the process results in a large share of PVC in the plastic waste. The potential formation and emissions of dioxins from the different process alternatives heavily depends on the process condition and is formed in combustion and cooling of exhausted gases. Actual measurements thus require a specific industrial monitoring system. In this case, only test and laboratory equipment exist. Even if the chloride load is high in the combustion and the following exhausted gas cooling, the dioxin formation should be relatively low due to the relatively high temperatures in the steel scrap reactor (cooling phase).

4. Conclusions and future work

The present paper describes a process integration study on an innovative process for simultaneous steel scrap preheating and surface cleaning that has been assessed within a research project financed by RFCS. Flow-sheeting models have been exploited for the simulation of the process and some scenarios have been investigated from an economic and environmental point of view.

The key advantages of the proposed technology are the recovery of automotive waste and conversion into energy and raw material, the exploitation of zinc-coated scrap, an otherwise problematic feedstock for steel production, the recovery of a valuable raw material (zinc), and a considerable energy saving in steel production.

The simulations allowed an assessment of different process configurations and potentials for energy saving and waste materials re-use that would otherwise be sent to landfill: the Cl rich fractions (e.g. ASR fractions) are currently not exploited and usually put on landfill. Process optimization has also been carried out in order to minimize the specific plastic and hydrochloric acid consumption that can potentially result in a 30% reduction of the operating costs, maintaining a satisfactory by-product recovery (valuable commercial Zn) and hot scrap temperature. The preheating of scrap also results in energy savings of around 320 MJ/t of scrap charged in the EAF.

Moreover, when the processes are combined with the typical standard process of the steelmaking industry, there are some benefits from an economic and environmental point of view and the new technologies appear to be viable and feasible. From an economic point of view and according to the input data and the explained assumptions, the main benefit for the implementation of such technologies comes not only from the Zn recovery and the savings of plastics landfill, but also from the savings in the EAF or BF/BOF obtained thanks to the scrap preheating before melting. The impact of the scrap preheating in the EAF costs scenarios can be quantified in a reduction of about 13%. Thanks to the saving landfill and Zn recovery, in the EAF scenarios the total cost increases about 5% in Scenario 1% and only 3% in the Scenario 2. At the end, however, the obtained costs in all the EAF scenarios are all less than the baseline 1: the best performance that corresponds to "PlastSep + Scenario 2" reach a cost reduction of about 2%. In the BF/BOF, the impact of the scrap preheating is less (the reduction is about 3%) with respect to the EAF and, at the end, the total cost is a little bit increase with respect to the baseline 2, nonetheless such increase is below 2% in the worst case. In order to quantify the energy and environmental impact, a comprehensive LCA was performed: the higher reductions with respect to the baseline were realized in the AP, POCP and HU in the EAF scenarios (−19%, −21% and −28% respectively). In all the remaining scenarios, with the exclusion of FAT and TE impacts, the obtained values in the EAF are lower than the baseline results and in the BF-BOF cases the results are in line or lower than the baseline. It can be concluded that such new technologies applied within the steelmaking can be considered efficient and energy-savings.

Future work will be focused on the industrial development of the proposed technologies, as well as an assessment of further process integration possibilities coming from lower temperature heat recovery in gasification/pyrolysis and scrap preheating (e.g. for steam production).

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Appendix A. Input variable for case studies

The values of the input variables for the 23 case studies are reported in Table A.1.

Table A.1
Case studies inputs.

Case #	ScrapZnIn (%) mass	ScrapTempOut (°C)	PE (%) mass	SLF (%) mass	PVC (%) mass
1	0.75	600	0	0	100
2	1.25	600	0	0	100
3	2	600	0	0	100
4	3	600	0	0	100
5	0.75	600	0	100	0
6	1.25	600	0	100	0
7	2	600	0	100	0
8	3	600	0	100	0
9	0.75	600	100	0	0
10	1.25	600	100	0	0
11	2	600	100	0	0
12	3	600	100	0	0
13	1.25	700	80	20	0
14	1.25	800	80	20	0
15	2	600	80	20	0
16	3	600	80	20	0
17	1.25	600	0	90	10
18	1.25	600	0	40	60
19	1.25	600	0	20	80
20	1.25	600	0	10	90
21	0.75	600	0	70	30
22	0.75	700	0	75	25
23	0.75	800	0	80	20

Appendix B. LCC details

The details of the process costs for the LCC calculation of the investigated scenarios are shown in Table B.1.

Table B.1
LCC details for the investigated scenarios.

	EAF (€/t_{LS})				BF-BOF (€/t_{LS})			
	VW-SiCon + Scenario 1	PlastSep + Scenario 1	VW-SiCon + Scenario 2	PlastSep + Scenario 2	VW-SiCon + Scenario 3	PlastSep + Scenario 3	VW-SiCon + Scenario 4	PlastSep + Scenario 4
Investment cost	6.7	6.3	5.0	5.0	1.9	1.8	1.7	1.6
Fixed cost related to the process								
VW-SiCon	1.98	–	1.98		0.7	–	0.7	–
PlastSep	–	0.97	–	0.97	–	0.26	–	0.26
Gasification	2.95	2.95	–	–	0.98	0.98	–	
Pyrolysis	–		0.4	0.4			0.1	0.1
Preheating	1.3	1.3	1.3	1.3	0.2	0.2	0.2	0.2
Scrubber	5.30	5.3	5.3	5.3	3.6	3.6	3.6	3.6
Total fixed cost	11.5	10.5	9.0	8.2	5.5	5.0	4.6	4.2
Operating cost related to the process								
VW-SiCon	1.37	–	0.74	–	0.3	–	0.2	
PlastSep	–	0.4	–	0.22	–	0.13	–	0.1
Gasification	2.3	2.3	–	–	0.73	0.73	–	
Pyrolysis	–	–	4.1	4.1	–	–	0.8	0.8
Preheating	1.3	1.3	1.3	1.3	0.7	0.7	0.7	0.7
Scrubber	13.6	13.6	13.4	13.4	3.5	3.5	3.5	3.5
Total operating cost	18.6	17.6	19.5	19.0	5.2	5.1	5.2	5.1
Total cost	30.1	28.2	28.5	27.0	10.7	10.1	9.8	9.3
Zn selling[a]	−22.1	−22.1	−22.1	−22.1	−5.6	−5.6	−5.6	−5.6
Savings costs for landfill plastics[a]	−3.9	−3.9	−2.2	−2.2	−0.9	−0.9	−0.5	−0.5
Alkali salt cake and lead cake selling[a]	−1.3	−1.3	−1.3	−1.3	−0.3	−0.3	−0.3	−0.3
Net total cost	9.4	7.1	7.9	6.4	5.8	5.1	5.1	4.5
EAF or BF/BOF cost with preheating savings	195	195	195	195	203	203	202	202
Final LCC	204.3	202	203	201	209	208	207	207

[a] Positive value means cost; negative value means savings and revenues.

References

[1] World Steel Association. Steel scrap: a world-traded commodity. <http://www.worldsteel.org/media-centre/Steel-news/Steel-scrap–A-world-traded-commodity.html> [accessed 05.11.14].
[2] World Steel Association. World steel in figures 2014. <http://www.worldsteel.org/dms/internetDocumentList/bookshop/World-Steel-in-Figures-2014/document/World%20Steel%20in%20Figures%202014%20Final.pdf> [accessed 14.07.15].
[3] European Integrated Pollution Prevention and Control Bureau (EIPPCB). Best Available Techniques (BAT) reference document for iron and steel production. Industrial Emissions Directive 2010/75/EU; 2010.
[4] Barreneche C, Fernández AI, Niubó M, Chimenos JM, Espiell F, Segarra M, et al. Development and characterization of new shape-stabilized phase change material (PCM)—polymer including electrical arc furnace dust (EAFD), for acoustic and thermal comfort in buildings. Energy Build 2013;61:210–4.
[5] Niubó M, Fernández A, Chimenos J, Haurie L. A possible recycling method for high grade steels EAFD in polymer composites. J Hazard Mater 2009;171(1):1139–44.
[6] Suetens T, Klaasen B, Van Acker K, Blanpain B. Comparison of electric arc furnace dust treatment technologies using exergy efficiency. J Clean Prod 2014;65:152–67.
[7] Ruetten J. Different ways of using Waelz Oxide – Overview and evaluation. In: Lead–zinc 2010 international symposium on lead and zinc processing. Vancouver, British Columbia, Canada; 3–6 October, 2010. p. 841–9.
[8] Ruetten J. The topical Waelz process for recycling of EAF dust, state-of-the-art and future challenges. In: Proceedings of lead–zinc 2010 international symposium on lead and zinc processing. Vancouver, British Columbia, Canada. p. 871–81.
[9] Larsson M, Angstrom S. A novel process for simultaneous scrap preheating and surface rinsing. In: Proceedings of SCANMET 3th, international conference on process development in iron and steelmaking, vol. 1. Lulea, Sweden; 2008. pp. 485–92.
[10] Ijomah M, Ijomah A. Chemical recycling of galvanized steel scrap. Indian J Chem Technol 2003:10159–65.
[11] Larsson M, Hahlin P, Angstrom S. The future of scrap preheating and surface cleaning. In: Proceedings of SCANMET 4th, international conference on process development in iron and steelmaking, vol. 1. Lulea, Sweden; 2012. p. 83–92.
[12] Porzio GF, Colla V, Matarese N, Nastasi G, Branca TA, Amato A, et al. Process integration in energy and carbon intensive industries through exploitation of optimization techniques and decision support. Chem Eng Trans 2013;35:193–8.
[13] Porzio GF, Colla V, Matarese N, Nastasi G, Vannucci M, Branca TA, et al. Process integration in energy and carbon intensive industries: an example of exploitation of optimization techniques and decision support. Appl Therm Eng 2014;70(2):1148–55.
[14] Friedler F. Process integration, modelling and optimisation for energy saving and pollution reduction. Appl Therm Eng 2010;30(16):2270–80.
[15] Gundersen T. What is process integration? In: Proceedings of international process integration jubilee conference, Gothenburg, Sweden; 2013.
[16] International Energy Agency (IEA). A worldwide catalogue on process integration; 2004.
[17] El-Halwaigi MM. Process integration. Amsterdam: Elsevier; 2006.
[18] Klemeš JJ, Kravanja Z. Forty years of heat integration: pinch analysis (PA) and mathematical programming (MP). Curr Opin Chem Eng 2013;2(461).
[19] Larsson M, Dahl J. Reduction of the specific energy use in an integrated steel plant—the effect of an optimisation model. ISIJ Int 2003;43(10):1664–73.
[20] Sahu G, Bandyopadhyay S. Minimization of resources requirement and inter plant cross flow across resource allocation networks. Chem Eng Trans 2011;25:279–84.
[21] Wang C, Bellqvist D, Nilsson L, Ivashechkin P, Reimer V, Rato R, et al. Techno-economic assessment of recovery and reuse of Low Temperature Heat ($T < 350°$ C) in the Steel Industry by Means of Process Integration. Energy Procedia 2014;61:2188–91.

[22] Lundkvista K, Larsson M, Samuelsson C. Optimisation of a centralised recycling system for steel plant by-products, a logistics perspective. Resour Conserv Recycl 2013:7729–36.
[23] Wang YP, Smith R. Wastewater minimisation. Chem Eng Sci 1994;49 (7):981–1006.
[24] Thevendiraraj S, Klemes J, Paz D, Aso G, Cardenas GJ. Water and wastewater minimisation study of a citrus plant. Resour Conserv Recycl 2003;37:227–50.
[25] Simate GS. The treatment of brewery wastewater for reuse by integration of coagulation/flocculation and sedimentation with carbon nanotubes 'sandwiched' in a granular filter bed. J Industrial Eng Chem 2015;21:1277–85.
[26] Sueviriyapan N, Siemanond K, Quaglia A, Gani R, Suriyapraphadilok U. The optimization based design and synthesis of water network for water management in an industrial process: refinery effluent treatment plant. Chem Eng Trans 2014;39:133–8.
[27] Klemes JJ, Varbanov PS, Kravanja Z. Recent developments in process integration. Chem Eng Res Des 2013;91:2037–53.
[28] Cailean D, Wukovits W, Teodosiu C, Ungureanu F, Friedl A. Integrated Sono-Fenton ultrafiltration process for 4-chlorophenol removal from aqueous effluents: process modeling and simulation (Part 2). Clean Technol Environ Impact 2014;16(6).
[29] Porzio GF, Nastasi G, Colla V, Vannucci M, Branca TA. Comparison of multi-objective optimization techniques applied to off-gas management within an integrated steelwork. Appl Energy 2014;31:1361085–97.
[30] El-Halwagi MM. Sustainable design through process integration: fundamentals and applications to industrial pollution prevention, resource conservation and profitability enhancement, USA; 2012.
[31] Chouinard-Dussault P, Bradt L, Ponce-Ortega JM, El-Halwagi MM. Incorporation of process integration into life cycle analysis for the production of biofuels. Clean Techn Environ Policy 2011;13:673–85.
[32] Kalakul S, Malakul P, Siemanond K, Gani R. Integration of life cycle assessment software with tools for economic and sustainability analyses and process simulation for sustainable process design. J Clean Prod 2014;71: 98–109.
[33] Denz N, Ausberg L, Bruns M, Viere T. Supporting resource efficiency in chemical industries – IT-based integration of flow sheet simulation and material flow analysis. In: Proceedings of 21st CIRP conference on life cycle engineering. Procedia CIRP, vol. 15; 2014. p. 537–42.
[34] Colla V, Branca TA, Vannucci M, Fornai B, Amato A. Quantitative sustainability assessment through Key Performance Indicators in ULCOS project. In: Proceedings of 2nd international seminar on society and materials (SAM2). Nantes, France; 2008.
[35] Yilmaz O, Anctil A, Karanfil T. LCA as decision support tool for evaluation of best available techniques (BATs) for cleaner production of iron casting. J Clean Prod 2014:1–11.
[36] Ciroth A, Hunkeler D, Huppes G, Lichtenvort K, Rebitzer G, Rudenauer I, et al. Environmental life cycle costing. Pensacola: SETAC Press/Publishing House Taylor and Francis; 2008.
[37] Carlsson RM. Economic assessment of municipal waste management systems-case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). J Clean Prod 2005;13(3):253–63.
[38] Dong J, Chi Y, Zou D, Fu C, Huang Q, Ni M. Energy–environment–economy assessment of waste management systems from a life cycle perspective: model development and case study. Appl Energy 2014;114:400–8.
[39] Afrane G, Ntiamoah A. Analysis of the life-cycle costs and environmental impacts of cooking fuels used in Ghana. Appl Energy 2012;98:301–6.
[40] Östman M, Lundkvist K, Larsson MIPo, Environmental system effects when including scrap preheating and surface cleaning in steel making routes. In: Proceedings of world renewable energy congress, Linköping, Sweden; 8–13 May 2011.
[41] Schultmann F, Engels B, Rentz O. Flowsheeting-based simulation of recycling concepts in the metal industry. J Clean Prod 2004;12(7):737–51.
[42] Fröhling M, Bartusch H, Schwaderer F, Schultmann F. An inter-company approach to improve resource and energy efficiency and reduce greenhouse gas emissions in metal industries by linking flow sheet models. World Metall – ERZMETALL 2009;62(5):288–98.
[43] Porzio GF, Fornai B, Amato A, Matarese N, Vannucci M, Chiappelli L, et al. Reducing the energy consumption and CO_2 emissions of energy intensive industries through decision support systems – an example of application to the steel industry. Appl Energy 2013;112:818–33.
[44] Porzio GF, Prussi M, Chiaramonti D. Process analysis and modeling for 2nd generation lignocellulosic bioethanol production. Chem Eng Trans 2011; 25:869–74.
[45] Porzio GF, Prussi M, Chiaromonti D, Pari L. Modeling lignocellulosic bioethanol from poplar: estimation of the level of process integration, yield and potential for co-products. J Clean Prod 2012;34:66–75.
[46] Kappes M, Porzio GF, Colla V, Vannucci M, Krumm W. Steam gasification process of chlorine-rich shredder granules: experiments and flow-sheeting modelling for process evaluation and scale-up. Chem Eng Trans 2013;35: 1321–6.
[47] Hewitt K, Wall T. The zinc industry. Cambridge Woodhead Publishing Limited; 2000.
[48] KCL-ECO. <http://kcl-eco-demo.software.informer.com> [accessed 17.12.14].
[49] Gluch P, Baumann H. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Build Environ 2004;39(5):571–80.
[50] Lopez A, Di Iaconi C, Mascolo G, Pollice A. Innovative and integrated technologies for the treatment of industrial water. 1st ed. London: IWA Publishing; 2012.
[51] Bentz DP, Prasad KR. Thermal performance of fire resistive materials – I. Characterization with respect to thermal performance models. NIST (National Institute of Standards and Technology) Report NISTIR 7401. <ciks.cbt.nist.gov/~bentz/nistir7401.pdf> [accessed 28.04.14].
[52] CEWEP. Landfill taxes and bans. <http://www.cewep.eu/storage/med/media/data/taxes/293_CEWEP_-_LandfillTaxesbans_February2010_final-website.pdf?fCMS=60a9a1372cc004a7d6ec2808c0797dd0> [accessed 17.12.14].
[53] Steel Plantech JP. «ECOARC™®». <http://steelplantech.com/en/product/ecoarc> [accessed 17.12.14].
[54] Memoli F, Bianchi FM. New track record for Consteel® due to new environment-friendly features. MPT Int 2007;5:58–65.
[55] Argenta P, Bianchi FM. The EAF technology evolution and the Consteel® system. La Metallurgia Italiana 2005;1:41–7.
[56] Rummler K. New Generation in pre-heating technology for electric arc furnace steelmaking. KR Tec GmbH. <http://kr-tec.net/epc_paper_b.pdf> [accessed 17.12.14].
[57] Lee B. SOHN I. Review of innovative energy savings technology for the electric arc furnace. Miner Metals Mater Soc 2014;66(9):1581–94.
[58] Dal Magro F et al. Enhancing energy recovery in the steel industry: matching continuous charge with off-gas variability smoothing. Energy Convers Manage 2015.
[59] Berkeley L. The State–of-the-Art Clean Technologies (SOACT) for steelmaking handbook. 2nd ed. Washington DC: California American Iron and Steel Institute; 2010.
[60] Sugasawa T, Kato H, Yasuhiro S. The new progress on Ecoarc in Thailand. <https://steelplantech.com/wp-content/uploads/2013/11/201305_The-New-Progress-On-ECOARC-In-Thailand.pdf> [accessed 08.07.15].
[61] Yamaguchi R, Mizukami H, Maki T, Ao N. ECOARC technology. In: 58th electric furnace conference; 2000. p. 325–38.
[62] JFE Technical Report. Ecologically-friendly and economical arc furnace "ECOARC". Environmental Plant Systems Res Dept. Engineering Research Center. JFE Engineering; 2004.
[63] Giavani C, Malfa E, Battaglia V. The evolution of the Consteel EAF. In: Proceedings of 10th European electric steelmaking conference (EEC 2012); Graz, Austria.
[64] Ángel OJ, Hipólito B, Luis G, Nikolás G, Cesar S. Association ISP, et al. BAT Guide for electric arc furnace iron & steel installations. IPPC – Entegre Kirlilik Önleme ve Kontrol T.C. Çevre ve Şehircilik Bakanlığı; October 2012.
[65] Kevin Kennedy Associates. New energy saving electric arc furnace designs. <http://www.kevinkennedyassociates.com/newenergy-saving-electric-arc-furnace-designs> [accessed 08.07.15].
[66] Nardin G, Dal Magro F. Stato dell'arte del recupero energetico da forno elettrico ad arco e sistemi innovativi. <http://animp.it/animp/images/PDF_archivio/UNI%20UDINE_Nardin_Memoria.pdf> [accessed 03.09.14].
[67] Jones JAT. New steel melting technologies: part X, new EAF melting processes. Iron Steelmaker 1997;24:45–6.
[68] FUCHS Technology AG. Eco-friendly and efficient: COSS Furnace –Continuous Optimized Shaft System. <http://www.fuchstechnology.net/en/fulfilment/furnace-systems/coss-furnace.html> [accessed 16.12.14].
[69] Utne IB. Life cycle cost (LCC) as a tool for improving sustainability in the Norwegian fishing fleet. J Clean Prod 2009;17(3):335–44.
[70] Kawauchi Y, Rausand M. Life cycle cost (LCC) analysis in oil and chemical process industries. Department of production and quality engineering, Norwegian University of Science and Technology (NTNU); June 1999.
[71] Al-Salem SM, Lettieri P. Kinetics of polyethylene terephthalate (PET) and polystyrene (PS) dynamic pyrolysis. World Acad Sci Eng Technol 2010;66: 1267–75.
[72] Kern S, Pfeifer C, Hofbauer H. Co-gasification of wood and lignite in a dual fluidized bed gasifier. Energy Fuels 2013;27:919–31.
[73] Fraunhofer Institute Umsicht. Analyse und bewertung der Nutzungsmoglichkeiten von Biomasse. Untersuchung im Auftrag von BGW und DVGW, Band 3: Biomassevergasung, Technologien und Kosten der Gasaufbereitung und Potenziale der Biogaseinspeisung in Deutschland. Final report. Wuppertal, Leipzig, Oberhausen, Essen (in German language); 2005.
[74] Hamel S, Hasselbach H, Lotter D, Krumm W. Synthesis gas production from biomass and waste by Integrated Pyrolysis and Combustion. In: Proceedings of 4th international symposium on waste treatment technologies waste symposium Sheffield, UK; 2003.
[75] Ruetten J. Application of Waelz and other processes on treatment of steel mill (EAF) dust. Duisburg: DK Recycling & Roheisen GmbH, ValoRes GmbH; 2008.
[76] International Organization for Standardisation (ISO). International Standard ISO 14040:2006. Environmental management-life cycle assessment-principles and framework. Geneva, Switzerland; 2006.
[77] International Organization for Standardisation (ISO). International Standard ISO 14044:2006. Environmental management-life cycle assessment-requirements and guidelines. Geneva, Switzerland; 2006.