Technological innovation as a driver of sustainability in steel production

Giuseppe Tomasoni *, Elena Stefana *, Paola Cocca *, Filippo Marciano *, Diana Rossi *

** Department of Mechanical and Industrial Engineering, University of Brescia, via Branze 38, 25123 - Brescia – Italy (giuseppe.tomasoni@unibs.it, elena.stefana@unibs.it, paola.cocca@unibs.it, filippo.marciano@unibs.it, diana.rossi@unibs.it)*

Abstract: The iron and steel industry plays a vital role in the global economy, but it is highly intensive in energy, emissions, and materials. This sector is facing increasing challenges, such as the rising of energy prices, stringent environmental regulation, and uncertain context. Moreover, the post-pandemic economic environment and the recent upheavals in the global geopolitical context have sent energy prices soaring. In such a context, it is very important for steel-producing companies to invest in technological innovations of their processes to increase their efficiency, improve the environmental performance, and enhance long-term sustainability. The design and selection of new technologies can be supported by means of Life Cycle Assessment (LCA), i.e. a scientific method to understand and address environmental aspects and potential impacts throughout a product's life cycle. In this paper, we propose an LCA application to assess the environmental impacts and benefits associated with technological innovations recently implemented in scrap handling and melting departments of an Italian steel company. We used SimaPro software, collected primary data from the company, and employed the Ecoinvent database to gather additional data. We adopted ReCiPe 2016 as life cycle impact assessment method. The analysis highlighted that the installation of a new injection system of additives with a revised chemical composition for Electric Arc Furnace (EAF), and the adoption of a system for handling scraps and identifying the optimal mix of charge mostly contribute to the reduction of environmental issues related to the production of billets. Such environmental benefits are obtained through the decrease of energy consumption in EAF, and, in particular, of the consumption of natural gas and coal for electricity production.

Keywords: Climate change, Sustainable industrial systems, Sustainable technologies, Carbon footprint, Energy efficiency.

I. INTRODUCTION

Energy-intensive industries constitute a significant part of the economy and are responsible for a large amount of energy use, resource consumption, and emissions (Nurdiawati and Urban, 2021). Among them, the iron and steel industry plays a vital role in the global economy (IEA, 2020), but, at the same time, it is highly intensive in energy, emissions, and materials (IEA, 2020; Remus et al., 2013). Indeed, this sector is currently responsible for 8% of global energy demand and 7% of total emissions from the energy system (IEA, 2020). It is also a large contributor to climate change (Ryberg et al., 2018).

As a consequence, the iron and steel industry is facing a number of critical challenges, as well emphasised in the literature (e.g. IEA, 2020; Johansson and Söderström, 2011; Karakaya et al., 2018; Peters et al., 2019):

- rising of energy prices;
- increased competition for raw materials;
- required improvements of the energy and resource efficiency;
- stringent environmental regulation aiming at mitigating greenhouse gas emissions and climate change;
- shifting towards more sustainable modes of production, and switching to low-carbon production processes;
- growing trend of the global steel demand;
- uncertain context.

In particular, in addition to persistent factors, the current levels of uncertainty about short- and long- term impacts on the iron and steel industry may be unprecedented due to both Covid-19 coronavirus pandemic (IEA, 2020) and market consequences of Russia-Ukraine war.

Consequently, the iron and steel industry should review its energy use to meet future climate targets and energy prices (Johansson and Söderström, 2011), reach the climate neutrality by 2050 (de Bruyn et al., 2020), and thus improve the environmental performance of steel production (Ryberg et al., 2018). To achieve this aim, companies can invest in technologies (technical measures) and/or implement management practices (low-cost and non-technical measures) (Stefana et al., 2019). Specifically, the adoption of innovative technologies represents one of the main pillars for steel sustainable growth, which helps to meet environmental requirements and promote sustainable steel production (Peters et al., 2019). Technological progress can thus improve energy efficiency, and is crucial for the transition to a low carbon economy (Sun et al., 2021). A strong focus on techniques having the potential for achieving a high level of environmental protection in the activities of the iron and steel industry is also provided by Remus et al. (2013).

The design and selection of new technologies in the iron and steel industry can be supported by means of Life Cycle Assessment (LCA) (Burchart-Korol, 2011). This is the most scientific method to evaluate the environmental impact of a steel production process (Li et al., 2021). It is developed to understand and address environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition to final disposal (ISO, 2006a). Furthermore, it is attracting increasing attention from researchers and practitioners due to its ability to compare environmental impacts of different products or production processes (Olmez et al., 2016). In the context of the iron and steel industry, Tongpool et al. (2010) employ LCA to assess the environmental impacts of individual steels on ecosystem, resources, and human health, while Li et al. (2021) use this method to evaluate a steelmaking process of the coal gasification shaft furnace-electric furnace.

In the scientific literature about LCA applications to steel production processes, the majority of articles propose the application of this method focusing on the melting production process: in order to reduce the environmental impacts related to this process, studies propose the employment of alternative process technologies and/or fuels (e.g. Burchart-Korol, 2013; Lin et al., 2016). Other contributions are mainly related to the recycling possibilities. Indeed, in most cases, the use of recycled materials in manufacturing requires less energy and generates less solid waste and fewer air emissions and waterborne wastes than acquiring and using virgin materials (Yellishetty et al., 2011). However, issues about the steel quality and the potential expensive separation or removal of residual elements should be properly taken into account (Yellishetty et al., 2011). A particular form of recycling attracting most attention from environmental perspective in steel processes concerns the waste disposal and the opportunity to reuse Electric Arc Furnace (EAF) slags for reducing the consumption of natural aggregates and resources (e.g. Esther et al., 2020; Evangelista et al., 2018).

In such a context, this paper proposes an LCA application to assess the environmental impacts and benefits associated with technological innovations recently implemented in scrap handling and melting departments of a steel company located in northern Italy. The remainder of this paper is organised as follows. In Section II we summarise the methods utilised for this research, whereas the results are presented and discussed in Section III. Concluding remarks are provided in the final section.

II. Methods

We conducted LCA according to the requirements of ISO 14044 (ISO, 2006b), performing the following four phases:

- goal and scope definition;
- inventory analysis;
- impact assessment;
- interpretation.

In the first phase, we defined the system to be analysed, its boundary, the functional unit, the impact assessment methodology, and data requirements. The investigated system was the process of the company producing secondary steel products by means of an EAF. This type of furnace is commonly used for scrap-based production (IEA, 2020). It heats charged materials through an electric arc, and uses electricity, coal, heavy fuel oil, and natural gas as energy sources (Lin et al., 2016).

The goal of this analysis is to assess and compare the environmental impacts of technological innovations introduced in the scrap handling and management, and in the melting processes. Such technological innovations and the corresponding scenarios are briefly described in Table I. We performed a comparative analysis between these scenarios and the baseline scenario representing the conditions of the processes before the implementation of the considered technological innovations.

The system boundary was set as "cradle-to-gate": we included upstream processes, transportation, production processes, and utility services, while we excluded the downstream production processes (e.g. rolling, subsequent treatment steps, and product use), as their environmental impacts were verified to be the same among the different scenarios. The functional unit was defined as 1 ton of semi-finished steel product, which is C20D (0.21 % C) billet (ISO, 2017).

We used SimaPro software (version V.9). We collected primary data from the company (e.g. transport kilometres, metal yield, productivity, energy consumptions, and mix of primary energy sources to produce the consumed electricity), and we employed the Ecoinvent database to gather secondary data required for the analysis (e.g. inventories for energy and transportation). We adopted ReCiPe 2016 as life cycle impact assessment method: it provides a harmonised implementation of cause-effect pathways for the calculation of midpoint and endpoint characterisation factors (Huijbregts et al., 2017). It transforms the long list of life cycle inventory results into a limited number of indicator scores, which express the relative severity of an environmental impact category (Burchart-Korol, 2013; Llantoy et al., 2020). It includes 18 environmental impact midpoint indicators and 3 damage indicators (Burchart-Korol, 2013; Llantoy et al., 2020).

The following section summarises the results obtained for the inventory analysis, impact assessment, and interpretation.

TABLE I
DESCRIPTION OF THE INVESTIGATED SCENARIOS

Scenario ID	Process step / Department	Technological innovations
1	Scrap handling	Introduction of a machinery to separate metallic from non-metallic materials and to detect radioactive elements in advance. Installation of a system to automatically select and load scrap in EAF, and to provide the optimal mix of charge according to the desired steel grade.
2a	Melting	Installation of a new lime injection system, with dynamic control properties.
2b	Melting	Installation of a new injection system of additives with a revised chemical composition, with dynamic control properties.
2c	Melting	Installation of new burners and oxygen lances.
2d	Melting	Implementation of a system for the monitoring of the Eccentric Bottom Tap-hole (EBT) status, including an automated duct cleaning and restoration system and a vision camera.
3	Scrap handling and Melting	Combination of the entire set of the technological innovations.

III. Results and Discussion

The Life Cycle Inventory (LCI) analysis collects and quantifies inputs and outputs with regard to the examined system (ISO, 2006a, 2006b). Fig. 1 displays the main LCI results: the vertical bars represent the contribution in percentage of the metal yield, EAF energy consumption, productivity, and power on time for each scenario, in comparison to the baseline scenario. The power on time is the net operation time for EAF not considering the setup time, and it contains electrical arcing, bridge, and chemical treatment time (Riedinger et al., 2010).

Scenarios 1, 2a, 2b, 2c, and 2d regard the introduction of specific technological innovations, while scenario 3 combines all the interventions implemented by the company (and, thus, 1, 2a, 2b, 2c, and 2d). Fig. 1 highlights that the inventories related to the metal yield in scenarios 2a, 2c, and 2d, and the power on time in scenario 2a are negligible from the environmental point of view. On the contrary, the innovations introduced in scenarios 1 and 2b are able to significantly improve the inventories. In particular, scenario 1 permits increasing the metal yield, whereas scenario 2b increasing the productivity, and reducing the EAF energy consumption and power on time.

The adoption of the entire set of technological innovations (scenario 3) allows improving mainly the energy consumption of the furnace, decreasing it by about 20.8%. Note that approximately 65% of the electrical energy consumed by the company comes from natural gas, approximately 17% from coal, and the remaining from other sources (e.g. renewable sources).

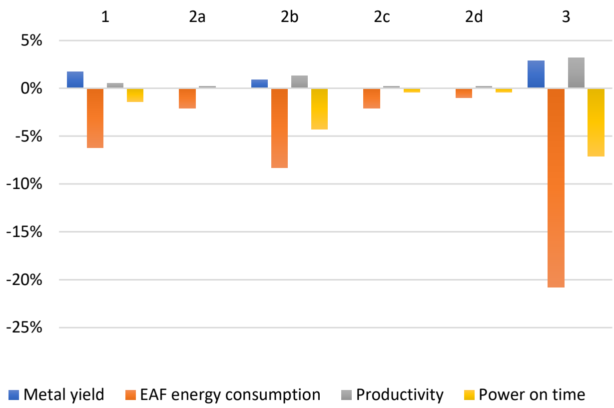

Fig. 1. Main inventory data in the investigated scenarios

The LCI results provide the starting point for the Life Cycle Impact Assessment (LCIA), whose objective is the understanding and evaluation of the magnitude and significance of the potential environmental impacts for the analysed system throughout its life cycle (ISO, 2006a, 2006b). The outcomes of this phase are reported in Table II and Table III.

Table II presents the results about the midpoint indicators obtained by using the ReCiPe method for each scenario under investigation. Each cell represents the environmental impact variation for a specific category that is attained through the introduction of the technological innovation defining a scenario, in comparison to the baseline scenario. All the results are negative values: this means that all the technological innovations produce environmental benefits for the different impact categories. Among the scenarios related to single departments, scenario 2b is characterised by the greatest impact variation for all the 18 midpoint indicators: the installation of a new injection system of additives into the EAF represents the scenario that most improves environmental issues. This is mainly related to the increase of both the metal yield and energy efficiency. Indeed, this scenario produces the greatest decrease of the energy consumption of EAF.

TABLE II
VALUES OF THE MIDPOINT INDICATORS IN THE INVESTIGATED SCENARIOS

Impact category	Scenario ID					
	1	2a	2b	2c	2d	3
Global warming (kgCO$_2$ eq)	-24.4	-9.45	-32.7	-8.28	-3.94	-82.8
Stratospheric ozone depletion (kg CFC-11 eq)	-1E-5	-3E-6	-1E-5	-3E-6	-2E-6	-3E-5
Ionizing radiation (kBq Co-60 eq)	-1.93	-0.66	-2.58	-0.65	-0.31	-6.45
Ozone formation, human health (Kg NOx eq)	-0.03	-0.01	-0.05	-0.01	-0.01	-0.12
Fine particulate matter formation (kg PM$_{2.5}$ eq)	-0.02	-0.01	-0.02	-0.01	-0.00	-0.06
Ozone formation, terrestrial ecosystems (kg NO$_x$ eq)	-0.04	-0.01	-0.05	-0.01	-0.01	-0.12
Terrestrial acidification (kg SO$_2$ eq)	-0.05	-0.02	-0.06	-0.02	-0.01	-0.16
Freshwater eutrophication (kg P eq)	-3E-3	-1E-3	-5E-5	-1E-3	-1E-3	-1E-3
Marine eutrophication (kg N eq)	-3E-4	-9E-5	-4E-4	-9E-5	-4E-5	-9E-4
Terrestrial ecotoxicity (kg 1,4-DCB)	-5.46	-3.74	-7.31	-1.85	-0.88	-20.1
Freshwater ecotoxicity (kg 1,4-DCB)	-0.19	-0.07	-0.26	-0.07	-0.03	-0.64
Marine ecotoxicity (kg 1,4-DCB)	-0.26	-0.09	-0.35	-0.09	-0.04	-0.88
Human carcinogenic toxicity (kg 1,4-DCB)	-0.50	-0.18	-0.66	-0.17	-0.08	-1.66
Human non-carcinogenic toxicity (kg 1,4-DCB)	-6.31	-2.22	-8.45	-2.14	-1.02	-21.2
Land use (m^{2}a crop eq)	-0.09	-0.03	-0.12	-0.03	-0.01	-0.30
Mineral resource scarcity (kg Cu eq)	-0.01	-0.00	-0.01	-0.00	-0.00	-0.03
Fossil resource scarcity (kg oil eq)	-7.87	-2.78	-10.54	-2.67	-1.27	-26.4
Water consumption (m^3)	-0.04	-0.02	-0.06	-0.01	-0.01	-0.14

Further relevant environmental benefits are obtained thanks to scenario 1: it maximises the metal yield through the introduction of a proper mix into the furnace and the minimisation of undesired components in the charge. This leads to a reduction of the energy consumption since energy is not used for heating non-metallic materials.

On the contrary, scenario 2d produces the smallest impact variations for each category: among the different investigated scenarios, the adoption of a system for the monitoring of the EBT status causes less reduction in environmental impacts. This is due to the smallest decrease of the EAF energy consumption in comparison to the other scenarios under investigation. As a consequence, it is characterised by the greatest values of the endpoint indicators, as shown in Table III. Each cell of this table reports the environmental damage variation for a specific area of protection considered in the ReCiPe method (i.e. human health, ecosystem quality, and resource scarcity) that is produced by means of the introduction of the technological innovation(s) defining a scenario, in comparison to the baseline scenario. Indeed, endpoint indicators summarise the environmental impact on three higher aggregation levels, and this simplifies the interpretation of the LCA results (Llantoy et sl., 2020). In accordance with Huijbregts et al. (2017), the units for the three levels are defined as follows:

- Disability Adjusted Life Years (DALY) for human health damage, which represent the years that are lost or that a person is disabled due to a disease or accident;
- species year (species.yr) for ecosystem quality, which is local relative species loss in ecosystems integrated over space and time, and including species densities for the considered types of ecosystems;
- dollars (USD2013) for resource scarcity, which represent the extra costs involved for future mineral and fossil resource extraction.

TABLE III
VALUES OF THE ENDPOINT INDICATORS IN THE INVESTIGATED SCENARIOS

Damage category	Scenario ID					
	1	2a	2b	2c	2d	3
Human health (DALY)	-4E-5	-1E-5	-5E-5	-1E-5	-6E-6	-1E-4
Ecosystems (species.yr)	-9E-8	-3E-8	-1E-7	-3E-8	-1E-8	-3E-7
Resources (USD2013)	-2.44	-0.87	-3.26	-0.83	-0.39	-8.18

All the scenarios under investigation produce negative values for the damage category indicators: this means that the adoption of technological innovations is able to decrease the potential environmental damages related to the production of steel products in comparison to the baseline scenario. The minimum endpoint indicator values among the scenarios in single departments are achieved by scenario 2b.

It is also possible to identify the contribution of the impact categories to the endpoint scores. For all the scenarios regarding technological innovations in single departments, global warming is the most influential impact category for the damage to human health (about 79%) and to ecosystems (about 63%). Ecosystem quality is also affected by fine particulate matter formation (about 28%). With regard to resource scarcity, the most influential impact category is represented by fossil resource scarcity. This is reasonable in the context of the steel production.

The combination of all the technological innovations (scenario 3) causes the greatest environmental benefits for the company. This is demonstrated by the results in Table II and Table III about the midpoint and endpoint indicators. In this scenario, the positive effects of all the innovations are integrated: all the impact categories are characterised by relevant negative variations, and this is mainly related to the reduction of the EAF energy consumption achieved by each scenario in single departments.

All these benefits in terms of impact categories are also confirmed by the results obtained by endpoint indicators and damage categories. The most influential impact categories for the areas of protection for scenario 3 are similar to those for the scenarios in single departments.

The material and energy flows, and the technological innovations in scenario 3 are displayed in Fig. 2. This figure is a network flow chart (Sankey diagram), where each box represents the contributing factors to the output (in our analysis: the billet production), the thermometers in the boxes depict the environmental benefits generated by the factors, and the arrows identify the links among them. The width of the arrows is proportional to the environmental benefits produced by the interventions of the examined scenarios.

The cut-off is equal to 5%: only factors contributing more than 5% in terms of environmental benefits are visualised. Other factors, such as transport activities or additive consumption, are not displayed.

Fig. 2 shows that the installation of a new injection system of additives introduced in EAF mostly contributes to the reduction of environmental issues related to the production of billets, followed by the adoption of a system for managing scraps and identifying the optimal mix of charge. Such environmental benefits are obtained through the decrease of energy consumption in EAF, and, in particular, of the consumption of natural gas and coal for electricity production.

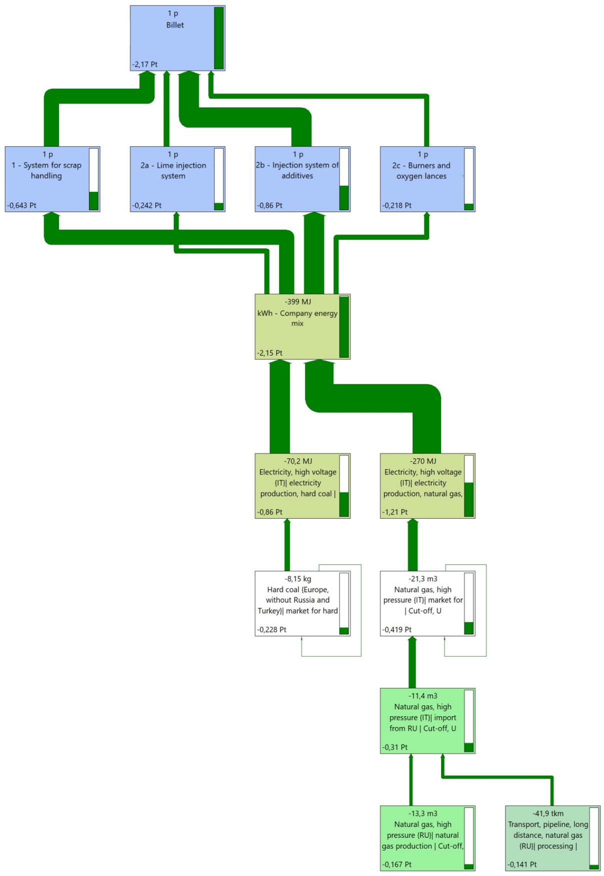

Fig. 2. Sankey diagram of scenario 3

This result appears particularly interesting for the current context in which steel companies operate and compete. Nowadays, the iron and steel industry should be able to decrease the resource deployment and develop energy efficiency programmes. It will help achieving sustainable development goals, and also mitigating the effects related to the existing kinds of uncertainties. The design and adoption of proper technological innovations in critical parts of the production processes represent a key element of this strategy, combined with a greener electricity supply. Further environmental benefits could be obtained implementing management practices able to mitigate energy demand, minimise the resource consumption, or reuse resources (Stefana et al., 2019).

The financial investments characterising innovative technologies may represent a barrier for their adoption, especially in Small and Medium-sized Enterprises (SMEs). LCA can support companies during the selection and prioritisation of strategic investments. It is a tool that highlights those interventions can produce more and what kinds of environmental benefits, and thus a ranking about their relevance can be developed. LCA can then be integrated with additional analyses concerning the social and economic sustainability in order to provide an overall overview of benefits and weaknesses of the various possible technological options.

IV. Conclusions

This paper proposes an LCA application to assess the environmental impacts and benefits associated with technological innovations recently implemented in scrap handling and melting departments of an Italian steel company. Such assessment was performed according to the traditional LCA phases, including goal and scope definition, inventory analysis, impact assessment, and interpretation. The installation of a new injection system of additives introduced in EAF, and the introduction of a system for scrap handling and providing the optimal mix of charge produce relevant environmental benefits. Indeed, they increase the metal yield and decrease the furnace energy consumption, in comparison to the baseline scenario representing the conditions of the processes before their implementation. The adoption of these innovations in combination of other interventions (e.g. lime injection system, burners and oxygen lances, system for the monitoring of the EBT status) further enhances the sustainability performance of the company thanks to the reduction of the consumption of natural gas and coal for electricity production.

Future research activities could be focused on carrying out uncertainty analysis and Monte Carlo simulations about the LCA results. This may highlight if an intervention remains relevant from the environmental perspective also in the presence of high uncertain data and/or parameters, or may compare uncertainty per impact category. Additionally, an integrated sustainability assessment of the technological innovations investigated in this paper could be performed. In this regard, proper methods should be developed and/or applied in order to analyse social and economic sustainability, and thus identify the interventions able to increase the long-term sustainability of the steel companies.

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