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Externality evaluation in the steel industry

Ghader Hassanzadeh[a], **Mohsen Salimi**[b], **Hamidreza Habibiyan**[a], **Morteza Hosseinpour**[b,*]

[a]*Department of Energy Engineering and Physics, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran*

[b]*Renewable Energy Research Department, Niroo Research Institute (NRI), Tehran, Iran*

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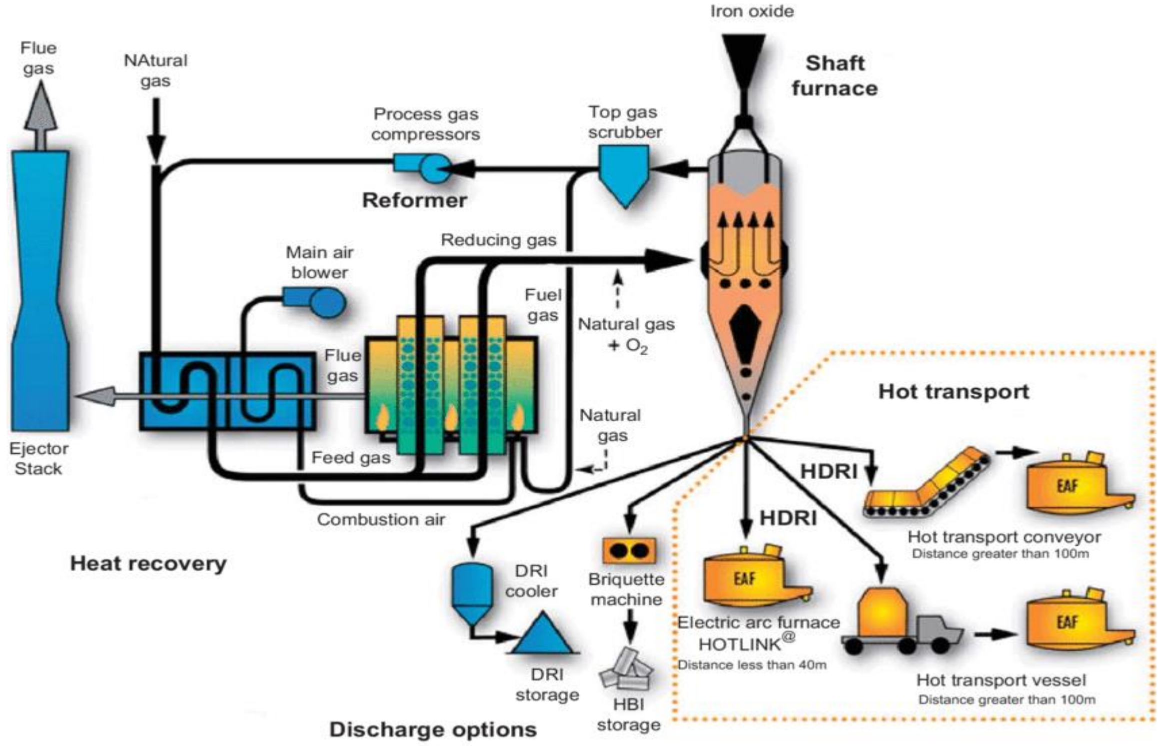
*** Corresponding author:**
Mhosseinpour@nri.ac.ir

Abstract

The purpose of this study is to evaluate the externalities of the steel industry. Externalities in the steel industry refer to the impacts that steel production has on society and the environment, which are not accounted for in the final product price. One of the most robust methods of investigating this issue is the life cycle assessment (LCA) approach to evaluate the externalities of the steel industry. Our study focused on Mobarakeh Steel Company which the assessment is conducted based on the ISO 14040 standard in four steps: goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation. The software SimaPro version 9.5.0.2 with the Ecoinvent database was applied with supporting ReCiPe H method, which has 18 midpoint indicators and 3 endpoint indicators. The results show the shares of mining and concentrate production process accounted for 38% of the environmental impacts while 26.6% of the impacts were related to the electric arc furnace process. The share of environmental impacts of the DRI unit was15%. In addition, three indicators, human carcinogenic toxicity, fossil resource depletion, and ozone formation in terrestrial ecosystems, were among the most influential indicators in these processes. To quantify the externalities, the cost of each of the identified environmental and social damages are evaluated based on available sources as well as the monetary value calculated for each type of damage. Accordingly, the total externality cost of producing one ton of steel sheet was approximately 846 EUR. Of this total cost, the share attributed to global warming damage was around 462 EUR, identified as the costliest environmental and social damage.

Graphical Abstract



1. Introduction

The concept of externalities in the steel industry refers to the impacts of steel production on society and the environment that are not accounted for in the final product price. These are the social and environmental costs that arise as a consequence of steel manufacturing but are not reflected in the market price of the steel commodity. An example of externalities in the steel industry is air and water pollution. The steel production process can cause air and water pollution in the region where the industrial unit is active and create problems and pose health risks for the local community living in proximity to the industrial facilities. Additionally, steel manufacturing is a highly water-intensive industrial activity, and the improper management of water resources, it can reduce water resources and destroy the environment. In general, externalities in the steel industry point to the social and environmental costs of this industry, some of which may remain hidden and unrecognized due to not being included in the final product price.

The steel industry, after the oil and gas industry, is the second-largest industry in the world with a turnover of 900 billion dollars globally. Global crude steel production reached 1888.2 million tons in 2023, which has increased by 0.52% compared to 2022. Iran plays a significant role in global steel production, ranking tenth worldwide with an output of 31.1 million metric tons in 2023. Notably, over 77% of Iran's steel is produced using electric arc furnace (EAF) technology. In this ranking, China ranks first with 1,019.1 million tons produced annually[1] .The EAF, a critical component in steel production, features a molten metal bath with carbon electrodes installed in the upper section. During the charging process, these electrodes move downward, and an electrical current is established through the use of transformers. Transformers are devices that transfers the transmission of electrical energy between two or more coil windings via electromagnetic induction. The primary raw material inputs to the EAF are scrap metal and sponge iron.[2]. Direct reduced iron (DRI), also known as sponge iron, is a type of iron product that is produced through a direct reduction process. In this process, oxygen is removed from iron ore without melting the ore, unlike the traditional blast furnace ironmaking route. The direct reduction process results in a porous, sponge-like iron material, hence the name "sponge iron" or "direct reduced iron". The two main direct reduction processes used are[3]:

- Natural gas-based processes like MIDREX, HYL, and Purofer, with MIDREX being the most widely used.
- Coal-based processes like Jindal DRC and SL/RN.

The choice between the two main direct reduction processes - natural gas-based or coal-based - for the production of DRI is largely dependent on the location of the manufacturing plant and the availability of natural resources .In the case of Iran, the country's abundant natural gas reserves make the natural gas-based direct reduction process the preferred choice for DRI production[4] .steel production despite its plays a pivotal role in the economy, it is accompanied by significant greenhouse gas emissions. the iron and steel industry is the second-largest industrial consumer of energy globally, after the chemical sector, and is among the major emitters of CO_2, accounting for approximately 3.2% of total greenhouse gas emissions, 7% of global carbon dioxide, and 15% of industrial emissions[5] .Given the growing environmental risks and the need to prevent irreversible damage from global warming, the increase in global temperature must be kept below 2 ^{o}C, preferably below 1.5 ^{o}C[6] .This requires actions to reduce the effects of processes that have significant environmental impacts. As mentioned, steel is one of the industries that has high potential for reducing greenhouse gas emissions, so the effects of each part of the production process on the environment must first be identified in order to take actions to reduce these effects. One of the methods that can be used to assess these effects is the Life Cycle Assessment (LCA) approach. LCA involves the evaluation of the life cycle of a product by collecting and assessing the inputs, outputs, and potential environmental impacts،evaluating effects such as natural resource depletion, mineral material consumption, water and energy use, toxicity in aquatic and terrestrial environments, global warming, ozone depletion, and more for each production stage of the product's production .One of the most important features of this tool is that it can quantify all of the aforementioned effects for a specific geographical region. This process also helps to identify major environmental issues and find solutions to reduce them. There is a general consensus on the formal structure of LCA, which consists of four stages[7]:

- goal and scope
- inventory analysis
- life cycle impact assessment
- interpretation

In order to provide a comprehensive and accurate interpretation using the LCA method for the steel industry, it is essential to first examine the steel production pathway. This will ensure a well-defined scope and boundaries, and avoid any issues in the input-output analysis.

1.1. Steelmaking

1.1.1. Raw Material Preparation & Mixing

Iron ore is typically obtained through extraction, then crushed into smaller particles and screened to ensure a uniform size distribution, then crushed iron ore is then mixed with additive materials such as limestone, dolomite, or bentonite. These additives help improve the pelletizing process and the properties of the final pellets. The goal of this mixing is to achieve the desired chemical composition and characteristics of the pellets. [8]

1.1.2. Pelletizing

The mixed materials are transformed into pellets using discs. The mixture is turned into small spherical balls by rolling, adding water and adhesives at this stage helps to facilitate the formation of pellets. The freshly formed pellets contain moisture and need to be dried. Drying is typically performed in industrial dryers to remove the excess water, which results in the production of robust pellets and suitable for transportation and handling. The dried pellets then undergo a process called induration, where they are heated in a furnace at high temperatures. Induration involves heating the pellets to strengthen them and improve their mechanical properties. After this process, the pellets are cooled down to ambient temperature. The cooling process is crucial to stabilize the pellets before handling or transportation. the cooled pellets are screened to separate them into different size fractions. The final pellets undergo quality control measures to evaluate their physical and chemical properties. Various tests, including size distribution, and chemical composition analysis, are conducted to ensure the pellets meet industry standards. Final pellets are stored in silos or warehouses before being sent to the steelmaking units[8].

1.1.3. DRI

The production of DRI from iron ore pellets in the direct reduction unit, where the iron ore pellets are converted to metallic iron without undergoing melting. DRI is a valuable source of iron for steelmaking, and its production from pellets in the reduction unit contributes to more sustainable and efficient steel production. The production of steel in the electric arc furnace utilizing DRI and scrap iron is a common and environmentally-friendly method. Iron ore pellets are typically introduced into the direct reduction reactor with specific size and compositional characteristics. The pellets serve as the feedstock material for the DRI production process. Within the direct reduction reactor, the iron ore pellets are heated to elevated temperatures, typically in the range of 800 to 1050 ºC, in the presence of a reducing gas (typically natural gas).

Under these conditions, the iron oxide present in the pellets undergoes a reduction reaction where oxygen is removed, and metallic iron is formed .The overall reaction can be represented by Eq. (1) [9].

$$Fe_2O_3+3CO\leftrightarrow 2Fe+3CO_2 \tag{1}$$

Carbon monoxide in the reducing gas acts as the reducing agent, converting the iron ore to metallic iron. The heat generated during the reduction process is recovered and utilized within the DRI system, which helps maintain the elevated temperatures required for the reduction reaction. After the reduction process, the DRI product is cooled. This cooling can be achieved through various methods, such as water quenching or air cooling. The cooled DRI product then undergoes screening to separate it into different size fractions and classifications .The screened DRI is then either directly utilized or stored for further use. The production of sponge iron (Figure 1) with the MIDREX method is as follows: first, methane gas enters the broken unit to decompose it into two reducing gases, oxygen and hydrogen. This decomposed methane is heated in a cylindrical furnace. Simultaneously with the heating of the decomposed methane, iron ore is fed into the furnace from the top to react with the decomposed methane gas. When the decomposed methane gas is heated in the furnace, the iron ore collides with it and loses its oxygen. The final product is porous pellets of pure iron that are hardened[9].

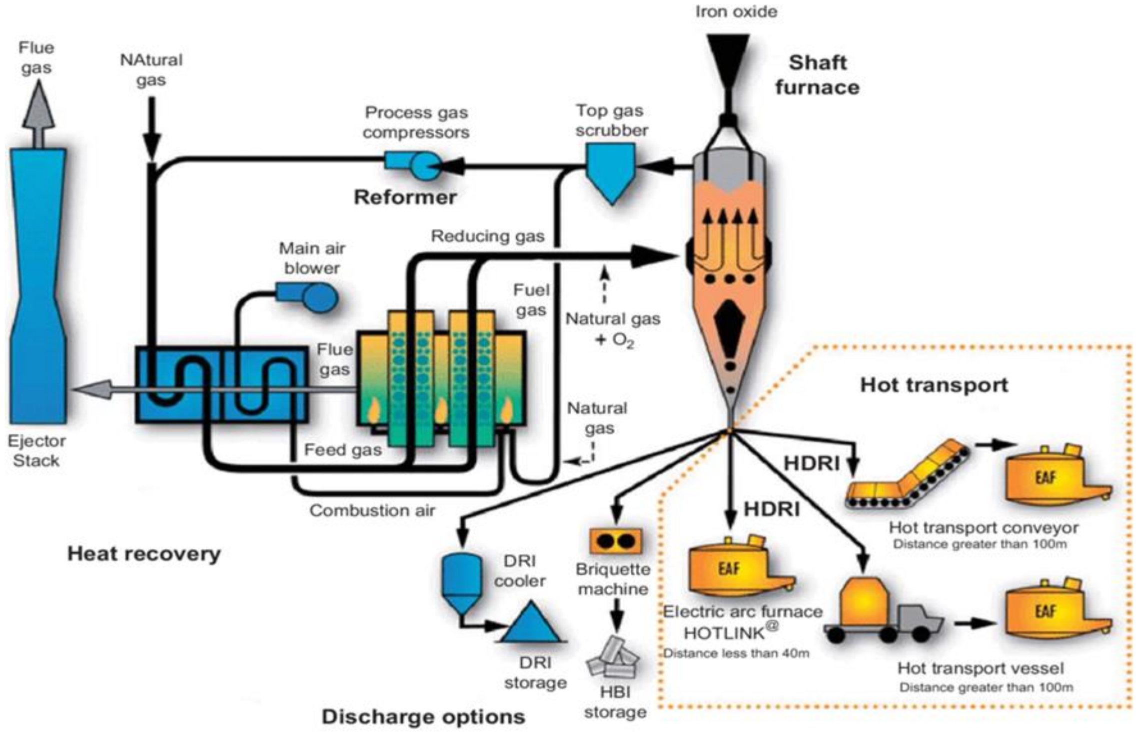


Fig. 1. Flow sheet of the MIDREX process[10].

1.1.4. EAF

An electric arc is generated in the furnace by the passage of electricity through graphite electrodes The heat generated by the electric arc in the furnace melts both DRI and scrap iron. In the electric arc furnace, DRI is converted to metallic iron in the presence of carbon from the scrap iron, and the overall reaction can be represented by the Eq. (2)

$$Fe_2O_3+3CO \leftrightarrow 2Fe+3CO \tag{2}$$

The carbon present in the scrap iron acts as a reducing agent, reducing the iron oxide in the DRI to metallic iron. Alloying elements are also added to the furnace at this stage to achieve the desired composition and properties of the steel to meet the specific requirements for various applications The steel composition can be adjusted. Oxygen is injected into the furnace to improve the efficiency of the steelmaking process and remove impurities. Stringent quality control measures are implemented throughout the process to ensure that the steel meets specified standards and fulfills customer requirements[9].

1.1.5. Ladle Furnace (LF)

In this process, molten steel is subjected to refining and composition adjustment before casting. The molten steel is transferred from the EAF for further purification to the LF preheating furnace. In the LF preheating furnace, the molten steel is heated to the appropriate temperature for subsequent operations Preheating is essential to ensure the desired temperature of the steel is maintained throughout the refining process. Alloy elements are added to achieve the desired final steel composition. Adjustments are made to achieve specific metallurgical properties and ensure compliance with the required steel standards. Samples of molten steel are taken at various stages for monitoring, analysis, and ensuring compliance with specified quality standards. After completing the purification and alloying stages, the molten steel is ready for casting[8].

1.1.6. Casting

In the continuous casting process, the production of slabs involves a continuous and efficient operation. Molten steel is poured from the furnace into a refractory vessel with a refractory lining. The steel then flows through a series of refractory-lined tubes, known as the mold, where it takes the shape of a slab. The input temperature to the casting process is typically high, as the steel needs to remain in a molten state for proper casting. The precise temperature varies depending on the steel grade and casting conditions, but generally ranges from 1600°C to 1800°C. As the steel progresses through the casting section, it gradually cools and solidifies. Water is often sprayed on the mold walls to accelerate the cooling process. The output temperature from the casting section is lower than the input temperature, and it continues to decrease as the slab moves through the subsequent cooling zones[9].

1.1.7. Rolling

In the rolling process, the slab is placed in rolling stands to reduce thickness under pressure and tension operations Each rolling stand is equipped with four rollers. These rollers apply compressive forces to reduce the slab thickness as it passes through. The thickness reduction is controlled by adjusting the distance between the rollers in each stand. The slab temperature during rolling is carefully monitored to ensure it stays within the optimal range for shape change Tension control systems. This system helps prevent buckling and ensures uniform thickness reduction. The final product, usually referred to as "hot-rolled coil" or simply "rolled product," undergoes quality inspections to ensure it meets dimensional and surface quality requirements. Once the coil is fully formed, it is securely strapped for transportation. Labels are attached to the coil for product identification and tracking purposes. The coiled sheets are then transferred to the warehouse[9]

1.2. Study Case

In this text, we aim to examine the Mobarakeh Steel Company in Isfahan. The iron ore used in the factory is transported by rail lines from the mines of Gol Gohar, Chadormalu, Bafq, Zarand, Sirjan ,Sangans located in the provinces of Kerman, Yazd, and Razavi Khorasan, as well as a part of the required pellet from Gol Gohar, Ardakan to the complex. The iron ore and pellet are discharged and transferred to the storage and retrieval Unit by conveyor belts. The limestone is supplied from the Mobarakeh Steel limestone mine located 15kilometers southeast of the Mobarakeh Steel, where it is converted into calcined lime in two rotary horizontal kilns with a length of 38 meters and a diameter of 3.8 meters at a temperature of 900 to 1100 ^{o}C. The produced lime is used in the steelmaking unit. straight production line, numbered 1, consists of 5 similar modules of MIDREX Series 600 with a nominal capacity of 600 thousand tons per module, and one module of

Series 800 with a nominal capacity of 800 thousand tons. Unit 2 of the straight production line consists of two Mega modules of 5.1 million tons each. The duty of these units is to convert oxide pellets into sponge iron with a minimum iron concentration of 92% and 0.1% carbon. The steelmaking has 8 electric arc furnaces with a nominal capacity of 200 tons of molten steel in each furnace. The metallic charge ratio in these furnaces is a maximum of 10% scrap iron and 90% sponge iron, which can vary depending on the organization's conditions and the market. Three graphite electrodes with a diameter of 700 millimeters are used in these furnaces to create an electric arc. The metallic charge melts at a temperature of 1537 ºC, but to increase the fluidity of the molten materials and prevent temperature loss, it is raised to over 1650 ºC. Production of steel from scrap is a recycling process that reduces environmental impacts. Steel production using electricity generates two main byproducts: toxic dust from the EAF and non-hazardous slag. In every ton of steel, 10-15% by weight of slag and 15-20 kilograms of EAF dust are formed. Steel production from scrap consumes 56% less energy than producing it from iron ore and coal. Steel production from scrap reduces CO_2 emissions by up to 58% and also reduces harmful mining activities[11].

1.3. Literature review

Life cycle assessment (LCA) is an effective method for evaluating environmental impacts and has been widely used in the iron and steel industry. Some of the work that has been done on the application of the LCA method in the steel industry includes the studies by Rosi et al., which used LCA to conclude that blast furnace steel production has the highest CO_2 emissions and fossil fuel consumption. These studies not only provided many optimization measures for the development of a low-carbon iron and steel industry in China, but also collected valuable data for LCA[12]. In 2013, Burchart-Korol used LCA to evaluate the environmental impacts of steel production in Poland. In his research, he examined steel production through integrated production and EAF routes based on scrap iron. He concluded that in the EAF process, the consumption of fossil fuels, greenhouse gas emissions, and consequently the environmental impact are lower compared to the Blast Furnace-Basic Oxygen Furnace (BF-BOF) method. The greenhouse gas emissions for each ton of steel produced by the electric arc method were 913 kg of CO_2, significantly lower than the BF method, which produced 2459 kg of CO_2 per ton of steel[13]. Huimin Liu et al (2020)., used life cycle assessment method to carry out inventory and quantitative analysis on the environmental impact of steelmaking system .In this study, they examined four impact categories: human health, climate change, ecosystem quality, and resources. They found that the molten iron stage has the greatest impact on human health, followed by the greatest impact on resources. The impact of scrap steel on human health ranks third. Molten iron is a key process that affects human health, climate change, ecosystem quality, and resources. Additionally, processes such as fuels, working fluids, and auxiliary materials also cause certain environmental damage, accounting for a relatively small proportion[14] .Gulnur et al (2016)., evaluated the environmental effects of the steel industry using the LCA method in Turkey. They did this assessment using SimaPro software and IMPACT 2002+ impact assessment method with the purpose of comparing the impacts of processes (coke making, sintering, iron making, steel making) and final products (billet, slab, hot rolled wire rod, hot rolled coil), concurrently. System boundary was set as cradle-to-gate and functional unit was selected as 1 ton of final steel product. The study found that the steel making process exhibited the highest total environmental impact, followed by sintering. The highest impacts were in the categories of human health and climate change. The coke production process showed the highest impact on depletion of non-renewable energy sources, but had a negative contribution in the climate change category due to the avoided external energy consumption from the production of coke oven gas[15]. Wang et al. examined three nickel production processes, including the EAF route. They reported that

electricity consumption was the primary driver of environmental impact in the EAF process. However, the EAF process exhibited the lowest level of environmental impacts compared to the other nickel production pathways evaluated[16].
Most of the existing research on life cycle assessment (LCA) of the steel industry has been based on data from the researchers' own countries. Given that Iran is one of the major steel producers in the world, life cycle assessment of the steel industry using the LCA method has been carried out. (The case study is Khouzestan Steel). but in this work, we performed an LCA of the steel industry specifically for Mobarakeh Steel Company. The key distinction from prior studies is that we expanded the system boundaries to include the upstream processes of iron ore extraction and concentrate production - components that had not been incorporated in previous steel industry LCAs. Additionally, we quantified the monetary costs of the environmental damages associated with steel production. In other words, we determined the monetary value or externality costs of each environmental impact category, in order to establish the hidden or "external" costs per ton of steel sheet produced. This comprehensive LCA approach, incorporating the full production chain from iron ore to finished steel, along with the monetization of environmental impacts, distinguishes this study from previous assessments of the steel sector. The results provide a more holistic understanding of the environmental performance and associated externality costs of steel manufacturing.

2. Methods

As mentioned in the introduction section, according to ISO 14040 standard, a life cycle assessment consists of four main parts[17].
Definition of the goal and scope: The environmental impact of steel production activities in Mobarakeh Steel Company is identified through this study using the life cycle assessment method. The research objectives were achieved within the framework of parameters and its scope. The inputs and outputs of each stage of production are converted into functional unit of 1 ton of steel, which serves as the measurement or functional unit in this study Steel production in EAF is primarily carried out using sponge iron and scrap in ratios ranging from 90 to 10 to 70 to 30. The boundary under investigation includes iron ore extraction, pellet production, sponge iron production, EAF, continuous casting, and hot rolling. Figure 2 illustrates the system boundary and flow chart of each section of steel production along with the inputs and outputs of each section.
Inventory analysis: Data inventory analysis in production systems, including inputs from resources, materials, by-products, products, emissions and excess products. At this stage, input data are summarized as electrical energy, raw materials, and chemicals, while outputs become goods produced by each unit processing the products.
Life cycle impact assessment: environmental impact assessment is a part of life cycle assessment aimed at identifying and evaluating the significance of significant environmental impacts of a system due to its product life cycle.
Interpretation: The conclusions, limitations, and recommendations are all part of the interpretation. The interpretation of the results of the latest life cycle assessment section explains the outcomes and provides options for reducing these outcomes [16].
We assess the boundary of our evaluation by focusing on steel production, from iron ore extraction to the production of steel sheets as shown in figure 2. The input and output data for steel sheet production at the steel plant will be as shown in table 1. According to figure 2, the first stage is iron ore extraction and concentrate production. The mining activity can be described by operations of dismantling, loading and transportation of ore and waste. Dismantling is done mainly by tractors or dozers and to a lesser extent with the use of explosives. Loaders load trucks with waste and shippers feed conveyor belts with ore. Waste is transported to final repositories exclusively by off-road diesel trucks, but ore is transported to the

processing facilities mostly by electric conveyor belts. Mining activities use tractors, excavators, loaders, diesel trucks and stationary equipment such as shippers and electric conveyor belts. In Processing, ore is crushed and classified into particle size sieves and then feed the concentration plant. In this Plant, ore undergoes a milling step to release silica and then is conducted to flotation cells where silica is removed to form two products: tailings (primarily SiO_2) and concentrate (mainly Fe_2O_3). Processing activities use crushers, screens, mills and water pumps, all electric driven. Grinding processes use ball grinders composed of metallic alloys. In the concentration step, the main chemicals used are: amine, starch and caustic soda. Then these concentrates are entered into the Pelletizing unit to produce our product[18].

2.1. Life Cycle Impact Assessment (LCIA)

Life cycle assessment (LCA) quantitatively demonstrates the full life cycle impacts of products. In this study, the LCA of steel sheet production was performed using SimaPro version 9.5.0.2 software and the Ecoinvent database. To select the method, considering that the iron and steel industry also has negative impacts on human health and resource consumption, the ReCiPe Midpoint H method was chosen for modeling these categories. The main objective of the ReCiPe method is to convert the long list of life cycle inventory results in a study into a limited number of indicator scores that express the relative intensity of an environmental impact category. This method has 18 midpoint indicators (climate change, ozone depletion, ionizing radiation, carcinogenicity, non-carcinogenicity, etc.) which ultimately include three main endpoints: human health, ecosystem damage, and resource scarcity, obtained using the ReCiPe Endpoint H method[21].

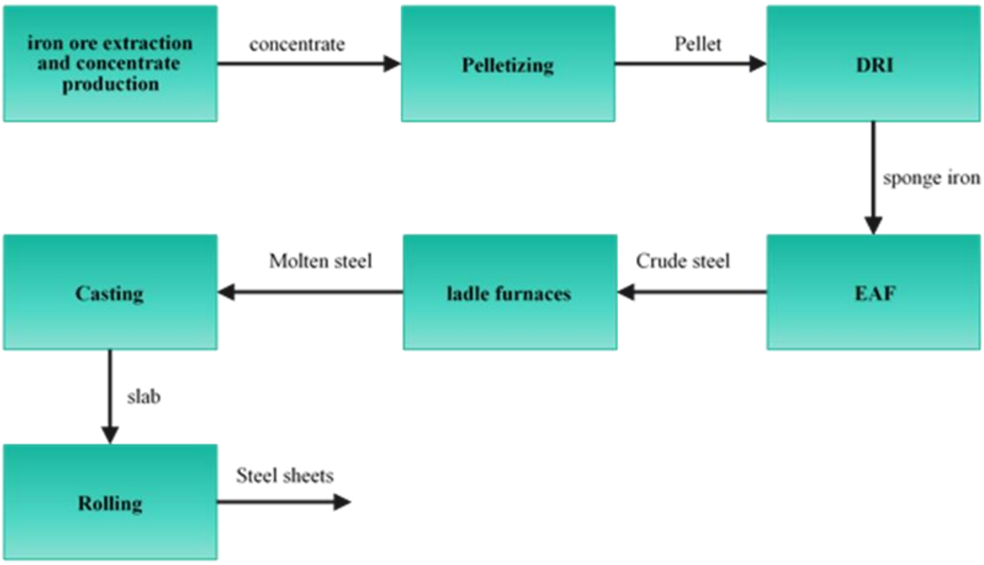


Fig. 2. system boundary and flow chart of each section of steel production.

Table 1. Input of available units to produce one ton of steel sheet.

Inputs outputs	Unit	Concentrate	Pellets	DRI	EAF	Ladle furnaces	Casting	Rolling	References
Diesel	kg	0.63	-	-	-	-	-	-	[18]
Conveyor belt	m	1.42e-5	-	-	-	-	-	-	[18]
Explosives	kg	26.34	-	-	-	-	-	-	[18]
NaOH	kg	1.36	-	-	-	-	-	-	[18]
Amines	kg	0.24	-	-	-	-	-	-	[18]
Grinding media	kg	2.3	-	-	-	-	-	-	[18]
Floculant	kg	0.06	-	-	-	-	-	-	[18]
Coagulant	kg	0.003	-	-	-				[18]
Lime	kg	0.02	7.2	0.5	-	-	-	-	Expert
Iron ores	ton	3	-	-	-	-	-	-	Expert
Concentrate	ton	-	2	-	-	-	-	-	Expert
Bentonite	kg	-	5.74	-	-	-	-	-	[4]
Natural gas	m^3	-	18	217.64	-	35	1.02	34.96	Expert
Electricity	kWh	200.6	45	152.1	575	57	17.3	101.4	Expert
Water	m^3	1.75	0.23	2.7	1.9	0.47	1.5	0.99	Expert
Oxygen	kg	-	-	22	12.87	-	-	-	[4]
Pellets	ton	-	-	1.9		-	-	-	Expert
Ferromanganese	kg	-	-	-	0.15	0.15	-	-	[4]
Ferrosilicon	kg	-	-	-	1.2	0.94	-	-	[4]
Iron scrap	ton	-	-	-	0.21	-	-	-	Expert
Dolomite	kg	-	-	-	4.17	-	-	-	[4]
Limestone	kg	-	-	-	91.76	0.05	-	-	[4]
Electrode	kg	-	-	-	1.6	0.7	-	-	[19]
Petroleum coke	kg	-	-	-	0.14	0.08	-	-	[4]
Aluminium	kg	-	-	-	0.17	0.01	-	-	[4]
Refractories	kg	-	-	-	7.6	11.3	-	-	[20]
Sponge iron	ton	-	-	-	1.21		-	-	Expert
Crude steel	ton	-	-	-	-	1.14	-	-	Expert
CaCl2	kg	-	-	-	-	0.09	-	-	[4]
Nitrogen	kg	-	-	-	-	0.84	-	-	[4]
Argon	kg	-	-	-	-	0.94	-	-	[4]
Molten steel	ton	-	-	-	-	-	1.04	-	Expert
Bullion	ton	-	-	-	-	-	-	1.02	Expert

3. Results

The results of the assessment for 1 ton of steel sheet production, considering the contribution of each process, are presented in Table 2 and Figure 3 using the ReCiPe H method. The normalized results are provided in Table 3 and Figure 4, and the contribution of each steel manufacturing unit process to the three main endpoint indicators is shown in Figure 5 .In the production of one ton of product, the input from the previous process was not considered; for example, the production of sponge iron was done without scrap input, and similarly for other processes .This approach provides a detailed breakdown of the environmental impacts at each stage of the steel sheet manufacturing. The normalized results also give insight into the relative significance of the different impact categories. Based on the results obtained, the total amount environmental and human health impacts of producing 1 ton of steel sheet are reported as 4.4 pt. Around 1.94 pt (44%) of this is related to human carcinogenic toxicity, with 35% of this impact coming from the EAF unit due to the use of alloy materials such as ferromanganese and refractory materials. 25% of the human toxicity impact is from mining and concentrate production. The share of the Fossil resource scarcity index is 0.61 pt, with 40% of it related to the sponge iron unit, which uses natural gas and electricity as its fuel sources, 20% related to the EAF unit and 15% related to the concentration unit. The next rank of environmental impact consists of the ozone formation (terrestrial ecosystems) with a share of 0.35 pt and 0.30 pt is related to ozone formation (human health) index, the contribution of other indices can also be seen in Table 3.

Table 2 .Results of the LCA of 1 ton of steel sheet, considering the contribution of each process, using the ReCiPe. Midpoint H method.

Impact category	Unit	Concentrate	Pellets	DRI	EAF	ladle furnaces	Casting	Rolling	Total
Global warming	kg CO2 eq	363.7815	43.01469	245.3403	527.018	77.89444	13.14018	138.5361	1408.725
Stratospheric ozone depletion	kg CFC11 eq	0.000384	1.32e-05	6.74e-05	0.000155	2.29e-05	4.6e-06	4.32e-05	0.00069
Ionizing radiation	kBq Co-60 eq	0.439215	0.330841	1.658158	4.464688	0.521387	0.132309	1.118703	8.6653
Ozone formation, Human health	kg NOx eq	3.768856	0.101016	0.578424	1.07652	0.187729	0.029536	0.319903	6.061984
Fine particulate matter formation	kg PM2.5 eq	1.57826	0.071935	0.310047	0.943497	0.127057	0.025577	0.237016	3.29339
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.848591	0.108889	0.661126	1.102194	0.203717	0.030474	0.342873	6.297864
Terrestrial acidification	kg SO2 eq	3.191391	0.118987	0.560669	1.48893	0.222821	0.041055	0.387651	6.011503
Freshwater eutrophication	kg P eq	0.009573	0.001733	0.007918	0.02216	0.002912	0.000644	0.005766	0.050707
Marine eutrophication	kg N eq	0.076207	0.000127	0.000712	0.001878	0.000259	3.97e-05	0.000396	0.079618
Terrestrial ecotoxicity	kg 1,4-DCB	1587.226	29.59825	167.4545	498.2218	59.22823	9.401174	90.05178	2441.182
Freshwater ecotoxicity	kg 1,4-DCB	5.351973	0.013964	0.096371	0.209714	0.069777	0.003754	0.042433	5.787987
Marine ecotoxicity	kg 1,4-DCB	3.394966	0.04104	0.279835	0.589385	0.141411	0.010618	0.124047	4.581301
Human carcinogenic toxicity	kg 1,4-DCB	5.223703	0.337149	2.524438	6.898751	3.934512	0.085258	1.044753	20.04856
Human non-carcinogenic toxicity	kg 1,4-DCB	76.33773	5.689376	26.71086	83.76876	13.63881	2.031131	18.66685	226.8435
Land use	m2a crop eq	74.6	0.712275	4.119621	7.34572	1.777854	0.208665	2.184539	90.96952
Mineral resource scarcity	kg Cu eq	118	0.11127	0.437105	1.047817	0.42373	0.010361	0.147107	120.6691
Fossil resource scarcity	kg oil eq	95.5	25.05291	235.6559	117.0476	47.02843	4.042427	75.19316	599.3403
Water consumption	m3	5.72	0.478021	4.348807	5.255098	0.994508	1.077112	2.299532	20.16983

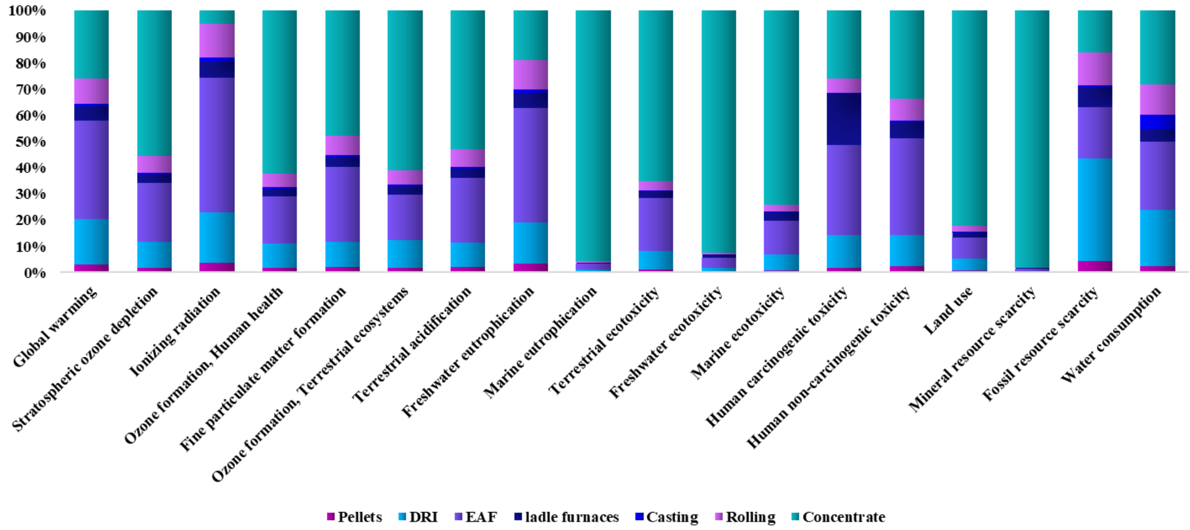


Fig. 3. Results of the life cycle assessment of 1 ton of steel sheet, considering the contribution of each process, using the ReCiPe Midpoint H method.

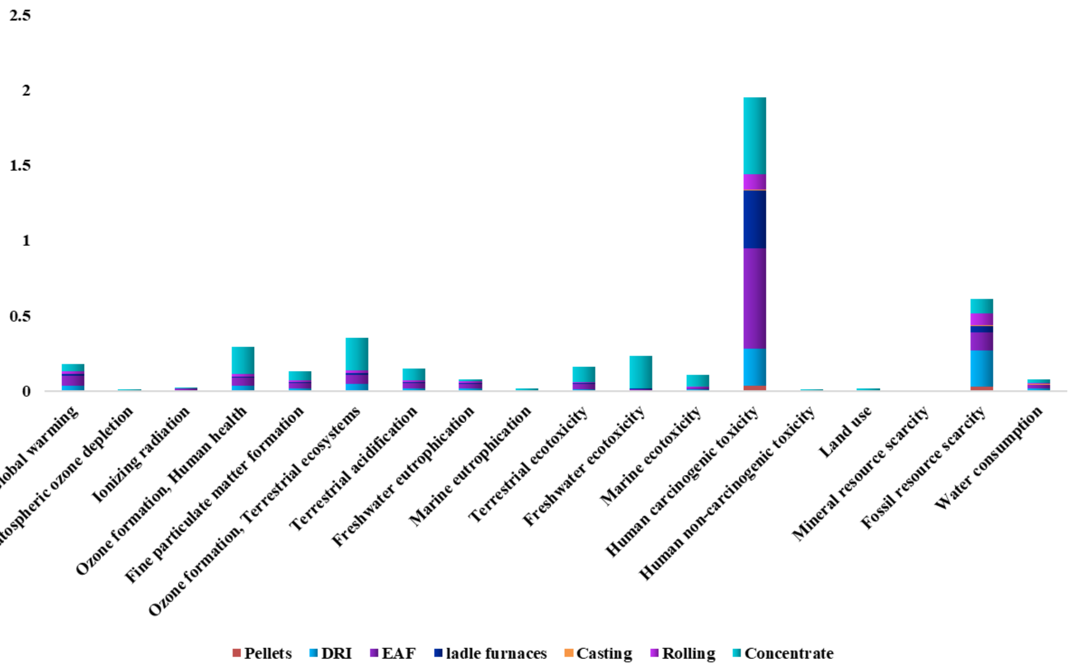


Fig. 4. Normalized results of the life cycle assessment of 1 ton of steel sheet, considering the contribution of each process, using the ReCiPe Midpoint H method.

Table 3. Normalized results of the life cycle assessment of 1 ton of steel sheet, considering the contribution of each process, using the ReCiPe Midpoint H method.

Impact category	Unit	Concentrate	Pellets	DRI	EAF	Ladle furnaces	Casting	Rolling	Total
Global warming	pt	0.045472682	0.005377	0.030668	0.065877	0.009737	0.001643	0.017317	0.176091
Stratospheric ozone depletion	pt	0.006415654	0.000221	0.001125	0.002582	0.000382	7.69e-05	0.000722	0.011525
Ionizing radiation	pt	0.000913568	0.000688	0.003449	0.009287	0.001084	0.000275	0.002327	0.018024
Ozone formation, Human health	pt	0.183166405	0.004909	0.028111	0.052319	0.009124	0.001435	0.015547	0.294612
Fine particulate matter formation	pt	0.061709961	0.002813	0.012123	0.036891	0.004968	0.001	0.009267	0.128772
Ozone formation, Terrestrial ecosystems	pt	0.216675664	0.00613	0.037221	0.062054	0.011469	0.001716	0.019304	0.35457
Terrestrial acidification	pt	0.077869939	0.002903	0.01368	0.03633	0.005437	0.001002	0.009459	0.146681
Freshwater eutrophication	pt	0.01474262	0.00267	0.012193	0.034126	0.004485	0.000992	0.00888	0.078089
Marine eutrophication	pt	0.016536906	2.75e-05	0.000154	0.000408	5.62e-05	8.62e-06	8.59e-05	0.017277
Terrestrial ecotoxicity	pt	0.104439457	0.001948	0.011019	0.032783	0.003897	0.000619	0.005925	0.16063
Freshwater ecotoxicity	pt	0.212473336	0.000554	0.003826	0.008326	0.00277	0.000149	0.001685	0.229783
Marine ecotoxicity	pt	0.078084222	0.000944	0.006436	0.013556	0.003252	0.000244	0.002853	0.10537
Human carcinogenic toxicity	pt	0.507221567	0.032737	0.245123	0.669869	0.382041	0.008279	0.101445	1.946716
Human non-carcinogenic toxicity	pt	0.002442807	0.000182	0.000855	0.002681	0.000436	6.5e-05	0.000597	0.007259
Land use	pt	0.012088576	0.000115	0.000667	0.00119	0.000288	3.38e-05	0.000354	0.014737
Mineral resource scarcity	pt	0.000987036	9.27e-07	3.64e-06	8.73e-06	3.53e-06	8.63e-08	1.23e-06	0.001005
Fossil resource scarcity	pt	0.09722632	0.025554	0.240369	0.119389	0.047969	0.004123	0.076697	0.611327
Water consumption	pt	0.02143781	0.001793	0.016308	0.019707	0.003729	0.004039	0.008623	0.075637

pt: point

During the production of one ton of steel product, the EAF process accounts for 26.6% of the total environmental impacts, mainly due to electricity consumption (approximately 46%) and the use of additives such as alloys (around 17%). 38% of the impacts are related to the mining and concentrate production unit, primarily due to iron ore extraction activities (approximately 72%), the blasting process, and explosive materials such as nitroglycerin used in processes like crushing rocks (around 21%). Another significant process in terms of impact is the sponge iron production unit, accounting for 15%, The dominant factors underlying this impact are the consumption of natural gas (70%) and electricity (25%). The ladle furnace unit accounts for 11% of the environmental effects, primarily due to alloy addition (approximately 56%), natural gas consumption (around 15%), and electricity consumption (approximately 12.5%). the rolling process also has a 7% impact, mainly due to electricity consumption (59%) and natural gas consumption (38%).

According to Table 3, the total impact of the mining and concentrate production unit was 1.66 pt, with around 0.50 pt related to the release of carcinogenic substances. The data indicates that the presence of cadmium and arsenic ions accounts for 69% of the total impact. Emissions of toxic gases into the environment will have an impact of approximately 0.22pt and rank second, with 83% of these emissions attributed to grinding media. Additionally, freshwater contamination with a score of 0.212 ranks third. Another significant impact of this unit is the depletion of natural resources, specifically the reduction of iron ore due to mining activities.

The total impacts of the EAF process, 1.17 pt, were obtained, with 57% of it related to the emission of carcinogenic substances (Approximately. 60% of this carcinogenic impact is due to the use of refractory materials and alloys like ferromanganese in the EAF process). The indicator of fossil resource scarcity in the EAF unit accounts for approximately 0.12 pt. It is clear that the main input of the EAF is electricity, which has a fossil fuel-based origin. Therefore, around 86% of the electricity consumption is the factor contributing to this indicator in the EAF unit. This unit also has a significant impact on the global warming index, with its share in this indicator being approximately 0.066pt.

The third unit that significantly contributes to environmental impact is the sponge iron production unit, with a share of approximately 20.66%. his unit has the most significant impact on reducing fossil fuel indicators due to high natural gas consumption and the emission of carcinogenic substances, both accounting for a 36% share. Another significant impact area for the sponge iron production unit is the global warming index, with a share of approximately 0.031pt. Another unit that has a significant environmental impact is the Ladle Furnace (LF) unit. The total impact of this unit is 0.49pt, with 77% of it attributed to being carcinogenic, this is entirely reasonable as the ladle furnace is the location where molten steel and required alloys are mixed to produce steel sheets. Approximately 90% of the total environmental and human health impacts associated with the production of one ton of steel sheets are concentrated in these four units mentioned (EAF, DRI, and LF).

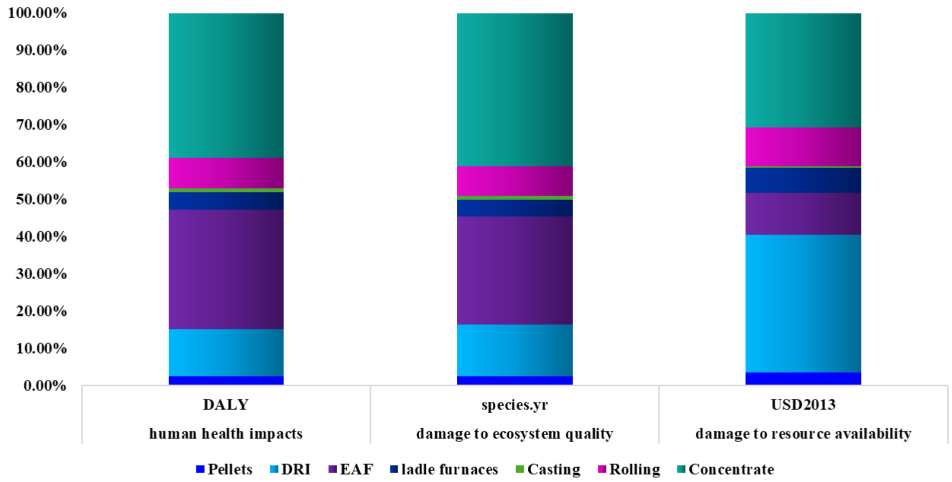


Fig.5. The share of each steel production input in the endpoint indicators.

The other steel production units, such as Rolling (0.28 pt), Pellet Production (0.09 pt), and Casting (0.02pt), also have smaller but still notable contributions to the overall environmental impact). Figure 5 illustrates the contribution of each steelmaking unit to the endpoint indicators. the total impacts of the units are based on the normalized value of 0.16pt. The total effects by endpoint indicators are given in Table 4 .The extraction and concentration unit has an overall impact of 38%. When disaggregating the level of impacts by indicator, it is approximately 39%, 41%, and 30% on the human health, ecosystem, and resource indicators, respectively. The EAF unit has an impact of around 31%. This furnace affects the human health indicator by 32%, the ecosystem indicator by 29%, and the resource indicator by 11% .The direct reduced iron production unit has a 12.6% impact on the human health indicator, a negligible 2.4% impact on the ecosystem indicator, and a significant 37% impact on the resource indicator. The impacts of the other units are also presented in Table 4. In Table 5, the results obtained in this study are compared with the findings from other studies in Iran and other countries, as well as different steelmaking methods. The significant difference in this study compared to other studies lies in the scope

Table 4. The normalized results of the effects of each steelmaking unit on the final indicators of ReCiPe Endpoint H.

Damage category	Unit	Concentrate	Pellets	DRI	EAF	Ladle furnaces	Casting	Rolling	Total
human health impacts	pt	0.0573	0.003688	0.018622	0.047245	0.007099	0.001319	0.012094	0.147367
damage to ecosystem quality	pt	0.001979	0.000117	0.00067	0.001399	0.000217	4.57e-05	0.000383	0.00481
damage to resource availability	pt	0.002342	0.000271	0.002823	0.000858	0.000522	3.26e-05	0.000794	0.007642
total	pt	0.061621	0.004076	0.022115	0.049502	0.007838	0.001398	0.013271	0.15982

of this study, which starts from iron ore extraction and concentrate production and continues to steel sheet production. However, it is observed that in most indicators, there is not a considerable difference, and the environmental effects of steel production are almost similar.

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Table 5. Comparison of life cycle assessment results the present study with existing scientific sources.

Impact category	Unit	this study EAF ReCiPe	Scientific resources based on the analysis method and furnace type EAF ReCiPe [22]	IMF ReCiPe [23]	EAF + BF CML [24]	BOF ReCiPe [22]	IMF CML-IA [25]
Global warming	kg CO_2 eq	1408.725	913	5289	605	1703	720
Stratospheric ozone depletion	kg CFC11 eq	0.00069	-	0.001	0.000061	-	0.000027
Ionizing radiation	kBq Co-60 eq	8.6653	-	19.84	-	-	-
Ozone formation, Human health	kg NO_x eq	6.061984	-	5.6	-	-	-
Fine particulate matter formation	kg PM2.5 eq	3.29339	0.93	17.58	-	4.61	-
Ozone formation, Terrestrial ecosystems	kg NO_x eq	6.297864	-	-	1.102194	-	-
Terrestrial acidification	kg SO_2 eq	6.011503	2.96	7.83	2.02	4.81	5.5
Freshwater eutrophication	kg P eq	0.050707	0.55	0.47	-	0.81	-
Marine eutrophication	kg N eq	0.079618	0.17	0.001	-	0.30	-
Terrestrial ecotoxicity	kg 1,4-DCB	2441.182	0.07	14392	63.4	0.17	0.043
Freshwater ecotoxicity	kg 1,4-DCB	5.787987	8.3	-1.4	370	12.77	5.2
Marine ecotoxicity	kg 1,4-DCB	4.581301	8.46	6.2	472000	13.32	27000
Human carcinogenic toxicity	kg 1,4-DCB	20.04856	412	398	570	643	590
Human non-carcinogenic toxicity	kg 1,4-DCB	226.8435					
Land use	m^2a crop eq	90.96952	21.17	202	-	57.96	-
Mineral resource scarcity	kg Cu eq	120.6691	-	145	-	850	-
Fossil resource scarcity	kg oil eq	599.3403	171	1328	-	529	-
Water consumption	m^3	20.16983	2.24	56.7	-	87.44	-

4. Life Cycle Cost (LCC) Evaluation

As stated, external costs, also known as externalities, arise when the social or economic activities of one (group of) person(s) have an impact on another (group of) person(s) and when that impact is not fully accounted, or compensated for, by the first (group of) person (s). For example, automobiles that emit NO_x from their exhaust harm human health, but this harm is not factored in by the vehicle purchaser. This unaccounted-for impact is recognized as an externality or hidden cost.

In essence, externalities refer to the difference between social costs (i.e. all costs to society) and private costs (i.e. the costs directly borne by the user). Social costs encompass the full spectrum of economic and environmental consequences, whereas private costs only reflect the expenditures directly incurred by the individual or organization undertaking the activity[26]. As mentioned in the previous sections, we have identified various types of environmental and social impacts. The goal now is to quantify the monetary value of these externalities.

One approach we can use for this is environmental lifecycle cost assessment. The product lifecycle refers to the timeframe from the initial identification of the need for a product, to the final disposal or decommissioning of that product. The lifecycle cost (LCC) encompasses all the costs associated with the product over this entire lifecycle. LCC analysis, is an engineering economics-based decision-making tool. It allows for the examination and analysis of all the visible and hidden costs of an asset throughout its lifecycle. Over the years, the LCC concept has evolved and is now widely used across many industries. LCC analysis provides a comprehensive view of the true economic implications of a product or system, going beyond just the initial purchase price or short-term operating costs[27].

Currently, there are three types of life cycle costs (LCC): conventional LCC, environmental LCC, and social LCC. Conventional LCC encompasses all the costs that are directly covered by the producer or the end-user during the product's life cycle, such as investment costs and operational costs. Environmental LCC contains conventional LCC and the value of externalities (positive or negative) resulting in different phases of the product life cycle. Costs are directly related to one or more actors in the supply chain and thanks to the expression in monetary values they can be internalized in the account of polluters. The third kind of LCC is societal LCC. It includes environmental LLC and the value of externalities covered by anyone in the society, which could potentially occur in the future as a result of various phases of the product life cycle and which are not internalized in the account of polluters. This concept is still in the development phase[27][28]. According to the above definitions, we can use the second type of life cycle cost to calculate the externality of the steel industry.

Calculating the value of environmental LCC is not easy, because it requests to express in monetary terms environmental effects which don't have a market value in most cases. The primary objective of this section is to present a conceptual framework for expressing the results of the LCA of the production of one ton of steel product in monetary terms and to calculate the environmental life cycle costs based on these results. We obtained data from the existing literature regarding the damage cost estimates identified in the life cycle assessment section. Given that these data had different values, we calculated the average of these costs. Additionally, since these costs were originally calculated for different years, we adjusted them to the base year of 2023 using the Consumer Price Index (CPI) according to Eq. (3), and the results are presented in Table 6[29]. CPI index values were obtained from [30].

$$Final\ value_{\ i} = Present\ value_j \times \frac{CPI_{final,i}}{CPI_{initial,j}} \tag{3}$$

where:

Final value: represents the MVCs for the year i adjusted for inflation;

Present value: represents the MVCs in the year j (this is the year set as the "Present year");

CPIfinal,i: represents the CPI value for the year i;

CPIfinal,i: represents the CPI value for the year j (this is the year set as the "Present year").

By multiplying the damage estimates calculated in the life cycle assessment section using the Simapro software with the corresponding damage cost per impact category provided in Table 6, the externality cost of producing one ton of steel sheet can be obtained, as shown in Table 7. It is worth noting that the average of the cost estimates was used in this assessment. According to Table 7, the total externality cost of producing one ton of steel sheet is approximately 846 846 EUR, with the global warming impact accounting for the largest share at 462 EUR.

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Table 6 . Base life cycle cost of a product.

Impact category	Unit	value			References		
		Min	Max	Ave	Min	Max	Ave
Global warming	€$_{2024}$ /kg CO_2	0.0355	0.8261	0.328	[29]	[29]	[29]
Stratospheric ozone depletion	€$_{2024}$/kg CFC-11 eq	38.59	138.69	66.93	[29]	[29]	[29]
Ionizing radiation	€$_{2024}$/kBq U-235 eq	0.00012	1.218	0.257	[29]	[29]	[29]
Fine particulate matter formation	€$_{2024}$ /kg $PM_{2.5}$ eq	41.3	43.41	42.36	[31]	[32]	[32][31]
Terrestrial acidification	€$_{2024}$/kg SO_2 eq	0.259	19.17	4.9	[29]	[29]	[29]
Freshwater eutrophication	€$_{2024}$/kg P eq	0.259	16.95	5.479	[33]	[32]	[33][32][34][35]
Marine eutrophication	€$_{2024}$/kg N eq	2.3	24.6	12.019	[33]	[32]	[32][33][26][34][35][36]
Freshwater ecotoxicity	€$_{2024}$/kg 1–4DB eq.	0.0036	68.74	20.96	[37]	[38]	[39][34][38][37]
Human toxicity	€$_{2024}$/kg 1–4 DB eq	0.0293	0.387	0.148	[29]	[29]	[29]
Land use	€$_{2024}$/m^2 a	0.107	0.87	0.48	[34]	[26]	[26][34]
Fossil resource scarcity	€$_{2024}$/MJ	0.0016	0.021	0.013	[29]	[29]	[29]
Water consumption	€$_{2024}$/m^3	0.0061	0.259	0.117	[35]	[40]	[31][40][35]

Table7. Life cycle cost of one ton of steel sheet.

Impact category	Base cost (€$_{2024}$)	Impact rate	Externality of 1 ton of steel sheet (€$_{2024}$)
Global warming	0.328	1408.725	462.0618
Stratospheric ozone depletion	66.93	0.00069	0.0461817
Ionizing radiation	0.257	8.6653	2.2269821
Fine particulate matter formation	42.36	3.29339	139.5080004
Terrestrial acidification	4.9	6.011503	29.4563647
Freshwater eutrophication	5.479	0.050707	0.277823653
Marine eutrophication	12.019	0.079618	0.956928742
Freshwater ecotoxicity	20.96	5.787987	121.3162075
Human toxicity	0.148	246.89206	36.54002488
Land use	0.48	90.96952	43.6653696
Fossil resource scarcity	0.013	599.3403	7.7914239
Water consumption	0.117	20.16983	2.35987011
Total	153.991	_	846.2069773

5. Recommendations for Sustainable Steel Production

Despite the significant progress made by the steel industry in recent decades, there remains substantial potential to further enhance production efficiency and reduce energy consumption and greenhouse gas emissions. This potential is estimated to be around 20 percent[41]. The actual efficiency of the steel industry is around 32.9%, which is primarily due to the significant energy waste in this industry[42]. The following methods are recommended to increase efficiency:

- Increase utilization of recycled steel: Recycling steel requires significantly less energy and resources compared to producing steel from iron ore. Implementing policies and incentives to enhance the collection and recycling of steel scrap can reduce the environmental impact and improve overall efficiency.
- Improve energy efficiency in steel mills: Investing in energy-efficient technologies, such as EAF, can lower the energy consumption and greenhouse gas emissions associated with steel production, thereby increasing the industry's efficiency.
- Optimize production processes: Continuous improvement of production processes, such as optimizing material and energy inputs, reducing waste and byproducts, and adopting lean manufacturing principles, can enhance the overall efficiency of steel production.

For environmental considerations, it is logical to prioritize the units that have a higher environmental impact based on our research. In the study conducted, the iron ore extraction and concentrate production units were found to have the greatest impact on the natural resource depletion indicator, which is understandable due to the consumption of iron ore. However, in the human toxicity category, these units also had a significant impact due to the use of explosives and mining activities. The EAF unit is another major contributor to the high energy consumption in the steel production process. The predominant impact of this unit is the use of fossil fuels to supply the required energy. However, in this unit, we can also utilize clean energy alternatives, such as hydrogen or renewable energy sources, to provide the electricity needed. Nevertheless, the economic feasibility of the energy supply method must be considered. One of the influential factors affecting steel production is the impurity of the scrap feed. The introduction of these impurities into the furnace leads to increased energy consumption, as these impurities absorb energy. Pre-heating the consumed iron scrap can result in the removal of moisture, volatile substances, and hydrocarbons. Pre-heating the iron scrap and sponge iron can reduce the melting time and, consequently, the electricity consumption. This, in turn, can lead to a decrease in the dust emissions from the furnace. The energy required for this pre-heating can be obtained from the heat of the exhaust gases from the chimneys. For the sponge iron production unit, we can also use hydrogen gas as the reducing agent instead of natural gas. Additionally, we can utilize the off-gas from the chimneys to pre-heat the sponge iron, further reducing the electricity consumption.

6. conclusion

The steel industry is one of the most energy-intensive sectors, and its emissions have detrimental impacts on global warming. In this study, the externalities of steel production using the Electric Arc Furnace (EAF) were investigated. To identify the externalities of the steel industry, the Life Cycle Assessment (LCA) method was utilized, which is a powerful tool for evaluating environmental impacts. The key findings regarding the process-level impacts are as follows :Mining and concentrate production: This process accounts for 38% of the total environmental impacts, with the majority (around 72%) stemming from the iron ore extraction activities. EAF process: This process contributes 26.6% of the total impacts, primarily due to electricity consumption (around 46%) and the use of alloying additives (around 17%). Direct reduction (sponge iron) process: This process ranks third in terms of environmental impact, contributing 15% of the total. The main contributors are natural gas consumption (70%) and electricity use (25%). Additionally, carcinogenicity, fossil fuel reduction, and ozone formation) Terrestrial ecosystems and human health (were deliberately influential factors in these processes. These impact categories demonstrate the diverse environmental implications of the steel production system, ranging from human health concerns to resource depletion and ecosystem damage. The key points regarding the external costs associated with the production of 1 ton of steel sheets are: Total external costs: Approximately 846 EUR per ton of steel. Global warming impact: The most costly impact, accounting for around 462 EUR per ton. This represents the largest share of the external costs. Ionizing radiation: The second highest impact, costing around 139.5 EUR per ton. Freshwater ecotoxicity: The third highest impact, costing approximately 121.3 EUR per ton. It is hoped that the obtained results will assist decision-makers and professionals in the steel production sector as well as in the life cycle assessment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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