Lifecycle Assessment of Steel Rebar Production with Induction Melting Furnace: Case Study in Turkey

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Abstract: This paper demonstrates the utilization of the lifecycle assessment (LCA) methodology to determine the environmental burdens of steel rebar production with induction melting furnace technology. The data were obtained from an existing steel plant. The functional unit was selected as 1 t of steel rebar production. System boundaries were studied as cradle to gate. The lifecycle impact assessment analyses were considered in 11 impact categories. Analyses results summarized that the global warming potential of steel rebar production is approximately 720 kg CO_2 eq/t product. Electricity consumption was the major impact with effects on greenhouse gas emissions, fossil fuels–based abiotic depletion, ozone layer depletion, human toxicity, freshwater toxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication. Most of the impacts of steel rebar have resulted from steel billet because the steel billet is a semifinished product of steel rebar production. **DOI:** 10.1061/(ASCE)HZ.2153-5515.0000385.

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Introduction

Steel manufacturing is an extremely energy-intensive process. Traditionally, steel production has been divided into two production routes. The primary route uses iron ore as a ferrous resource and the secondary production route uses steel scrap as a ferrous resource and is less energy intensive than the primary route. Blast furnace (BF), basic oxygen furnace (BOF), and open hearth furnace (OHF) are the most used primary route methods, while the electric arc furnace (EAF) method is mostly used for the secondary route (Morfeldt et al. 2015). In Turkey, crude steel production is mainly based on the secondary route, with approximately 33.2 million tons in 2016 with an increase of approximately 50% from that of 2005 (Fig. 1). The Turkish steel sector has 31 steel plants, composed of 24 steel plants by the EAF route mode, three integrated steel plants, and four steel plants that use induction melting furnaces (IMFs) (TÇÜD 2015). Because the Turkish steel industry highly depends on the secondary route, it obtains 34% of its needed iron scrap from local sources and the rest is imported. The amount of imported scrap was 17.716 million tons in 2016, and the majority came from the United States, Russia, and the United Kingdom, with the United States ranking first (Demirdoven 2016; WSA 2011). The Turkish iron and steel industry accounts for approximately 25% of overall energy use in the manufacturing industry, hence it is of particular interest in the context of environmental impacts (Olmez et al. 2016). The first environmental impact regarding the steel industry is global warming resulting from foreground (natural gas burning) and background (production of consumed electricity) greenhouse gas emissions. In Turkey, CO_2 emissions of steel production are responsible for 3.6% of the total emissions (amounting to total greenhouse gas emissions of 467.6 million tons of CO_2 eq.) in the European Union; this percentage is 4.7% for the steel sector (Morfeldt et al. 2015).

Global warming potential is one of the indicators of an environmental performance and other indicators can be investigated by conducting a lifecycle assessment (LCA) study. LCA is a method that evaluates all the environmental impacts resulting from a service or a product. Among the tools available to assess environmental performance, LCA provides a holistic approach to evaluate environmental performance by considering the potential impacts from all stages of manufacture, product use, and end-of-life stages. LCA is a useful method to evaluate the steel production process in terms of environmental performance. Many researchers have performed LCA analysis for steel production based on country-specific data. Table 1 shows a summary of these studies.

As can be seen from Table 1, past studies have focused on blast furnace or electric arc furnace technologies. Different from the literature, this study focused on the environmental assessment of the steel production process with induction melting furnace.

Methodology

The LCA was performed following the requirements of ISO 14040 (ISO 2006). The four stages of the LCA include determination of the goal, scope, and system boundary; inventory analysis of inputs and outputs; assessment of environmental impact; and interpretation of results with proposals for enhancement applied.

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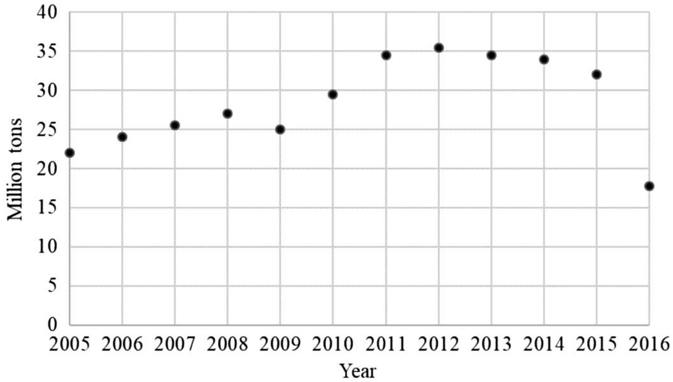

Fig. 1. Total crude steel production in Turkey between 2005 and 2016

Goal and Scope

The aim of this study was to carry out a LCA of steel rebar production by using induction melting furnace technology. The system boundary included the following processes: extraction and production of raw materials, transportation of raw materials, preparation and melting in the induction furnace, continuous casting plant, manufacturing of steel billet (semifinished product), cold rolling plant, and manufacturing of steel rebar (final product), respectively. Fig. 2 shows the system boundary with a process flow diagram. During the production, some valuable waste products [filter dust (fly ash), slag, and refractory wastes] were generated that were received by other factories. Processing of these wastes by other plants was excluded in the study. Infrastructure and the end-of-life phases were also excluded. The functional unit was selected as production of 1 t of steel rebar. All calculations were carried out considering this functional unit.

Lifecycle Data Inventory

Foreground data were mainly gathered from a steel factory in Turkey, while *Ecoinvent* was used for the background data. The steel rebar production is carried out in two stages in the factory. First, steel billet is produced in the steel mill section by using induction melting furnace, and then steel rebar is produced in the hot rolling plant. The steel billet is a semifinished product in order to use it in the steel rebar production phase. Foreground data regarding to steel billet production are given in Table 2. These data were associated with appropriate data from *Ecoinvent* in terms of data quality indicators (DQI) requirements (e.g., geographical and technological conditions). Electricity profile data were adapted from Günkaya et al. (2016) by using the electricity generation mix percentages of Turkey for 2017. The considered electricity generation mix is composed of 35% natural gas, 24.6% hydraulic, 31% coal (mainly hard coal, imported coal, and lignite), 10.9% wind, and 2% geothermal. Process water was used in the casting and hot rolling processes and recycled during the production. The transportation

Table 1. Literature Summary of LCA Studies on Steel Production

Researchers	Country: steel production routes	Main impacts and responsible processes
Olmez et al. (2016)	Turkey: integrated route (BF/BOF)	Human health and climate change Hot rolled coil
Renzulli et al. (2016)	Italy: BF	Ecotoxicity Blast furnace and coke oven operations
Hasanbeigi et al. (2016)	China, Mexico, Germany, and United States: EAF and BF	Electricity and pig iron consumption
Hu et al. (2014)	China: BF, BOF, EAF	Global warming potential and photochemical ozone creation potential Blast furnace
Gomes et al. (2013)	France: EAF combined with BF	Ecotoxicity Direct emissions from steel production
Burchart-Korol (2013)	Poland: integrated route (BF) and EAF	Human health Coke consumption in the blast furnace and iron ore consumption in the sinter plant

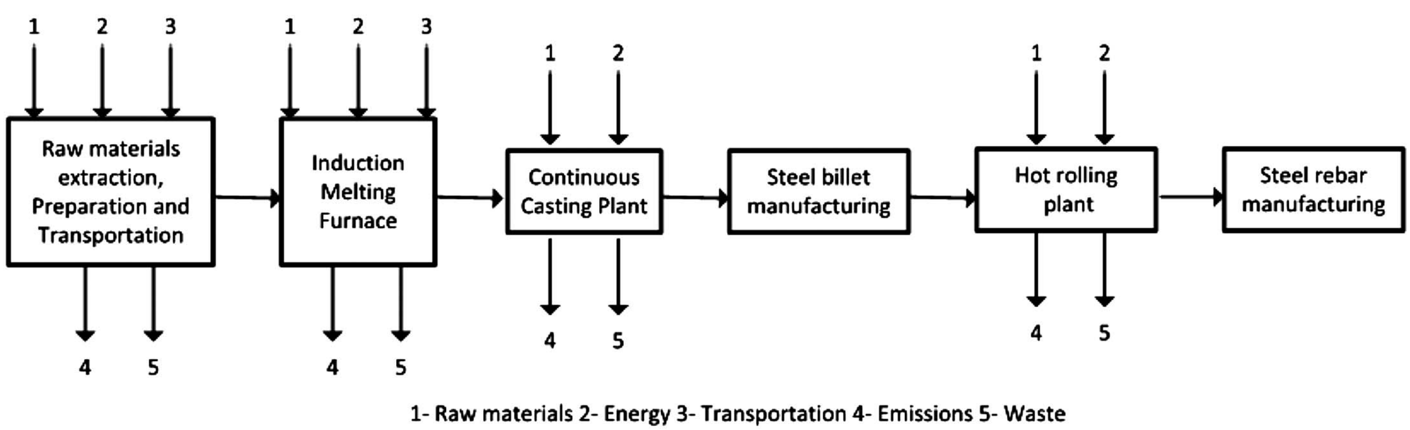

Fig. 2. System boundary and process flow diagram of steel rebar production

Table 2. Lifecycle Inventory of 1-t Steel Billet Production

Inputs and outputs	Units	Amounts	Average distances from suppliers to factory (km)
Inputs			
Iron scrap	kg/t	1,075	245
Ferrosilicon	kg/t	3.0	220
Ferrosilicon manganese	kg/t	8.0	220
Refractory	kg/t	14.0	70
Carbon black	kg/t	1.3	200
Fluorspar	kg/t	0.5	200
Limestone	kg/t	20.0	400
Liquid oxygen	kg/t	2.9	70
Aluminum electrode	kg/t	0.03	500
Graphite electrode	kg/t	0.8	450 + 12.500
Electricity	kWh/t	800	—
Natural gas	m^3/t	1.5	—
Process water	m^3/t	0.14	—
Transportation by freight lorry	$t \cdot km$	267.9	—
Transportation by freight transoceanic ferry[a]	$t \cdot km$	10	—
Outputs (emissions to air)			
CO_2	g/t	5,562	—
CO	g/t	516.93	—
NO	g/t	26.38	—
NO_2	g/t	187.75	—
Dust	g/t	43.87	—
Volatile organic compound	g/t	1.14	—
Total volatile organic compound (carbon)	g/t	12.59	—
HCl	g/t	0.87	—
HF	g/t	0.90	—
Pb	g/t	0.85	—
Cd	g/t	0.03	—
Hg	g/t	0.001	—
Zn	g/t	6.51	—
Ni	g/t	0.01	—
Cr	g/t	0.03	—
PCDD/F	g/t	1.63×10^{-8}	—
TPAH	g/t	0.07	—

Note: PCDD/F = polychlorinated dibenzodioxins/dibenzofurans; TPAH = total polycyclic aromatic hydrocarbon. Foreground data regarding steel rebar production are given in Table 3; as can be seen, the main component of steel rebar production is steel billet.
[a]Calculated by using distances between ports (National Imagery and Mapping Agency 2001).

data were calculated according to average distances between the steel plant and its suppliers (Table 2). The amount of atmospheric emissions was calculated from flue gas measurement by using the flue gas flow rate. There are no water emissions resulting from the production.

Lifecycle Impact Assessment

Environmental evaluation of the process was performed according to the *CML-IA* method for impact categories of abiotic depletion (elements and fossil fuel) (kg Sb eq. and MJ), global warming potential (kg CO_2 eq.), ozone layer depletion [kg trichlorofluoromethane (CFC-11) eq.], human toxicity [kg 1,4-dichlorobenzene (DB) eq.], freshwater aquatic ecotoxicity (kg 1,4-DB eq.), marine aquatic ecotoxicity (kg 1,4-DB eq.), terrestrial ecotoxicity (kg 1,4-DB eq.), photochemical oxidation (kg C_2H_4 eq.), acidification (kg SO_2 eq.), and eutrophication (kg PO_4^- eq.).

Depletion of abiotic resources consists of two impact categories, abiotic depletion of elements and abiotic depletion of fossil fuels.

Table 3. Lifecycle Inventory of 1-t Steel Rebar Production

Inputs and outputs	Unit	Amount
Inputs		
Steel billet	kg/t	1,031
Electricity	kWh/t	73.0
Natural gas	m^3/t	39.0
Process water	m^3/t	0.21
Outputs (emissions to air)		
CO_2	g/t	3,708
CO	g/t	37.8
SO_2	g/t	3.9
NO	g/t	179.7
NO_2	g/t	267.1
Dust	g/t	0.5

The element basis of abiotic depletion is related to extraction of minerals due to inputs in the system. The abiotic depletion factor (ADF) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and rate of deaccumulation (SimaPro 2017). Abiotic depletion of fossil fuels is related to the lower heating value (LHV) expressed in MJ per kg or m^3 fossil fuel. The reason for taking the LHV is that fossil fuels are considered to be fully substitutable (SimaPro 2017). The global warming characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as global warming potential for a time horizon of 100 years (GWP100) in kg carbon dioxide equivalent/kg emission (SimaPro 2017). The ozone layer depletion characterization model defines ozone depletion potential of different gases (kg CFC-11 equivalent/kg emission). The characterization factors of human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity are calculated with the Uniform System for the Evaluation of Substances (USES)–LCA (SimaPro 2017), describing fate, exposure, and effects of toxic substances for an infinite time horizon. Each toxic substance is expressed as 1,4-dichlorobenzene equivalents/kg emission (1,4-DB eq./kg) (SimaPro 2017). The photochemical oxidation (high NOx) model is developed by Jenkin, Hayman, and Derwent (SimaPro 2017) and defines photochemical oxidation expressed in kg ethylene equivalents per kg emission. Acidification potential is expressed in kg SO_2 eq./kg emission. Eutrophication potential is expressed in kg PO_4^{3-} eq./kg emission (SimaPro 2017).

Results and Discussion

The characterization results of the study are shown in Table 4 for each lifecycle phase of the steel rebar production. According to the results in Table. 4, the value of the element basis abiotic depletion is 7.4×10^{-6} kg Sb eq./t. The steel billet production stage is the major contributor to this impact as a result of ferrosilicon and ferrosilicon manganese production processes (92 and 3%, respectively) including molybdenite mine operation, chromite ore production, and ferronickel production. The fossil fuels–based abiotic depletion of steel rebar production is 9,500 MJ/t. This value results from electrical energy consumption for steel billet production (78.2%) and steel rebar production (natural gas consumption at furnace approximately 16.8%, electrical energy consumption 5%).

The GWP100 value of steel rebar production is 720 kg CO_2 eq./t. Electricity consumption for steel billet production is the major reason of this impact (93%). This large share of steel billet production stage resulted from electricity consumption (82%), raw materials acquisition (12%), and transportation by lorry (6%).

Table 4. Characterization Results of 1 t of Steel Rebar Production

Impact category	Unit	Steel billet production	Energy consumption	Process water usage	Total
Abiotic depletion (element)	kg Sb eq./t	7.3×10^{-6}	1.8×10^{-8}	2.3×10^{-10}	7.4×10^{-6}
Abiotic depletion (fossil fuels)	MJ/t	7.3×10^{3}	2.2×10^{3}	6.8×10^{-1}	9.5×10^{3}
Global warming (GWP100)	kg CO_2 eq./t	6.7×10^{2}	5.2×10^{1}	6.7×10^{-2}	7.2×10^{2}
Ozone layer depletion (ODP)	kg CFC-11 eq./t	2.1×10^{-5}	5.6×10^{-6}	1.1×10^{-9}	2.7×10^{-5}
Human toxicity	kg 1,4-DB eq./t	5.6×10^{1}	3.4×10^{0}	4.8×10^{-3}	5.9×10^{1}
Freshwater aquatic ecotoxicity	kg 1,4-DB eq./t	4.8×10^{0}	3.8×10^{-1}	4.9×10^{-4}	5.2×10^{0}
Marine aquatic ecotoxicity	kg 1,4-DB eq./t	2.6×10^{4}	1.6×10^{3}	5.3×10^{0}	2.7×10^{4}
Terrestrial ecotoxicity	kg 1,4-DB eq./t	4.0×10^{-2}	3.0×10^{-3}	8.5×10^{-6}	4.3×10^{-2}
Photochemical oxidation	kg C_2H_4 eq./t	1.4×10^{0}	1.1×10^{-1}	1.5×10^{-4}	1.5×10^{0}
Acidification	kg SO_2 eq./t	5.1×10^{0}	4.0×10^{-1}	5.3×10^{-4}	5.5×10^{0}
Eutrophication	kg PO_4^{3-} eq./t	4.3×10^{-1}	3.2×10^{-2}	4.1×10^{-5}	4.6×10^{-1}

The impact of the ozone layer depletion value of steel rebar production is approximately 2.7×10^{-5} kg CFC-11 eq./t. The steel billet production process has an impact of almost 80.4% on steel rebar production mainly due to the subprocesses such as crude oil production process (60%) and natural gas transportation by pipeline from long distance (35%). In this process, crude oil was consumed for transportation whereas natural gas was consumed for electricity generation.

The human toxicity impact value of steel rebar production is 59 kg 1,4-DB eq./t. This environmental impact results from steel billet manufacturing (95.0%) and electricity consumption (5.0%) processes. In the steel billet production process, disposal of the hard coal ash subprocess for electricity generation (60%) and coke production subprocess for ferrosilicon production (16%) are the main components of this impact. Ferrosilicon production and energy generation released heavy metals emissions including selenium, molybdenum, arsenic, and nickel, and also hazardous benzene and chromium. The freshwater aquatic ecotoxicity impact has the value of 5.2 kg 1,4-DB eq./t. This impact is mainly attributed to steel billet production (94%) due to disposal of hard coal and lignite coal ashes and generation of slag during the electricity generation. These processes have caused this impact by emitting arsenic, molybdenum, vanadium, selenium, and nickel emissions to the water ecosystem. The value of marine aquatic toxicity impact is 27×10^{3} kg 1,4-DB eq./t for steel rebar production. Particularly, steel billet production process (96%) chiefly caused to this impact. As it is in the freshwater aquatic ecotoxicity, disposal of hard coal ash and manganese have an important role on marine aquatic toxicity impact due to heavy metal emissions (hydrogen fluoride, selenium, molybdenum, and vanadium) to air and water ecosystems. The terrestrial ecotoxicity value of 1-t steel rebar production is 4.3×10^{-2} kg 1,4-DB eq./t. This amount almost arises from all the steel billet production. In the production of steel billet, transportation of raw materials and electricity generation (based on

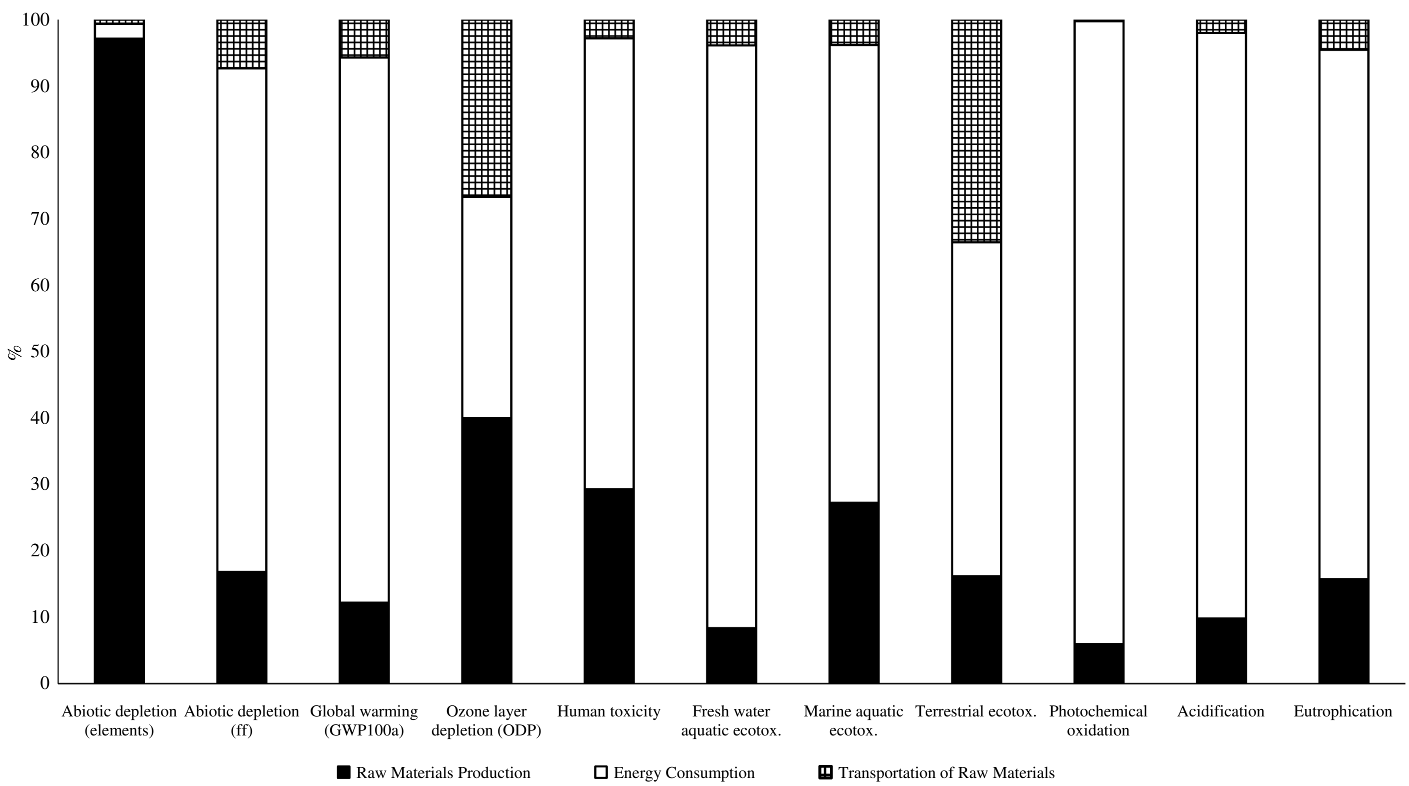

Fig. 3. Process contributions to environmental impacts of steel billet production

Table 5. Comparison of Steel Production's Environmental Impacts

Impact category	Unit	This study (steel rebar/IMF)	References: Gomes et al. (2013) (steel rebar/EAF + BF)	Burchart-Korol (2013) (Crude steel/EAF)	Burchart-Korol (2013) (Crude steel/BOF)
Abiotic depletion (element)	kg Sb eq./t	7.4×10^{-6}	5.16×10^{0}	—	—
Abiotic depletion (fossil fuels)	MJ/t	9.5×10^{3}	—	8.1×10^{3}	3.5×10^{4}
Global warming (GWP100)	kg CO_2 eq./t	7.2×10^{2}	6.05×10^{2}	9.1×10^{2}	2.5×10^{3}
Ozone layer depletion (ODP)	kg CFC-11 eq./t	2.7×10^{-5}	6.14×10^{-5}	—	—
Human toxicity	kg 1,4-DB eq./t	5.9×10^{1}	5.70×10^{2}	3.5×10^{2}	6.4×10^{2}
Freshwater aquatic ecotoxicity	kg 1,4-DB eq./t	5.2×10^{0}	3.70×10^{2}	7.0×10^{0}	1.3×10^{1}
Marine aquatic ecotoxicity	ton 1,4-DB eq./t	2.7×10^{1}	4.72×10^{2}	—	—
Terrestrial ecotoxicity	kg 1,4-DB eq./t	4.3×10^{-2}	6.34×10^{1}	6.0×10^{-2}	1.7×10^{-1}
Photochemical oxidation	kg C_2H_4 eq./t	1.5×10^{0}	2.07×10^{-1}	—	—
Acidification	kg SO_2 eq./t	5.5×10^{0}	2.02×10^{0}	2.5×10^{0}	4.8×10^{0}
Eutrophication	kg PO_4^{3-} eq./t	4.6×10^{-1}	9.35×10^{-1}	1.4×10^{-1}	8.1×10^{-1}

natural gas, hard coal, and lignite consumption) processes have dominantly affected the terrestrial ecotoxicity as a result of mercury, nickel, and zinc emissions to the atmosphere.

The photochemical oxidation impact value of steel rebar production is calculated as 1.5 kg C_2H_4 eq./t. This impact indicator mainly resulted from steel billet production (93%). In the background of steel billet production, the natural gas and the lignite coal burned in thermal power plants during the electricity generation caused this impact due to carbon monoxide and sulfur dioxide emissions.

The values of acidification and eutrophication potentials are 5.5 kg SO_2 eq./t and 0.46 kg PO_4^{3-} eq./t, respectively. Electricity consumption during the steel billet production process has caused these impacts.

As indicated in the detailed investigation of the impacts, steel billet production has the dominant role on the environmental impact of steel rebar. Fig. 3 presents the contribution of the production phases (raw material extraction and production, energy consumption, transportation) to each of the impact categories for 1 t of steel billet production. The environmental burdens of the raw materials extraction and production process has major effects on the element basis of abiotic depletion, ozone layer depletion, marine aquatic ecotoxicity, and terrestrial ecotoxicity indicators. On the other hand, energy consumption has effects on the fossil fuel–based abiotic depletion, global warming potential, human toxicity, freshwater aquatic ecotoxicity, photochemical oxidation, acidification, and eutrophication. The effect of transportation is low relative to the raw material extraction and energy consumption.

In the literature, LCAs of steel production processes are based on electric arc furnace and blast furnace. For that reason, the findings of this study were compared with findings of other researchers for EAF, BF, and BOF systems (Table 5). In this table, although the abiotic depletion (fossil fuel) value of this study seems at first higher than that of EAF (Burchart-Korol 2013), it should be noted that the functional unit of EAF is crude steel, which is not a finished product. This means that if the process would continue, the value of fossil fuels–based abiotic depletion would be much higher than this study. This table also shows that the abiotic depletion value of the fossil fuels–based production route (BOF) is approximately four times higher than this study despite being also based on crude steel. The global warming (GWP100) and eutrophication values of the IMF system are in the range of values of other systems. On the other hand, the values of element-based abiotic depletion, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity were lower than values of other systems, whereas the values of photochemical oxidation and acidification were higher.

Conclusion

Steel rebar production mainly depends on the steel billet production in IMF systems. When it was focused on the steel billet production, it was seen that the electricity consumption has an important role for lifecycle environmental impacts. This situation resulted from the environmental load of electricity generation. In Turkey, electricity generation is based on fossil fuels and this results in an increase on the impact of fossil fuels–based abiotic depletion. In addition to this impact, electricity consumption (due to electricity generation) also has an important role on global warming, freshwater aquatic ecotoxicity, photochemical oxidation, acidification, and eutrophication. For that reason, finding more energy-saving alternatives for steel production would help increase the environmental performance of the process. On the other hand, it can be concluded that IMF technology is more energy efficient than the EAF and BOF technologies. This observation is supported by the steel industry based on lower greenhouse gas emissions in Turkey.

In addition to energy-saving improvements, industrial symbiosis applications would also reduce the environmental impacts of steel production, especially those resulting from slag and fly ash generation. Dust released from steel production is used for its zinc content but the utilization area should be widened.

The findings of this study can help to understand the current environmental loads of steel production, and can also help to understand the levels of sustainability of this sector, which should be showed by users and decision makers in steel production. In the future, this study can be improved by considering symbiotic waste utilization cases and cleaner production approaches.

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