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Environmental impact assessment of steel reinforcing bar manufacturing process from scrap materials using life cycle assessment method: a case study on the Ethiopian metal industries

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Abstract

A clear understanding of the major environmental impacts of steelmaking from scraps, as well as potential solutions involving a circular economy paradigm, is essential. This study is conducted to pave the way for using life cycle assessment (LCA) to have sustainable development and effective resource management by evaluating the environmental impacts of the steel rebar manufacturing process using secondary resources. It is a cradle-to-gate LCA that includes scrap collection and sorting, transportation, melting, continuous casting, billet reheating, and reinforcing bar rolling. Inventory data were acquired as primary data from the factory and secondary data from ecoinvent v3.8, 2021 version integrated with SimaPro 9.4.0.2 faculty version. All of the analyses in this LCA were conducted using the Recipe 2016 Midpoint (H)V1.00 and Endpoint (I)V1.00 impact assessment techniques taking one-ton reinforcing bar production as reference flow. This LCA study shows that using renewable energy and bulk transport systems has a significant advantage in reducing the environmental impact created during steel production processes. Because of this, the global warming potential created during the rebar manufacturing process is 467 kgCO_2 eq as taken from the environmental impact calculation report. By charging hot billet from the continuous casting machine (CCM) to the rolling mill and using an efficient transportation system, the environmental impact of GWP can be reduced by 50%.

Article highlights

- Literature related to life cycle assessment in steel production was reviewed.
- The inventory analysis of inputs, outputs, and flows were quantified and the environmental impact of the product system was evaluated using Recipe Midpoint and Endpoint methods.
- Comparative analysis between the two production processes was done to minimize the environmental impact created during steel production.

Keywords Environmental impact · Induction furnace · Life cycle assessment · Reinforcing bar · Secondary resources · Steel production · Sustainable development

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1 Introduction

The supply and demand of materials are greatly increased in the world due to the rapid growth of the world economy. The Organization for Economic Co-operation and Development (OECD), an international organization and strategic advisor of G20, background report for the 2021 meeting on the role of the G20 on resource efficiency and circular economy, the amount of material produced at the global level by 2017 reached 88 billion tons [1]. In addition to the economic growth, urbanization and industrialization levels of different nations have higher contributions to the increment of material consumption.

The emerging economy in developing nations like China and India demands a high amount of steel materials to satisfy their needs for the infrastructure establishment. Steel is the world's second-largest industry sector, after oil and gas, with a global turnover of 900 billion dollars [2, 3]. For the past two decades crude steel production has increased more than twice, reaching 1951 million tons in 2021 compared to 852 million tons produced by 2001 [4]. Steel materials produced from iron ore and secondary resources using the basic oxygen furnace (BOF) and electric furnaces (EF) respectively are highly consumed materials with diversified applications for engineering, construction, infrastructure, industry, automotive, electrical-electronics, transport, and health in the world [5]. The steel industry plays the highest role in the nation's economic development and it is the milestone and initiator for the industrial growth in developed and developing countries [6, 7]. However, the Ethiopian steel industries are at the infant stage to have a significant contribution to the economic development of the country. The Industrial Policy Study and Research Department of the government of Ethiopia reported that the steel sector's economic role is limited to a 0.4% contribution to the gross domestic product (GDP) of the country in the year 2013 [8]. The main advantage of having a functional steel sector is transforming a country into an industrialized economy, hence it should recognized that the steel industries have the highest contribution to all aspects of the economy [6].

Globally crude steel production showed an increment since 1950 except for 1995, 2009, and 2015 had a decline of 2.2, 7.7, and 3.0% respectively [4]. However, the steel production process follows an energy and material-intensive process and releases a high amount of emissions to the environment [9]. The emissions released through the production, consumption, and disposal processes of steel have environmental impacts that create damage to human health, damage to ecosystem quality, and natural resource depletion. Due to the globalized economy in natural resources, the environmental influences from production processes are far from the place where products are being consumed [10].

Because of the environmental impacts of materials processing, nations are obliged to consider environmental impacts and sustainability when they develop strategic policies on economic growth. At this time production growth of steel is constrained by climate change policies and regulations, even though resources for steel production are abundant and secondary resources production are also well organized [11]. Steel production accounts for about 7.7% of the global greenhouse gas (GHG) emissions in 2015 [12] and is responsible for 12% of national CO_2 emissions in China [13]. In addition, Jinsoo Kim et al. [14] report that steel production is responsible for 7–9% of GHG emissions at the global level. To develop roadmaps for substantial emissions reduction within the steel sector, stakeholders and policymakers need information on trends in steel use, steel demand, and the amount of scraps available for recycling in different world regions to assure sustainable development [15]. Different tools and methods are in use to test the sustainability of the production process for economic growth. One of the methods that is helpful to evaluate sustainability is the life cycle assessment (LCA) of a product system or service.

Life Cycle Assessment (LCA) is a holistic cradle-to-grave quantitative comparative analysis and assessment of the environmental impacts of product systems considering the determined functional unit [16–18]. It is internationally accepted and universally applicable to quantify resource usage, energy consumption, and environmental emissions related to the manufacture of steel industry products [19, 20]. It provides a holistic approach considering the potential impacts from all stages of manufacture, product use, and end-of-life [17, 19]. The International Organization for Standardization (ISO) issued standards for LCA (ISO 14040/44). The World Steel Association (World Steel) gathered Life Cycle Inventory (LCI) data for steel-specific standard products based on ISO 14040/44: 2006 for each year of production in collaboration with the member steel producers [20]. The quality and relevance of LCA/LCI results, and the extent to which they can be applied and interpreted, depend critically upon the methodology used [19]. Practically, an LCA study shall be restricted within a certain system boundary, even though it aims to model all of a product's environmental, social, and economic impacts from cradle to grave [21].

Several studies were conducted to evaluate the environmental impact of steel production processes using the life cycle assessment (LCA) method. Boguslaw Bieda et al. [22] researched the continuous casting of steel (CCS) production process in Poland in a specific steel factory by applying the life cycle inventory (LCI) method covers a gate-to-gate system with a functional unit of 1-ton steel slab using a secondary data collected by ISPCCS for 2015 to develop LCI dataset. The study of Gulnur Maden Olmez et al. [3] in the Turkish integrated iron and steel industry uses an LCA method to compare the environmental impact of different processes and various steel products in cradle to gate system using 1 ton steel products functional unit. Huimni Liu et al. [23] use the LCA method to conduct inventory and quantitative analysis on the environmental impact of the steel-making process using on-site data in a cradle-to-gate system with 1 ton crude steel product. The calculations were done using Impact 2002+ integrated from Simapro software and Montecarlo Simulation was used for sensitivity analysis [23]. Dora Andreea et al. [24] performed a "cradle-to-gate" LCA study based on the CML 2001 impact assessment method in GaBi for an integrated steel mill with and without carbon capture and storage (CCS) considering one million metric ton hot rolled coil as a functional unit. He concluded that the introduction of CCS technologies leads to a significant decrease in the GWP indicator, while all other environmental indicators have a more or less significant increase compared to the conventional production process [24]. Dimos Paraskeva et al. [25] researched aluminum recycling LCA using the ReCipe impact assessment method to develop a Parametric LCA tool to simplify environmental impact calculation. The study incorporates the material hygiene concept during the recycling of aluminum that didn't get attention from other LCA studies [25]. Jana Gerta et al. [26] conducted a cradle-to-gate LCA study to give a comprehensive life cycle assessment in one of the integrated steel mills in Germany to produce 1 kg of hot rolled coil having measured primary data collected for 2018. The study was performed to show existing facts of the environmental problems based on the CML 2001 method using GaBi software and to identify the main emitters in the processes [26]. A holistic environmental assessment work was done by Pietro A. Renzulli et al. [27] on the integrated steel mill located in Taranto (Italy) applying LCA methodology up to the characterization step using Simapro 8.2 and ELCD to quantify the use of materials and energy including emissions in the lifecycle of the steel slab production process to indicate hotspots to propose alternative solutions. This LCA study used foreground data of onsite collected, data estimated based on Best Available Technique Reference Documents (BREF), and emissions data from the Italian Environmental Protection Agency were used for the LCA. [13]. Dorota Burchart-Korol et al. [28] conducted a cradle-to-gate LCA in the integrated steel plant and electric arc furnaces of the steel production process in Poland considering one ton of cast steel as a functional unit using Simapro 7.3.3 software. In this study, the environmental impact categories Global warming, Energy consumption, and Human health damage were evaluated by the impact assessment methods of IPCC (2007) GWP, cumulative energy demand (CED), and ReCiPe Midpoint (H) respectively. The study recommended that material substitution should be used as a pollution prevention method in iron-making processes to reduce environmental impacts [28]. Areinforcing bar production process of a cradle- to- gate LCA study was conducted by Alp Ozdemir et al. [29] to identify the highest contributor of the environmental impact from the secondary resources in induction furnace in Turkey using on-site data as a foreground data and a background data was taken from ecoinvent. All classifications, characterization, and calculations of impact categories of this study were performed based on CML-IA Environmental impact assessment method considering one metric ton of steel rebar production. The study concluded that the main contributor to the environmental impact is the billet production process (including melting) because of the highest consumption of electricity generated from fossil fuel combustion in maximum percentage [29].

The life cycle assessment works described above used cradle-to-gate or gate-to-gate systems on steel production except for one study that deals with aluminum. Most of the studies start from the raw material acquisition and end by producing molten steel, some are extended to the production of slabs, bars, or coils by applying regional-level impact assessment methods on different production systems with various functional units. All of the LCA comparative analyses were done between BOF and EAF route steel production processes which have significant differences in their energy and material consumption. There was only one LCA study conducted on the rebar manufacturing process from induction furnaces using secondary resources but didn't include any comparative analysis to indicate possible solutions for the reduction of environmental impact potentials. From the reviewed literature it was possible to understand that research done on steel production from induction furnaces is limited. The paper is intended to quantify the environmental impacts created in steel rebar manufacturing using induction furnaces for melting purposes from secondary resources by applying renewable energy except reheating of billet. A comparative LCA analysis was done between the reheating of billet using heavy fuel and by direct transferring of hot billet from the CCM to the rolling mill. Sensitivity analysis was done to show the influence of using a bulk transport system rather than a discrete transport system on the environmental impact of the production system. Uncertainty analysis of the environmental impact assessment results was done qualitatively in respect to the quality of scraps affecting the energy consumption and the quality of roads which affects the consumption of diesel fuel.

Table 1 Local production and imported reinforcing bar trend

Type of Product	2016	2017	2018	2019	2020
Locally Produced Reinforcing bar (ton)	383.511E+03	316.655E+03	396.85E+03	357.844E+03	363.834E+03
Imported Reinforcing bar (ton)	721.647E+03	375.726E+03	242.046E+03	403.082E+03	561.352E+03
Total consumption (ton)	110.516E+04	692.381E+03	638.896E+03	760.926E+03	925.186+03
The ratio of locally produced to the total consumption	3.47E-01	4.57E-01	6.21E-01	4.7E-01	3.93E-01

2 Methodology

According to ISO 14040/44, the four mandatory phases that should be addressed in an LCA are goal and scope definition, inventory analysis, environmental impact assessment, and interpretation of results [30, 31]. In the goal and scope definitions, the preliminary information of the LCA study purpose, functional unit, system boundary, and application area were described clearly. In the inventory analysis, the foreground data input/output flows and emissions were quantified exhaustively from the data sources of the factory, published journals, and reports. The background data were used from the ecoinvent data library in Simapro software. In the impact assessment part all the environmental impacts were classified into the different midpoint impact categories and endpoint damages. Both impact indicators and damages were analyzed using SimaPro 9.4.0.2 Recipe mid-point and end-point impact assessment methods respectively. In the interpretation of the result and discussion section, results obtained from the environmental impact assessment were analyzed, and the data reliability and consistency were addressed. Comparison analysis between the different manufacturing processes and applying efficient transport systems in the reinforcing bar manufacturing processes are also done and displayed in the form of a table in the result and discussion part.

2.1 Goal and scope definition

The goal of this LCA study is to quantify the environmental impacts created during the reinforcing bar manufacturing process from the secondary resources (scraps) using renewable energies and make a comparative analysis between the billet reheating process and direct charging of hot billet to the rolling mill from the continuous casting machine (CCM). The report of the study will be provided to the metal industry development institute (MIDI), national-level policy and strategy developers, the Environmental Protection Authority of Ethiopia (EPAE), and factories to create awareness of the environmental impact of the specific product system.

A reference flow of 1-ton steel reinforcing bar at the factory gate is used, the use of a functional unit in this cradle-to-gate study is not significant due to the lack of knowledge about the end-use condition of the product [18, 19]. According to the information obtained from the Metal Industry Development Institute (MIDI), at this time the steel industries established in Ethiopia to produce reinforcing bars have a design capacity of 4,354,453.00 tons. The trend of local production shown in Table 1 is less than 10% of the design capacity.

Even though the established reinforcing bar manufacturing industries have a design capacity of more than 4 million tons, the achievement is less than half a million tons. While locally produced rebar covers less than half of the total consumption (there is also unsatisfied demand due to the scarcity) on average as indicated in Table 1. It shows that the production of steel in Ethiopia will be increased in the future to satisfy the needs of the society if the constraints of power and raw material scarcity are resolved. The scarcity of raw materials is intensified due to the absence of an organized scrap dealer/yard at the country or regional level. Hence, factories are forced to purchase scraps collected at the individual level from different areas passing through brokers which leads them to use a discrete transport system. Scarcity of power is created because of the limited power plant availability in the country.

The Ethiopian metal industries engaged in reinforcing bar manufacturing only were observed during the study, other steel production factories are excluded from the study due to the absence of full information/data and their production system is not consistent or not well organized for mass production. The existing steel production process technology is a mini-mill factory equipped with an electric induction furnace to melt scraps, continuous casting to form billets, a billet reheating furnace, and a rolling mill to form reinforcing bars. There are three possible ways (options) to produce steel reinforcing bars in Ethiopia; (1) using billets produced locally from induction furnace from steel scrap materials

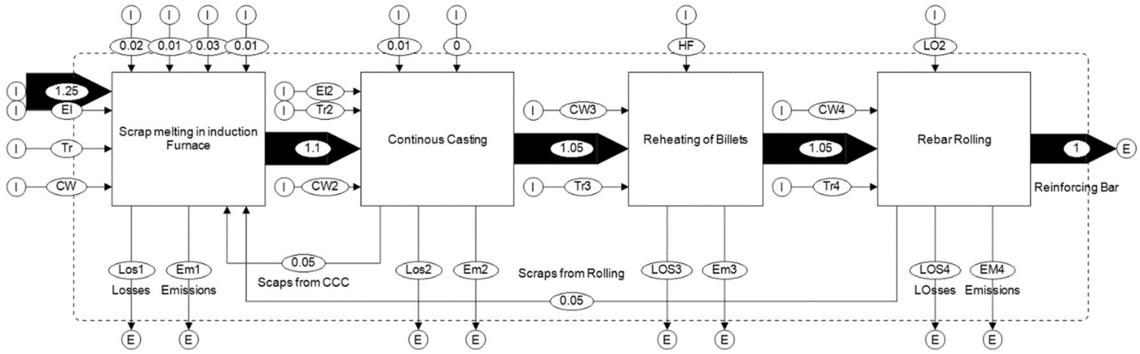

Fig. 1 Reinforcing bar production process model from locally produced billet- case 1

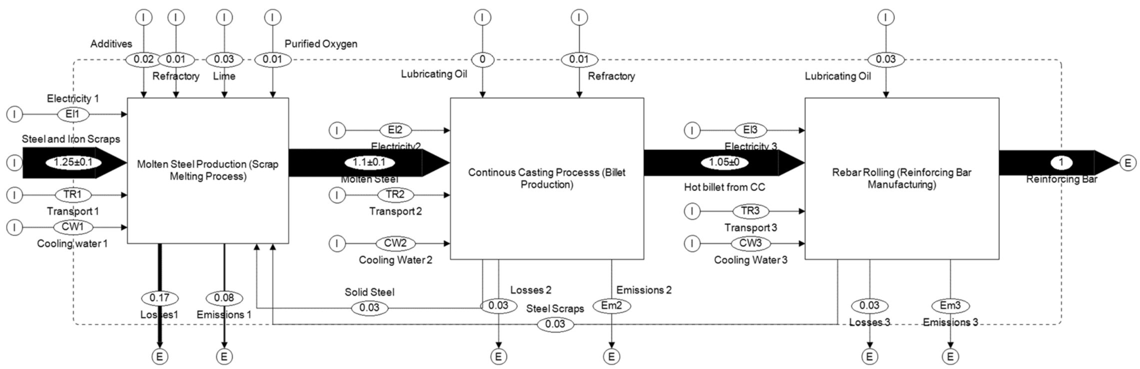

Fig. 2 Model for reinforcing bar production by direct transferring of hot billet- case 2

incorporating billet reheating furnace, (2) using locally produced billets by direct transferring of hot billets from CCM to rolling mill bypassing billet reheating furnace and (3) using the imported billets incorporating the billet reheating process. Reinforcing bar manufacturing process from the imported billet is excluded in this LCA study by the lack of detailed information about the production of the billet from foreign countries. The two production processes modeled as shown in Figs. 1 and 2 show the system boundary of the LCA work clearly and help to have a clear understanding of the product system. Even though there are two cases of the production processes modeled in this paper, all of the information described here consider case 1 as a base reference unless otherwise specified. This LCA study is a cradle-to-gate type covering all stages from the raw material collection to the factory gate of the rebar manufacturing process.

Except for the reheating process of billets done in the reheating furnace using heavy fuel combustion, all the required energy for the production process was provided from the local grid electric power generated from the hydropower plant even though the composition of electric power generation in Ethiopia is hydropower, wind farm and thermal with a mix of 90, 8, and 2% respectively in the country level.

2.2 Inventory analysis

In the inventory analysis phase of an LCA work data were collected, calculated, and modeled as input flows, output flows, and flows between the processes of production systems within the defined system boundary [21, 30, 32]. The inventory analysis includes all necessary activities, processes, and materials of the product system in the specified system boundary. The inventories were allocated to the different activities and/or processes of transportation, melting, continuous casting, and rolling. Maintenance and office activity inventories weren't included to avoid complexity. Always there are wastes and losses during the steel production process, some of the impurities may form oxides and be released into the atmosphere or nature. Hence to have 1000 kg of reinforcing bar there is a consideration of 20 % losses from input materials throughout the processes.

2.2.1 The transport system

In this cradle-to-gate LCA materials of scraps, additives, fuels, refractories, lubricating oils, and others were transported to the steel rebar manufacturing industry from different sources [19]. Input materials were transported from all areas of the country and the port of Djibouti by road transport using vehicles of different capacities. Since all the production processes are done in a single factory in a single line, transportation between the processes in the product system is not taken into consideration.

Input materials are classified as major (steel scraps) and minor (additives, refractories, purified oxygen, lubricating oils, and fuels) and collected from local and international markets. At the current time, most of the steel factories are found 60 km away to the east of Addis Ababa the capital of Ethiopia, whereas scraps were collected from all over the country using vehicles having 7000 kg to 10,000 kg capacity. Based on their potential, sixty percent of the scraps were collected within a 150 km radius including the capital of Ethiopia, and forty percent within a 750 km radius including regional state capitals and zone capitals from the factory, on average scraps, were collected at a distance of 400 km from the factory. Only the road transport system is included in the inventory analysis work. The in-sea transport of additive materials from the foreign market to port, use phase, end-of-life recycling, and waste scenario of the production systems weren't included in the study due to the absence of organized data.

All additives, refractories, fluxes (lime), lubricating oils, oxygen, and fuel were imported from the international market and transported a minimum distance of 876 km by road transport using vehicles having a capacity between 10,000 and 32,000 kg. To have a common approach with scrap transportation, the vehicles that can transport 10,000 kg at a time were selected as a base reference for all transportation systems. Vehicles with 30,000 kg and above capacity were considered to check the sensitivity of the transport system concerning the environmental impact results. All vehicles use diesel fuel and consume 240 g/km for 10,000 kg capacity and 345 g/km for 30,000 kg and above capacity vehicles on average. Emissions from the transport system were calculated based on the European Monitoring and Evaluation Program (emep) of the European Environmental Agency [33]. Emissions of carbon dioxide, methane, carbon monoxide, nitrogen oxides, NMVOC, dinitrogen monoxide, ammonia, lead, particulate matter, and sulfur dioxide are the common types considered in this transport system and are calculated by the following formula

$$E_i = C_f \times E_{fi} \tag{1}$$

$$where : Ei = emission\ of\ i\ from\ the\ system$$

$$Cf = Consumption\ of\ fuel\ during\ the\ transport\ system$$

$$Efi = emission\ factor\ of\ emission\ i$$

The amount of fuel consumption and emission calculation for road transport was done using Equation 1 as described before. The emissions created in the transport system were incorporated into each production process (activity) as required.

2.2.2 Melting process

Scraps collected from different sources are charged in the coreless induction furnace with an eight-ton capacity requires 550 KWh of electricity per ton of steel production. The furnace takes 3 hrs to melt the charges to produce eight tons of molten metal and make it ready for ladle transport. Additives are charged to the furnace when the temperature reaches 1500 ℃ to adjust chemical composition. Pure oxygen is introduced to agitate liquid metal and oxidize impurities to purify molten steel by forming slags (oxides) floating on the molten steel. The molten steel is transported by overhead crane with a ladle and poured to the tundish to feed to the continuous caster machine mold to form billets. From the expert assumption at the factory level, the amount of material lost between melting and billet formation is nearly fifteen percent of the charged material in the form of slag, sludge, emissions, and other wastes.

The foreground inventory data for the melting process were collected from the factory by interviewing experts in each section as shown in Table S1. Data that are difficult to determine or not available at the factory level are taken from the literature published by international journals passing through extensive peer reviews or reports of different associations. The background data was used from the ecoinvent 3 database library integrated with SimaPro 9.4.0.2 faculty version.

Emissions data were not available at the factory and there is no formal organization that can provide steel production process emissions inventory at the country level. Hence, the emissions from different activities and processes were calculated using emission factors from Europe, the United States, and England. Others that are difficult to estimate or calculate were taken from the literature. The inventory of steel production process from induction furnace didn't get full coverage by LCA practitioners because it is lately introduced technology and had a limited contribution to the amount of global steel production. Hence, electric arc furnace data which have a similar nature to electric induction furnaces were taken as equivalent data for special cases. Both induction furnaces and electric arc furnaces use scraps & additives as input materials and electricity as a power source.

The sources of emissions are the melting reaction of scraps with some dust during handling, preparation, and charging. The most common types of emissions that could be included are greenhouse gases, particulates, carbon monoxide, sulfur dioxide, nitrogen oxide, heavy metals, and wastes [34]. Heavy metal emission from the melting process is calculated by considering the emission factor per ton of molten liquid steel production [35]. The inventory data was analyzed based on the production process modeled in Fig. 1 and detail values were displayed in Table S1 of the supportive material. The inventory of production processes modeled in Fig. 2 is managed by removing direct emission records from the reheating furnace.

2.2.3 Continuous casting

In the continuous casting process, the main products are billets having $125 \times 125\,mm^2$ cross-section and 6000 mm length. The main inputs to the process are molten steel from the induction furnace, lubricating oil, electricity, and water. Boguslaw Bieda's reports on his LCI work on the continuous casting process indicated that the source of emissions in continuous casting is the heating and drying process of tundish [36]. The common emissions are dust particulate matter, sulfur dioxide, nitrogen dioxide, and carbon monoxide [36]. There are also wastewater, iron particles, and Iron scraps considered as wastes. The detailed inventory of the continuous casting process is included in Table S2 of the supportive material.

2.2.4 Billet reheating and roll forming process

Billet products from the continuous casting are stored in temporary storage to cool to room temperature and cut into the required length based on the capacity of reheating furnaces. The 6000 mm length cut billet is charged to the reheating furnace and has an energy source from heavy fuel oil combustion. When the temperature of the billet reaches 1150 ℃ transferred to the rolling mill with an exit temperature not less than 1100 ℃.

Nowadays new technology is introduced in the steel products manufacturing process, direct transferring of hot billet to the rolling mill bypassing the reheating process as shown in Fig. 2. This technology is practiced in one factory in Ethiopia. Usually, billets have 1100 ℃ surface temperature when exiting from their forming line (CCM) [37] which is sufficient for the hot rolling process. So direct transferring of billet through the high-speed casters to the rolling mill is helpful to eliminate the fossil fuel combustion for reheating of billets.

Roll forming of the rebar is accomplished in a hot rolling process passing through the number of reduction strands to get the required size and form. The rebar exit from the last strands will pass through the quenching box to improve its mechanical properties and the process can be called thermomechanical treatment (TMT). The roll-forming mill is running with the power of electricity from the hydropower grid of the country.

Since the reheating of billets is done by the combustion of heavy fuel, different types of emissions are released from the process. Emissions other than greenhouse gases were calculated using the emission factors set by the emissions inventory guideline of the International Panel on Climate Change (IPCC) [38]. The greenhouse gas emissions CO_2, CH_4, and N_2O were calculated by taking an emission factor of the stationary combustion from the international panel combustion control [39]. The emissions of different gases, particulates, and heavy metal from reheating furnaces can be calculated with;

$$E_e = Co_f \times E_f \tag{2}$$

Where: E_e= emissions of an element

C_{of} = Energy generated during the consumption of fuel

E_f = Emission factor of the element

According to the data obtained from the factory, the reheating furnace consumes 46 liters of heavy fuel oil to heat one ton of billets on average. One gallon of heavy fuel oil can generate 158.04 megajoules. To reheat 1050 kg of billets, 48.3 liters of heavy fuel oil is required and can generate 2016.59 MJ of heat energy. The detailed inventory data of inputs and outputs of the rolling process is found in Table S3 of the supportive material.

2.3 Impact assessment

Impact assessment is a crucial stage in life cycle assessment (LCA), where the environmental loads identified in the inventory phase are translated into logical and comparable potential impacts using characterization factors. The day-to-day activity of people to satisfy their needs including the processes of production adversely affects the environment [21]. The inventory analysis of different production systems showed that processes take input from nature and the techno sphere and release emissions and waste to nature. The environmental impact assessment calculation of the rebar manufacturing process conducted in this study was carried out with the Simapro 9.4.0.2 faculty version. As it was mentioned in the introductory part, life cycle impact assessment (LCIA) can be applied to show the significance of the potential environmental impacts in the production processes considering life cycle inventory results quantitatively and qualitatively [21, 30].

An LCA conducted in this study is a process-based impact assessment used to quantify the environmental impacts of the steel reinforcing bar manufacturing from secondary resources in the context of Ethiopia. The production process with higher environmental impact was identified based on the Recipe midpoint and endpoint impact assessment results. Midpoint impact assessment emphasizes the transitional environmental effects, which didn't reach the final damage. Endpoint impact assessment emphasizes the final damage categories and represents the ultimate consequences of the environmental effects on human health, ecosystem, and resource scarcity.

The environmental impacts of the product system are classified into seventeen midpoint impact categories and three endpoint damage categories according to the Recipe midpoint and endpoint impact assessment methods respectively. Some of the impact categories difficult to explain with the existing data/understanding were excluded. Selected midpoint impact categories are Global warming (GW), Ozone formation-human health (OFHH), Fine particulate matter formation (FPMF), Ozone formation-terrestrial ecosystems (OFTerEcos), Terrestrial acidification (TerAc), Freshwater eutrophication (FwEu), Terrestrial Ecotoxicity (TerEcoTox), Freshwater Ecotoxicity (FwEcoTox), Human carcinogenic toxicity (HCTox), Human non-carcinogenic toxicity (HNCTox), Mineral resource scarcity (MRS) and Fossil resource scarcity (FRS) are described in this paper.

The environmental impact assessment calculation with Recipe midpoint impact (H) methods for the production system (case 1) is indicated in Table 2. The system includes transportation, molten steel production (melting), billet production (continuous casting), and reheating of billet and rebar manufacturing processes (rolling).

Each of the impact categories has been described by its impact indicator to facilitate characterization. An environmental impact potential is a contribution of more than one elementary flow, so characterization is used to measure the impact of different elementary flows with one unit. As an example, the global warming potential is measured by $kgCO_2$ eq even though greenhouse gases methane, nitrous oxide, and others have higher impact potential. Methane and other emissions which have an impact on global warming are characterized by $kgCO_2$ eq. For example, one unit of methane is equivalent to 25 units of carbon dioxide [40].

An endpoint damage assessment shows the effect of the impact potentials in the cause-and-effect chain of the different production systems. The three endpoint damages are classified as human health, ecosystem quality, and natural resource scarcity. The damage assessment of these endpoint impact assessments is displayed in Table 3.

The second production system (case 2) includes transportation, molten steel production, billet production, and rebar manufacturing as the main processes. As shown in the goal & scope section, the production system of case 2 applies a technological modification to the production system of case 1 by directly transferring of hot billet to the rolling mill from the continuous casting. It bypasses the reheating of the billet and avoids heavy fuel combustion for the reheating purpose. The impact assessment results of this production system in different environmental impact categories using Recipe midpoint impact assessment are displayed in Table 4.

The endpoint damage assessment of the production system (case 2) is done for the three damage types. The assessment of the damages for the three damage types is displayed in Table 5.

Table 2 The environmental impact assessment result of the production system (case 1)

Impact category	Unit	Transport	Melting	CCM	RHB	Rolling	Total
Global warming	kg CO2 eq	8.045E+01	1.27E+02	3.04E+01	18.931E+01	3.93E+01	4.67E+02
Ozone formation, human health	kg NOx eq	6.2024E-01	5.06E-01	5.9E-02	3.98E-01	1.459E-01	17.3E-01
Fine particulate matter formation	kg PM2.5 eq	1.745E-02	2.13E-01	1.45E-02	6.1E-03	2.53E-03	2.8E-01
Ozone formation, terrestrial ecosystems	kg NOx eq	6.22E-01	5.2E-01	6.5E-02	4.044E-01	1.929E-01	18.0E-01
Terrestrial acidification	kg SO2 eq	6.216E-01	6.99E-01	1.323E-01	1.573E-01	1.93E-01	18.0E-01
Freshwater Eutrophication	Kg p equ.	0	3.57E-01	2.57E-03	1.0E-03	5.75E-03	4.5E-01
Terrestrial ecotoxicity	kg 1,4-DCB e	4.9E-03	9.77E-01	2.8E-03	1.5E-03	3.2E-03	9.89E-01
Freshwater ecotoxicity	kg 1,4-DCB e	0	92.78E-01	12.143E-01	7.25E-01	2.017E-01	107.67E-01
Human carcinogenic toxicity	kg 1,4-DBC e	1.005E-01	1.496E-01	5.724.527E+01	1.8E-03	4.3E-03	2.62E-01
Human non-carcinogenic toxicity	kg 1,4-DBC e	24.75E-01	22.783E+01	64.98E-01	33.83E-01	50.82E-01	24.527E+01
Mineral resource scarcity	kg Cu eq	0	8.335E-01	2.84E-2	9.4E-04	2.2E-03	8.65E-01
Fossil resource scarcity	kg oil eq	4.14E+01	1.625E+01	1.176E+01	4.704E+01	4.885E+01	16.53E+01

Table 3 The endpoint impact assessment of the three types of damages for the production system (case1)

Damage category	Unit	Transport system	Melting scraps	Continuous casting	Reheating billets	Rebar rolling	Total
Human health	DALY	2.01E-05	8.483E-02	1.166E-02	2.94E-04	6.50E-05	9.69E-02
Ecosystems	Species yr.	1.91E-07	4.65E-07	1.01E-07	8.39E-07	1.0E-07	1.6E-06
Resources	USD2013	1.9E+01	1.2E+01	0.3E+01	1.635E+01	1.885E+01	6.92E+01

Table 4 The environmental impact assessment of the production system (case 2)

Impact category	Unit	Transport	Melting	CCM	Rolling	Total
Global warming (GW)	kg CO2 eq	7.818E+01	12.704E+01	2.934E+01	3.952E+01	27.408E+01
Ozone formation, Human health(OF,HH)	kg NOx eq	5.817E-01	5.056 E-01	5.9E-02	1.447E-01	12.91E-01
Fine particulate matter formation (FPMF)	kg PM2.5 eq	1.76E-02	2.134E-01	1.41E-02	2.54E-02	2.705E-01
Ozone formation, Terrestrial ecosystems (OF, TerEcosy)	kg NOx eq	5.863E-01	5.197E-01	6.46E-02	1.88E-01	13.586E-01
Terrestrial acidification (Tac)	kg SO2 eq	2.576 E-01	5.11E-01	3.204E-01	2.22E-01	13.1E-01
Freshwater eutrophication (FwEut)	kg P eq	0	3.57 E-02	2.6E-03	5.8E-03	4.41E-02
Terrestrial ecotoxicity (TerEcoT)	kg 1,4-DCB e	0	9.767E-01	7.9E-03	3.2E-03	9.878E-01
Freshwater ecotoxicity (FWEcoT)	kg 1,4-DCB e	0	92.78E-01	12.15E-01	2.016E-01	106.941E-01
Human carcinogenic toxicity (HCT)	kg 1,4-DBC e	0	1.496 E-01	0.0057	0.0042	1.595E-01
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DBC e	24.75E-01	22.783E+01	65.0E-01	50.83E-01	24.1888E+01
Mineral resource scarcity (MRS)	kg Cu eq	0	8.335E-01	2.85E-02	2.2E-03	8.642E-01
Fossil resource scarcity(FRS)	kg oil eq	3.6E+01	2.857E+01	1.0E+01	4.066E+01	11.523E+01

3 Uncertainty and sensitivity analysis

Variations in the quality of input materials and using default emission factors for emissions calculation will contribute to the variations in the impact assessment results of the production system. The main sources for the uncertainty of the impact assessment results in the production system are the variation of the scrap quality, quality of roads, and variation in vehicle capacity during the transportation system. The quality of roads affects the fuel consumption of vehicles. The amount of emissions generated from the product system may vary depending on the quantity and quality of the inputs. The scraps collected from different sources may be contaminated during the usage, collection, and/or storage by heavy metals, chemicals, paints, and other impurities in different concentrations. For example, depending on their quality the

Table 5 The endpoint impact assessment of the three damage types in the production system (case2)

Damage category	Unit	Transport system	Scrap melting	Continuous casting	Rebar Rolling	Total
Human health	DALY	1.95E-05	8.483E-02	1.165E-02	7.70E-05	9.66E-02
Ecosystems	Species. yr	1.77E-07	4.65E-07	1.01E-07	9.80E-08	8.41E-07
Resources	USD2013	1.28E+01	1.2E+01	0.3E+01	1.885E+01	4.67E+01

Table 6 Percent reduction of environmental impacts using 30,000kg Vehicles rather than using 10,000 kg Vehicles

Impact category	Unit	Rebar:10,00 kg vehicle	Rebar:30,000kg vehicle	Reduction (%)
Global warming	kg CO2 eq.	4.67E+02	4.10E+02	12.2
Ozone formation, human health	kg NOx eq.	17.29E-01	14.32E-01	17.17
Fine particulate matter formation	kg PM2.5 eq.	2.764E-01	2.694E-01	2.5
Ozone formation, terrestrial ecosystems	kg NOx eq.	18.032E-01	15.033E-01	16.63
Terrestrial acidification	kg SO2 eq.	18.032E-01	14.692E-01	18.52
Freshwater eutrophication	kg P eq.	4.51E-02	4.485E-02	0.5
Terrestrial Ecotoxicity	kg 1,4-DCB e	9.894E-01	9.88E-01	0.14
Freshwater Ecotoxicity	kg 1,4-DCB e	107.67E-01	107.494E-01	0.16
Human carcinogenic toxicity	kg 1,4-DBC e	2.618E-01	2.608E-01	0.16
Human non-carcinogenic toxicity	kg 1,4-DBC e	24.5269E+01	24.2058E+01	1.3
Mineral resource scarcity	kg Cu eq.	8.65E-01	8.65E-01	0
Fossil resource scarcity	kg oil eq.	16.5173E+01	15.4659E+01	6.36

required amount of scraps for one ton of reinforcing bar production varies between 1.1 and 1.25 tons, this variation may vary the amount of energy consumption & emissions generated from the different processes and/ or activities. The variations in the mix-up of vehicles in different capacities, the skill of the driver, and road quality used to transport materials in the transportation system may vary the amount of fuel consumption in line with an increment of emissions released from the system and cause uncertainty on the results. Emissions were determined referring to emission factors from different countries and default values as indicated in the inventory analysis section, the scenario differences may cause uncertainty on the amount of emissions released from the different processes. The sensitivity analysis of the process was checked by varying the transportation system vehicle capacity. The transport system sensitivity analysis was done to show the variation in environmental impacts by using vehicles having a capacity of 30,000 kg instead of 10,000 kg capacity. When vehicles are changed from 10,000 kg to 30,000 kg capacity, global warming potential shows a reduction of 12.2% as shown in Table 6. In this case, all environmental impact potentials have a reduction in all categories like terrestrial acidification, ozone formation human health, and ozone formation terrestrial ecosystem record 18.52%, 17.17 and 16.63 respectively are in the first three lists.

The environmental impacts created by the production system after the technological modification are shown in Table 5. Direct transferring of hot billet to the rolling mill bypassing the reheating furnace can reduce 193 kg CO_2eq (41.3 % reduction). By applying an efficient transport system and technological modification, the global warming potential can be reduced by 238 kg CO_2eq (51% reduction) per one-ton reinforcing bar manufacturing.

4 Results and discussion

The life cycle impact assessment results of the product system were interpreted concerning the goal and scope definition to identify limitations and draw conclusions and recommendations [21, 41]. The midpoint and endpoint impact assessment results for the main activities and/or processes (transportation, melting, billet production, reheating of billet, and rebar manufacturing) of the two production systems are explained in Tables 2, 3, 4, 5 of the impact assessment section. The environmental impact contributions of each main activity and/or process in the product system are shown in Fig 3.

The transportation of materials in the product system has a higher environmental impact contribution on Ozone formation in both human health and terrestrial ecosystems. The reheating of billet in the manufacturing process has

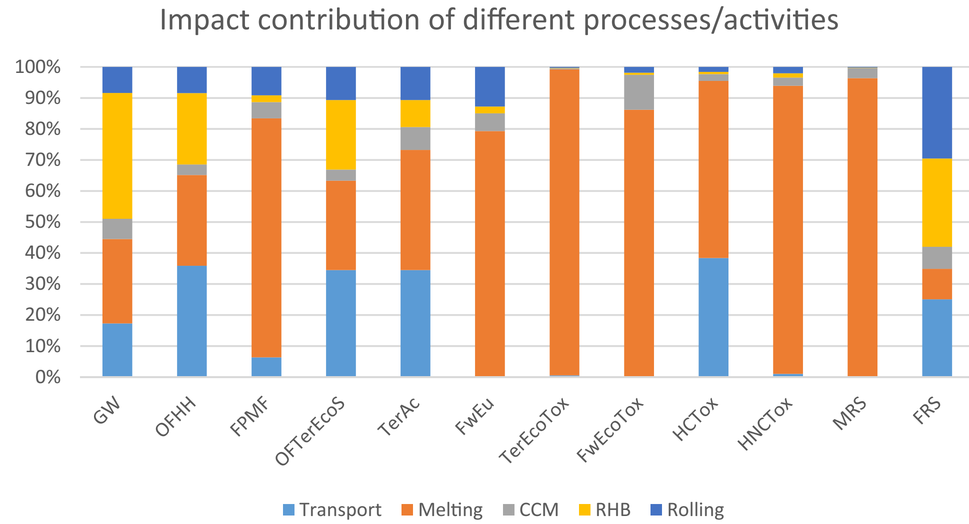

Fig. 3 Midpoint impact contribution of five main processes (case 1)

a higher environmental impact contribution on global warming because heavy fuel combustion is used as an energy source. The melting process has a higher environmental impact on terrestrial acidification, freshwater eutrophication, all toxicity, and mineral resources scarcity impacts as displayed in Fig 3. Since scraps were collected from different sources, there is a possibility of contamination by heavy metals, so different types of toxicity impact potentials are high in the melting process. The mineral resources scarcity is high in the melting process also due to the consumption of additives such as ferroalloys (manganese and silicon), lime, and refractory materials in the production of molten steel. The rolling process has a higher contribution to the fossil resource scarcity impacts followed by the reheating of billet and transport activities as second and third place respectively. It relates to the consumption of lubricating oil and combustion fuel. There is no high score of the environmental impacts in the continuous casting process.

The global warming potential is maximum in the billet reheating process having 189 kgCO_2eq with a 40% contribution due to the combustion of heavy fuel. Second, the scrap melting process had 127 kgCO_2eq with a 27 % contribution followed by the transport system, rebar rolling, and billet production with 17.2, 8.4, and 6.5% kgCO2eq contribution respectively. The emission inventories found from the product system in the different processes that contribute to global warming with a cut of 0.001% are carbon dioxide, methane, dinitrogen monoxide, sulfur hexafluoride, and others with an amount equal to 395.11, 62.4312, 9.2, 0.23, and 0.012 kgCO_2eq respectively. The billet production process has less environmental impact than the other processes.

According to the recipe endpoint impact assessment method, the production system contributes to human health damage, ecosystem damage, and resource depletion with varying impacts of the different processes as indicated in Table 3. The molten steel production process has higher human health damage due to the heavy metals contamination of scrap materials. The ecosystem damage is higher on the reheating of billet (RHB) due to the heavy fuel consumption in the process. Resource scarcity is higher in the transport system followed by rebar manufacturing due to the consumption of diesel fuel and lubricating oil. Reheating of billet and molten metal production take third and fourth place respectively.

Since the impact assessment results obtained are relative values and not normalized, ordered, or weighted, they cannot be used to predict the effects of the final manufactured product, threshold value exceedance, safety margins, or risk analysis [5]. Most of the data were collected at the plant by direct supervision and some were calculated about the globally accepted guidelines like IPCC, EMEP, and others, so the data available in this study are relatively reliable. The values of the environmental impacts obtained in this paper have variations from other studies with the justified reason, this shows the consistency of the data. A similar study conducted by Alp Ozdemir et al, 2018 on the environmental impact assessment of rebar production from induction furnaces in Turkey has recorded 720 kg CO_2eq global warming potential. The variation is 253 kg CO_2eq, showing a 35% reduction, it may be the effect of using fully renewable energy sources (hydropower) that avoids the combustion of fuel for electricity generation. According to the study conducted by the CRU group, steel produced by EAF in the US can reduce carbon emissions by 75% from the traditional BF- BOF steel production process. On the other hand, the World Steel (2020) report shows the CO_2 eq. is 1.85 tonnes per tonne of steel production [42]. Worldsteel (2020) in a public policy paper on climate change and the production of iron and steel confirmed that using one tonne of scrap will reduce 1.5 tonnes of CO_2 emission [43]. Referring to the aforementioned reports from the Worldsteel and CRU group, the reliability of the results obtained in this paper can be assured.

Table 7 Summary of the Environmental impact result of the two cases with one-ton rebar manufacturing

Impact category	Unit	Case1 including RHB	Case 2 direct charging of hot billet	Applying bulk transport
Global warming	kg CO_2 eq.	4.67E+02	2.74E+02	4.10E+02
Ozone formation, human health	kg NOx eq.	17.3E-01	12.91E-01	14.32E-01
Fine particulate matter formation	kg PM2.5 eq.	2.8E-01	2.71E-01	2.69E-01
Ozone formation, terrestrial ecosystems	kg NOx eq.	18.0E-01	13.59E-01	15.0E-01
Terrestrial acidification	kg SO_2 eq.	18.0E-01	13.1E-01	14.7E-01
Freshwater eutrophication	kg P eq.	4.5E-02	4.41E-02	4.5E-02
Terrestrial ecotoxicity	kg 1,4-DCB e	9.89E-01	9.878E-01	9.88E-01
Freshwater ecotoxicity	kg 1,4-DCB e	107.67E-01	106.941E-01	107.5E-01
Human carcinogenic toxicity	kg 1,4-DBC e	2.62E-01	1.595E-01	2.61E-01
Human non-carcinogenic toxicity	kg 1,4-DBC e	24.5268E+01	24.189E+01	24.206E+01
Mineral resource scarcity	kg Cu eq.	8.65E-01	8.642E-01	8.65E-01
Fossil resource scarcity	kg oil eq.	16.5173E+01	11.5233E+01	15.466E+01

Referring to the results obtained from this work, people can understand that using renewable energy and secondary resources in the production process of steel products has significant advantages in environmental protection and resource conservation. A comparison analysis done on the two cases of the production processes used for manufacturing of B500BWR modeled in Figs. 1 and 2, case 1 which uses billet reheating generated a higher amount of environmental impact in all of the environmental impact potentials as shown in Table 7. The main reason for the increment of the environmental impacts in case 1 is the combustion of heavy fuel in the reheating furnace. The comparisons of case 1, case 2, and bulk transport systems are displayed in Table 7.

Referring to Table 7 the global warming potential of the environmental impact reduces from 467 kgCO_2 eq. in case 1–274 kg CO_2 eq. in case 2 by direct hot billet charging. The surface temperature of billets at the exit from the continuous caster machine is around 1100 ℃ and the core part has a higher value [44]. This temperature is equal to the exit temperature of the billet from the reheating temperature, it is possible to bypass the reheating of billets by direct hot billet charging to the rolling mill. Based on the technological modification of the production system, it is possible to reduce 2016.59 MJ heavy fuel consumption. Bypassing the billet reheating furnace during the rebar manufacturing process could able to reduce global warming, ozone formation for human health, ozone formation for the terrestrial ecosystem, terrestrial acidification, human carcinogenic toxicity, and fossil resource scarcity by 41.3, 25.3, 24.5, 27.2, 39 and 30.2% respectively.

5 Conclusion and recommendation

The steel reinforcing bar manufacturing from secondary resources has an environmental and economic advantage in developing countries specifically in the case of Ethiopia where there are no established primary steel production processes. Manufacturing of steel reinforcing bars from secondary resources using induction furnace route with renewable energy sources reduces the environmental impact potential created in the product system at the higher amount.

Most of the emissions are generated from the billet reheating process from fossil fuel combustion during rebar manufacturing. By direct transferring of hot billet, the global warming potential is reduced by 193 kgCO_2eq in the production of one-ton reinforcing bar. The emissions generated from the transport system can be reduced by applying a bulk transport system. Using trucks (>30t) instead of vehicles (<10t) in one-ton reinforcing bar manufacturing can reduce 57 kgCO_2eq. Applying bulk transportation and direct transferring of hot billet to the rolling mill can reduce 238 kgCO_2eq or 51% of the global warming potential.

This life cycle analysis was conducted to determine the environmental impact of reinforcing bar manufacturing process from secondary resources using 100% renewable energy sources. It can be considered as the startup LCA work of the steel production process in Ethiopia and can serve as one source for the next LCA practitioners in the country. Most of the emissions in this work are calculated by referring to an emission factor from Europe or the United States, so an LCA work can be extended by directly measuring all the emissions at the factory level in Ethiopia. The sensitivity analysis on efficient transport systems and technological modification shows only the advantages of emission reduction for environmental impact, but the economic and societal advantage of the process requires further studies.

Author contributions TEF: Conceptualize the work, design the methodology, Investigate results, make data curation, Formal analysis, Validation, Writing original draft, and Writing – review & editing. AAT: Conceptualize the work, Visualization & Validate the work, Writing review & editing, Resources, and Principal supervision. All the authors have read and agreed to the published version of the manuscript.

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Declarations

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