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Life Cycle Assessment of an Integrated Steel Mill Using Primary Manufacturing Data: Actual Environmental Profile

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Abstract: The current dependency on steel within modern society causes major environmental pollution, a result of the product's life cycle phases. Unfortunately, very little data regarding single steel production processes have been found in literature. Therefore, a detailed analysis of impacts categorized in terms of relevance cannot be conducted. In this study, a complete life cycle assessment of steel production in an integrated German steel plant of thyssenkrupp Steel Europe AG, including an assessment of emissions from the blast furnace, the basic oxygen furnace, and casting rolling, is carried out. The functional unit is set to 1 kg hot-rolled coil, and the system boundaries are defined as cradle-to-gate. This study models the individual process steps and the resulting emitters using the software GaBi. Total emissions could be distributed into direct, upstream, and by-product emissions, where the biggest impacts in terms of direct emissions from single processes are from the power plant (48% global warming potential (GWP)), the blast furnace (22% GWP), and the sinter plant (79% photochemical ozone creation potential (POCP)). The summarized upstream processes have the largest share in the impact categories acidification potential (AP; 69%) and abiotic depletion potential fossil (ADPf; 110%). The results, including data verification, furthermore show the future significance of the supply chain in the necessary reduction that could be achieved.

Keywords: steel production; LCA; blast furnace; basic oxygen furnace; casting rolling; green steel; integrated German steel plant; primary data

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1. Introduction

Carbon dioxide (CO_2) emissions and other fossil greenhouse gas emissions in Europe and worldwide are among the most important issues nowadays, and this context influences the steel-making sector significantly. The steel industry is an important economic and social driver providing essential goods in buildings and infrastructure, as well as automotive and metal products. Nevertheless, this industry is a large energy consumer and one of the leading industrial contributors to global anthropogenic CO_2 emissions (about 6.7% of total CO_2 emissions) [1–5]. Research, policy, and industry show increasing attention toward the reduction of emission from the steel sector [6]. Many improvements have already been made in the iron and steel sectors to increase efficiency and reduce emissions. In the past 40 years, energy consumption has been halved, mainly due to energy efficiency improvements and increased scrap recycling rates [4]. However, the need for emission reduction and efficiency increase is expected to rise, and the regulations nowadays are more restrictive [7]. In late 2019, the European Commission (EC) published the European Green Deal, which resets the commitment to tackle climate and environmental-related challenges. Apart from the high energy demand that prevails in the steel industry [8], the production of steel is associated with significant greenhouse gas (GHG) emissions [9]. For the EC, the steel industry's decarbonization is a relevant further step, which is the

support planned for clean steel breakthrough technologies, leading to a zero-carbon steelmaking process by 2030 [8,10]. The recommendations given by the EU include the use of full life cycle assessments (LCAs) to measure footprints of products and materials and the innovative development of large-scale pilots with clean technologies [8]. To identify environmentally relevant emissions and to improve the manufacturing process in an economically affordable and environmentally sound way, LCA can be employed to trace and quantify the most significant sources of emissions across the whole life cycle, from raw material extraction to the final product's usage or disposal [1,9]. With the support of thyssenkrupp Steel Europe AG, a comprehensive, realistic, and up-to-date LCA model according to ISO 14040/44 [11,12] for the production of 1 kg hot-rolled coil, produced in a German integrated steel plant, has been developed and is described in detail. A complete picture of the steel production process's environmental profile is drawn, and the most emission-relevant processes are identified.

1.1. Steel Production

Given humanity's current reliance on steel, various studies have predicted that steel will need to be produced on an increasing scale throughout the 21st century to meet future material consumption needs. Primary steel production is expected to peak around 2045 due to the increasing secondary steel production, which will dominate the production and market by around 2065 [3,13]. The actual LCA study was developed with the support (provision of reliable primary data) of thyssenkrupp Steel Europe AG, hereinafter referred to as the producer, manufacturer, or company. Over a decade, the company has been working on meaningful environmental assessments of steel production. Its target is steel production with fewer emissions: steel production should become carbon neutral by 2050. As an initial interim target, emissions from its own production and processes and emissions from energy purchases shall be reduced by 30% by 2030 compared with the reference year 2018 [14]. In the integrated steel plant, steel production takes place via the blast furnace route (production of hot metal from ore) (Figure 1). The material preparation (Figure 1) process runs through the coke plant and the sinter plant. In the coke plant, pyrolysis of coking coal occurs, the aim being to produce solid coke. As a by-product, hydrogen-rich pyrolysis gas is produced, the calorific value of which is further used within steel production processes and in the internal power plant to generate electricity and steam for the integrated steel mill. Surplus electricity is supplied to the grid. The closed loop of the pyrolysis leads to a more sustainable steel production, as reported in literature as one possible area of improvement [2,7,8]. Sintering, making pieces of fine-grained ferrous materials by caking, is carried out in the sinter plant. For sintering, a mixture of moistened fine ore with coke breeze and additives such as limestone and dolomite is placed in the sinter belt and ignited from top to bottom (Dwight–Lloyd process). The resulting agglomerate is further discharged from the sintering plant, roughly crushed, and gently cooled. The sinter (product) is suitable for direct use in the blast furnace because its high porosity leads to good gas permeability and reducibility yet it has enough mechanical strength for the blast furnace process. In the blast furnace (Figure 1: iron making), oxidic iron carrier sinter, iron ore pellets, and lump ore are reduced to metallic iron and melted to hot metal. The produced hot metal contains, among other things, about 4–5% carbon and is therefore castable but brittle in the solid state and not weldable. Besides the product hot metal, the co-product blast furnace slag remains, which serves as substitute clinker for the cement industry. The calorific value of the blast furnace gas is used in the steel production route and besides, combined with the coke oven gas, it is used in an internal power plant to generate electricity and steam. In the basic oxygen furnace, liquid hot metal is converted by so-called refining (Figure 1: steel making) into liquid crude steel. In the process, oxygen is blown into the converter. The oxygen reacts with the solved carbon to gaseous carbon monoxide, which is highly exothermic. Therefore, scrap is used to cool the process and control the final temperature inside the converter. Besides carbon, other by-elements of the hot metal, such as silicon, phosphorous, sulfur, and manganese, are oxidized and are

transferred into the slag, increasing the quality of the liquid crude steel. Within the model's framework, about 14.8% (related to crude steel) share of cooling scrap is assumed, which is inserted in the steelworks process. Finally, the crude steel and the converter slag are cut off. The resulting slag is used as a raw material in the construction industry, where it substitutes primary raw materials [15]. The resulting carbon monoxide-rich blast oxygen furnace gas is incinerated within the steel production route for heat supply.

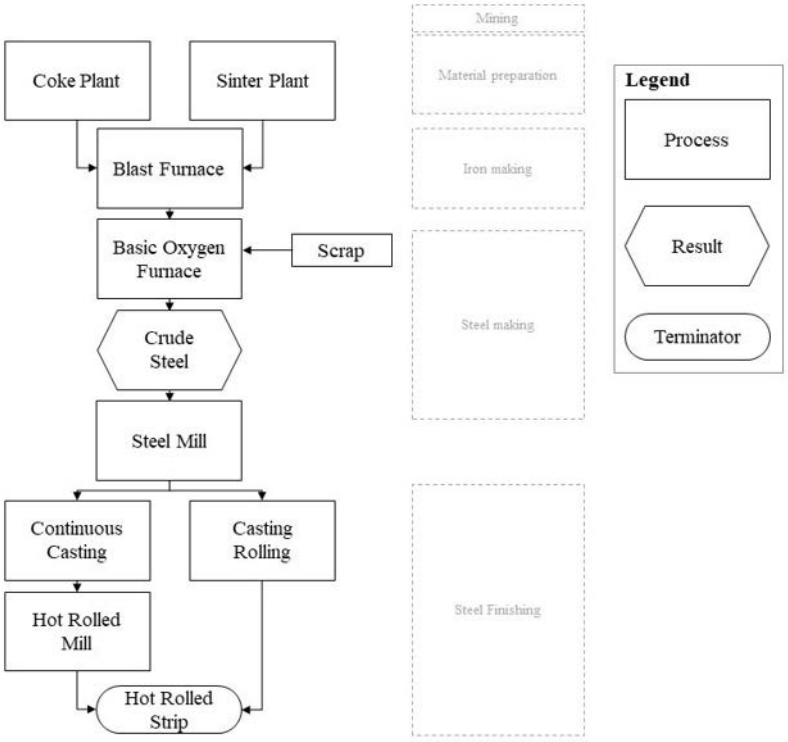


Figure 1. Steel production process.

In most cases, the crude steel from the basic oxygen furnace does not yet have the desired quality and must be post-treated in secondary metallurgy (steel finishing; the processes described above can be assigned to primary metallurgy), where the required characteristics of the steel are manufactured. This includes, for example, vacuum treatment or the use of alloying elements [16]. Alloying elements and secondary metallurgy processes are also implemented in the integrated steel plant. Steel leaving secondary metallurgy is cast in a continuous casting process (continuous casting plant) and transferred from the liquid to the solid phase by solidification or passed on via the casting rolling process. The steel cord produced in the continuous casting plant is cut to length, and the resulting solid pre-products are now called slabs. In hot rolling (hot-rolled mill), the slab is heated to forging temperature and then rolled in several rolling steps to form sheets or strips, leading to the desired final product (hot-rolled coil/steel). Alternatively, and as another decisive difference in this study, the finished treated liquid steel can be passed over the casting rolling line (casting rolling plant). The liquid steel is cast into a thin slab and then rolled into a hot strip, leading to the desired final product (hot-rolled coil/steel). The casting rolling plant is an efficient alternative to continuous casting and the hot-rolled mill process. The liquid steel is also cast and solidified but then cast into a thin slab and rolled into a hot strip in one round. The cooling and reheating step of the slab in the furnace is thus saved in the casting rolling plant.

1.2. Life Cycle Assessment

The LCA method offers a structured approach for assessing processes as well as systems and quantifying their potential environmental emissions and impacts. The LCA

supports decision makers, companies, scientists, and individuals in calculating and optimizing products and processes toward more environmentally friendly solutions. The method can help in identifying opportunities, in selecting relevant criteria, and in marketing [11]. For the life cycle of a product or a service, potential environmental impacts in a pre-defined system boundary are considered based on quantitative data on raw materials and energy consumption as well as emissions produced in all respectively relevant processes. Both direct environmental impacts of the foreground system, including on-site effects, and indirect environmental impacts of the background system, including upstream processes and the subsequent downstream path, are considered in the assessment of the investigated process or system. Considering the foreground system's material flows and information from databases of background processes, the LCA quantifies and characterizes all relevant input and output flows along the system boundaries from and into the environment. These inventory data are subsequently classified and assigned to a set of environmental impact categories and characterized on the basis of the relative characterization factors in a set of indicators. From 1994 to 2006, the ISO harmonized and standardized the LCA, leading to today's updated standards ISO 14040 (2006) and ISO 14044 (2018) [11,12], which provide a common structure of LCA, including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and the interpretation phase. [17]. Both norms, ISO 14040 and 14044, belong to the family of ISO 14000, which deals with environmental management standards [18]. ISO 14040 focuses on the principles and framework of LCA and has become the basic structure of all life cycle-based standards. It defines the currently used general structure of LCA. ISO 14044 requires adequate quality of data and contains all technical requirements and guidelines and is used together with ISO 14040 (framework/guidelines of LCA) [19] in several studies.

LCA of Steel: State of the Art

To give an outline of already published studies, some articles are listed below. Applied methods, impact categories, and results are briefly described. There is no claim for absolute completeness at this point, and the order of the studies presented has no significance. The study by Neugebauer and Finkbeiner [20] is considered important since it is a German study, from 2012, analyzing an integrated steel mill with a blast furnace. The basis of the study by Neugebauer and Finkbeiner [20] is an average value of data from different German steel mills. The authors use a modified equal-burden approach that divides the total emissions of the production equally over six assumed life cycles. Based on the assumptions, an overall environmental profile for steel is determined. This overall environmental profile is allocated proportionately to the six life cycles so that each life cycle carries the same load, regardless of the actual production emissions [20,21]. VDEh Stahlinstitut results [15] are considered as a reference, as they are modeled for a similar plant, based on older data from 2012/2013. These two German studies would also allow further comparisons across other impact categories. Chisalita et al. [1] are considered because theirs is a more recent study, in which GaBi and the CML 2001 methodology were used, with the database being composed of various sources. The study by Burchart-Korol [9] is considered since primary data from 2010 were used in this study and a blast furnace route was analyzed. All four studies named their system boundaries as cradle-to-gate; all selected studies used an integrated steel mill to produce steel and have given the results either in 1 t of produced steel or 1 kg of produced steel (Table 1).

Table 1. Comparative studies.

Author	Neugebauer and Finkbeiner	Burchart-Korol	VDEh Stahlinstitut	Chisalita et al.
Publication Year	2012	2013	2016	2018
Data Reference Year	2010/2011	2010	2012/2013	n.d.
Country	Germany	Poland	Germany	Netherlands
System Boundaries	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate
FU	1000 kg of hot-rolled coil	1 ton of cast steel produced	1 kg of steel	1 metric ton of hot-rolled coil
Integrated Steel Mill	x	x	x	x
Software	GaBi	SimaPro	GaBi	GaBi
Database	GaBi	Ecoinvent	GaBi	GaBi
Number Midpoint Indi.	7	2	5	10

Burchart-Korol [9] named the sinter plant as the largest contributor to metal and mineral depletion. Electricity was considered to have the highest impact on greenhouse gas emissions and fossil fuel consumption for the electric arc furnace route. Data for the analysis were obtained from steel plants in Poland [9].

The data used in the study by VDEh Stahlinstitut was derived from operational data surveys conducted by four providers, which represent quantity-weighted average results. The blast furnace and indirectly the power plant were mentioned as the main emitters with GWP [15].

Chisalita et al. [1] additionally presented approaches of two post-combustion CO_2 capture technologies (carbon capture and storage (CCS)), which are innovative aspects in this LCA. The study showed that the integration of CCS could significantly reduce the GWP while raising other impact categories due to the increased fuel demand [1].

In addition to the four studies mentioned above (Table 1), which will be discussed again later, other studies have been published and are briefly described below. Another LCA in 2016 was conducted in Turkey by Olmez et al. The study was carried out using SimaPro and the IMPACT2002+ impact assessment method. A field study for data collection was conducted in an integrated iron and steel production facility. Information on the purchase of raw materials, energy, and auxiliary materials was not obtained from the facility but was taken purely from the inventories in the SimaPro database [2]. In 2018, Ma et al. [22] published a water footprint and LCA on crude steel production in China. The data on crude steel, energy consumption, and waste generation were collected from an iron and steel plant located in Shandong Province. A combination of the IMPACTWorld+ model, the IPCC report, the USEtox model, and ReCiPe was applied. Direct emissions were identified as relevant for global warming; nevertheless, the study showed a strong focus on the water footprint [22]. Cui et al. [23] focused explicitly on one of the major emitters in the steel industry, the sinter plant, and carried out the LCA and the LCC for this purpose. The steel company selected for this study is located in China, which provided data from the actual production process [23]. Besides, there are studies addressing the steel industry and related environmental and energy issues and name the LCA or the carbon footprint but do not conduct a complete steel LCA by themselves [3,13,24–27]. Another approach was taken by García et al. [7], who conducted a gate-to-gate LCA study with the functional unit 1 MWh of thermal energy produced and delivered to the steel plant in SimaPro. The reference year for the data was 2014, where the foreground system's inventory data were taken directly from the studied industrial unit (plant in northern

Spain) and the inventory data corresponding to the background system were taken from the Ecoinvent database [7]. In 2020, Liu et al. [28] focused on comparing economic and environmental costs and benefits of producing and trading ferrous materials and goods of 15 top iron ore mining and producing countries. An LCA (in OpenLCA) for 1 ton of steel was used to determine the environmental production hotspots, whereby the system scope was the whole world and the foreground boundary was a selected country, leading to environmental impacts associated with a ton of ferrous material/good produced or traded at country level [28].

The current study differs from the previously published studies in that it is based on very up-to-date (2018) primary data according to ISO 14040/44 [11,12]; the route under consideration includes an integrated steel mill with a blast furnace and a basic oxygen furnace, a casting rolling plant is included, and the study describes in detail the implementation of the LCA for 1 kg hot-rolled coil for the first time. The measured and reported primary data from a German producer serve as a verified data basis for the LCA, and no average values from different producers over several years are used. In the current study, the CML 2001, January 2016, method is used to map all relevant impact categories and to enable a comparison with other studies. Detailed description and presentation of the results and detailed data verification complete the study. In particular, the study is prepared against the background of an emerging change. The producer focuses on the sustainability strategy; the determined values serve as a forward-looking basis for optimization. The following sections describe the applied methodology, show the results, and include a discussion.

2. Methodology

A complete LCA case study was carried out with the software GaBi [29], in accordance with ISO 14040/44 [11,12] of the steel production route based on primary data from 2018. Due to confidentiality agreements with the manufacturer, absolute data on scrap input and other input flows cannot be provided. In the following section and in Section 3 (Results), the four steps of LCA regarding steel production and related to this study are described in more detail.

2.1. Goal and Scope

The goal of this LCA study is to provide a comprehensive and actual life cycle assessment of 1 kg of hot-rolled coil (functional unit (FU)) produced in an integrated steel mill in Germany in 2018. The system boundaries include all sub-processes of the hot-rolled coil/steel production, considering the life cycle stages from cradle-to-gate [30]. The following processes are included (Figure 2): sinter plant, coking plant, blast furnace, basic oxygen furnace, steel plant, continuous casting plant, hot strip mill, casting rolling mill, power plant as well as associated processes of wastewater treatment (water management), and scrap processing. The equipment and machinery used to produce steel are not included within the study because their manufacturing impact is negligible compared to that of the others. Explicitly, no transport processes between raw material extraction and plant are considered. This is due to already integrated transport routes in GaBi. According to the Life Cycle Assessment Methodology Report of the World Steel Association, there are two possible application methods for scrap modeling: with end-of-life recycling and without end-of-life recycling. In this study, the excluded end-of-life recycling method is applied, in which no environmental impact is assigned to the external scrap [5]. For the internal scrap (14.8%) accumulation, a closed-loop scenario is applied. Excess process gases are converted into electricity and steam in the company's own power plant. Surplus electricity is fed into the German power grid. The required raw material inputs are considered for all processes. The utilization phase of the products manufactured from the steel and their associated process steps and their environmental impact are not part of this case study (cradle-to-gate).

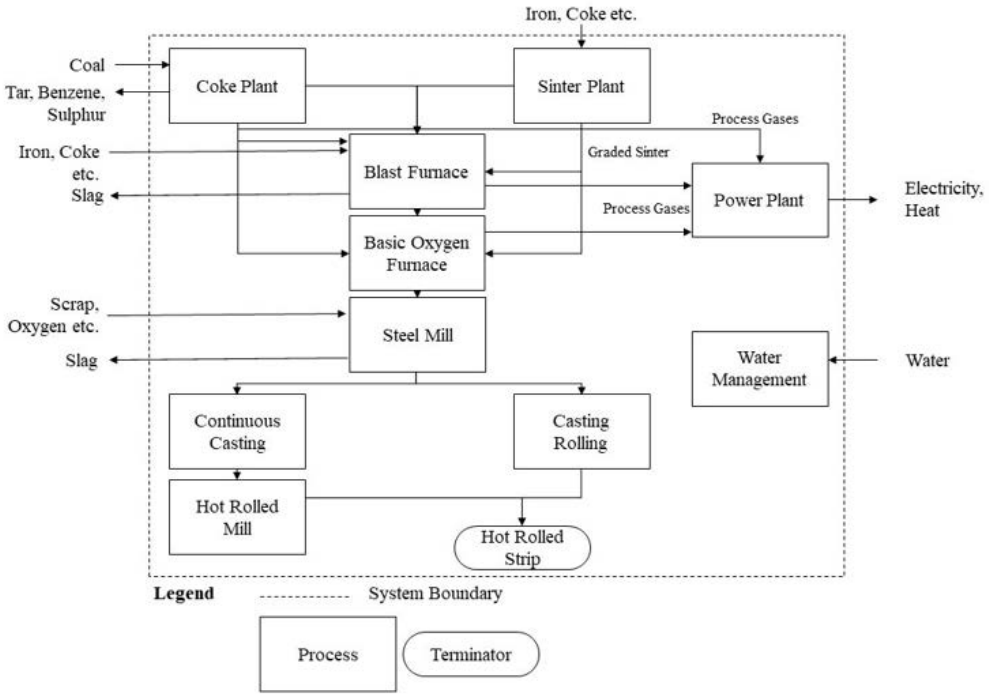


Figure 2. Simplified system boundaries.

All upstream processes refer to the FU of 1 kg hot-rolled coil. Large parts of the residual materials, like slag, gases, and scrap, arising in production are recycled or serve as secondary raw materials for other industries. Cleaning and treatment of incidental wastewater also take place within the system boundaries. Accruing process gases are initially used for caloric energy supply and, as already mentioned, are converted into electricity and steam in the company's own power plant and used internally. A credit note is issued in accordance with the German electricity mix (DE: Electricity grid mix ts) stored in the GaBi database (GaBi 9, SP39, Version Professional and Extensions). The assumption of a credit according to the German electricity mix can be regarded as conservative, due to the growing demand for renewable energy [31,32]. Further credits are granted for the by-products of the blast furnace and converter slag, district heating, benzene, tar, and sulfur. Credits for surplus district heating are given following the GaBi process EU-28: District heating mix ts. GaBi database references are used in this study for the allocation of credits. With regard to slag, it should be noted that this study uses primary data from the manufacturer and does not require any allocation factors [5,33]. The system expansion is implemented according to the avoided burden approach. Recycling processes are not considered in this study due to the defined system boundaries. The excluded end-of-life recycling method is applied, meaning that no environmental burden is assigned to the externally used scrap (14.8%) by giving it a credit [5]. Credits for saved primary production processes are allocated according to their actual applications. The exact use of the by-products produced is supplied by the producer (Table 2).

Table 2. Credit processes.

By-Product (Source)	Function Outside the Plant	Used GaBi Data Sets
Blast furnace slag (Blast furnace)	Cement production Road building Landfill	EU-28: Gravel 2/32 ts [1] DE: Landfill for inert matter (Steel) PE 1
Converter slag (Converter)	Road building Fertilizer	EU-28: Gravel 2/32 ts DE: Lime (CaO; finelime) (EN 15804 A1-A3)
Process gases (Blast furnace, coke plant, converter)	The process gases produced are primarily used internally. Excess process gases are converted into electricity and heat in the power plant. Produced electricity is internally used. Excess electricity is fed into the power grid.	DE: Electricity grid mix ts
District heating (Blast furnace, hot-rolled mill)	District heating	EU-28: District heating mix ts
Tar (Coke plant)	Tar	EU-28: Bitumen at refinery ts
Sulfur (Coke plant)	Sulfur	DE: Sulfur (elemental) at refinery ts
Benzene (Coke plant)	Benzene	DE: Benzene mix ts

[1] ts: Data source thinkstep.

The steel production process modeling is implemented based on available primary information: operating data, thermal energy used, and power consumption. Production data of high representativeness in terms of timeliness, plant technology, and capacity utilization regarding the year 2018 have been selected by the manufacturer, representing the most recent data available at the start of the project. Primary data from the production site, located in Germany, are used, measured, and reported according to 2009/29/EC. The cut-off criterion of 1 w-% is applied regarding all primary input flows, whereby it is ensured that no environmentally relevant flow is cut off. Secondary data used, taken from the GaBi database (SP39), implicitly consider the cut-off criteria defined by GaBi [34]. The background data sets have been chosen, if possible, with German references. Alternatively, the European or global data sets have been applied. High temporal representativeness is guaranteed as the last revision of the data was carried out less than five years ago [5]. The listed dominant input materials are all carbon or iron carriers and are, therefore, recorded by the company according to the 2009/29/EC guidelines on emissions trading [35] following legally binding rules and annually reporting to the Deutsche Emissionshandelsstelle (DEHSt) [36].

2.2. Life Cycle Inventory

The LCI contains all quantitative inputs and outputs of needed materials and emissions of the product modules described in Section 1.1 and shown in Figures 1 and 2. According to the 2009/29/EC [35] on emissions trading, the company is obliged to monitor greenhouse gas emissions and report them annually to the Deutsche Emissionshandelsstelle [36]. For this purpose, all material flows containing carbon and iron are collected, monitored, and recorded, which correspond to the facility's direct emission data. The accuracy requirements for quantity measurement, sampling, and analysis correspond to the specifications of the Deutsche Emissionshandelsstelle. These collected and reported data are also used for the LCA case study. Data not subject to reporting requirements are

from purchasing and controlling, as well as from internal substance-specific throughput measurements of the producer. In addition to the primary data, the following secondary data are required: data on external raw materials used in the processes, data on the supply chain of electricity mix and energy sources used, and data on credits recognized for by-products. The data have been taken from the existing GaBi database and are shown in Table 3. Country-specific data sets consider the transport of the material to the respective country. Data on raw material production and energy supply reflect the current state of technology, considering the geographical location (primary data production location: Germany; secondary data: GaBi database, SP39, mostly with German reference).

Table 3. Secondary data used.

Material/Energy Flows	Used GaBi Data Sets (SP 29)
Aluminum	DE: Aluminum ingot mix ts
Argon	DE: Argon (gaseous) ts
Bauxite	EU-28: Bauxite ts
Quicklime	DE: Lime (CaO; quicklime lumpy) ts
Calcium hydroxide	DE: Calcium hydroxide ($Ca(OH)_2$; dry; slaked lime) ts
Calcium silicate	EU-28: Calcium silicate ts
Chrome	DE: Ferro chrome mix ts
Landfill	DE: Landfill for inert matter (steel) PE
Iron ore	DE: Iron ore mix PE
Iron pellets	DE: Pellet feed mix PE
Groundwater	EU-28: Tap water from groundwater ts
Limestone, dolomite	DE: Limestone ($CaCO_3$; washed) ts
Copper	DE: Copper mix (99.999% from electrolysis) ts
Manganese	ZA: Ferro manganese ts
Molybdenum	RER: Molybdenum, at regional storage
Sodium chloride	EU-28: Sodium chloride (rock salt) ts
Nickel	DE: Ferro nickel PE
Process water (desalinated; deionized)	EU-28: Process water ts; DE: Water (desalinated; deionized) ts
Quartz sand	DE: Silica sand (Excavation and processing) ts
Oxygen	DE: Oxygen (gaseous) ts
Lubricating oil	DE: Lubricants at refinery ts
Sulfuric acid	DE: Sulfuric acid mix (96%) ts
Silicon	GLO: Ferro silicon mix ts
Nitrogen	DE: Nitrogen (gaseous) ts
Synthetic graphite	DE: Synthetic graphite (via petrol coke) PE
Titanium	GLO: Titanium ts
Water (desalinated; deionized)	DE: Water (desalinated; deionized) ts
Tin	GLO: Tin ts
Steam	DE: Process steam from natural gas 95% ts
Natural gas	DE: Natural gas mix ts
Coal	DE: Project hard coal mix
Coke	DE: Coke mix ts
District heating mix Electricity mix	EU-28: District heating mix ts DE: Electricity grid mix ts

Large parts of the residual materials arising in production are recycled, for example, via the sinter plant in steel production, or serve as secondary raw materials for other industries. Purification and treatment of wastewater generated in the production process occur within the system boundaries. A system area extension for by-products is considered. The process gases produced are initially used to provide caloric energy. Excess process gases are converted into electricity in the company's own power plant. Surplus electricity is fed into the German power grid.

2.3. Life Cycle Impact Assessment

The purpose of the impact assessment is to examine the data collected in the life cycle inventory regarding certain environmental effects, the so-called impact categories, and subsequently provide additional information. The CML method developed in 2001 by the Institute of Environmental Sciences at the University of Leiden (Netherlands) is an internationally recognized midpoint method for impact assessment that is applied in various life cycle assessments [37]. As shown by Back and Finkbeiner [38] using the example of acidification potential (AP) and eutrophication potential (EP), newer methods do not necessarily lead to more reliable results than the CML 2001 method [39]. It is a common standard method that ensures comparability with previous investigations [15]. For this reason, the CML 2001 method, status January 2016, is used for this case study. The aim of the CML method applied is to quantitatively map as many material and energy flows as possible between the natural environment and the product system in the life cycle. The impact categories used in this study are climate change (global warming potential (GWP)), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), abiotic depletion potential fossil (ADPf), abiotic depletion potential of resources (ADPe), and ozone layer depletion potential (ODP). This selection of impact categories was made based on the previous report [15] and the Life Cycle Inventory Methodology Report for Steel Products [5]. The impact assessment results are relative statements and do not make any predictions about effects on final manufactured products, threshold value exceedances, safety margins, or risks. The results are not normalized, ordered, or weighted due to the subjective values required for this purpose.

3. Results

3.1. LCI Results

As shown in Table 4, the life cycle inventory results are distributed over direct emissions, the upstream chain, and by-products, resulting in the sum of the total emissions. Direct emissions only include emissions from the plants at the integrated steel mill site. The emissions produced in the production of raw materials used are listed as upstream emissions and include material (auxiliary) and energy processes and the treatment processes at suppliers. Credit notes are listed for by-products that replace primary raw materials. Table 4 shows that carbon monoxide (CO) is emitted almost exclusively by direct emission processes at the production location. Likewise, CO_2 is also influenced by the direct emissions; upstream and by-products compensate each other partially (upstream 25%, by-products −21%). This is due to the carbonaceous process. Gases are completely combusted in the integrated steelworks, producing carbon dioxide.

Table 4. Inventory analysis in percentage per production cluster.

	Direct Emissions	Upstream Chain	By-Products
CO	99%	5%	−4%
CO_2	95%	25%	−21%
CH	1%	107%	−8%
NMVOC	1%	116%	−17%
NO_x	31%	80%	−11%
SO_2	45%	62%	−7%

The main emitter of SO_2, NO_x, CO and CO_2, direct emissions is the sinter plant. Coke introduced as fuel adds sulfur to the sintering process, reacting to form SO_2. Since the sintering temperature is between 1200 and 1300 °C, thermal NO_x formation is possible. In this process, nitrogen from the combustion air reacts to form nitrogen oxide. Due to the Dwight–Lloyd process principle (Section 1.1), incomplete combustion occurs, resulting in carbon monoxide (CO).

3.2. LCIA Results

This section presents the potential environmental impacts of 1 kg of hot-rolled coil using the CML midpoint method. The impact categories considered are GWP, AP, EP, POCP, ADPf, ADPe, and ODP. The evaluation of the LCA shows the following potential environmental impacts, cradle-to-gate, of 1 kg of hot-rolled coil produced in Germany (Figures 3 and 4; Tables 4 and 5): GWP describes the contribution of a trace gas to the greenhouse effect in relation to carbon dioxide [15,37,40,41]. The LCIA results in a GWP (2.1 kg CO_{2e}/kg of hot-rolled coil) being influenced by 90% of direct emissions; 27% of the emissions result from the upstream chain, including material (auxiliary) and energy processes and the treatment processes at suppliers, and −17% are credited to by-products (Figure 3; Tables 5 and 6).

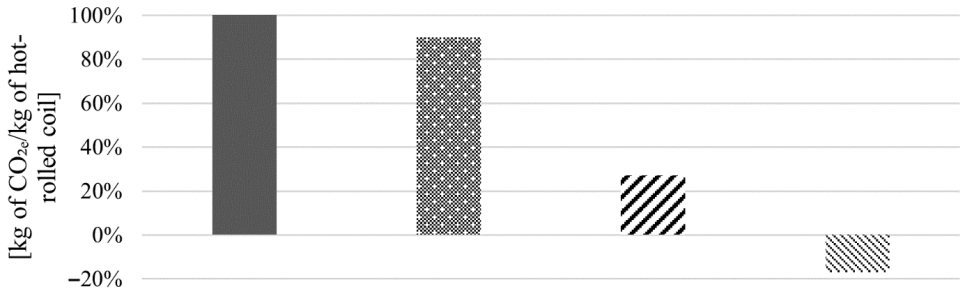


Figure 3. Global warming potential (GWP) results (kg CO_{2e}/kg of hot-rolled coil).

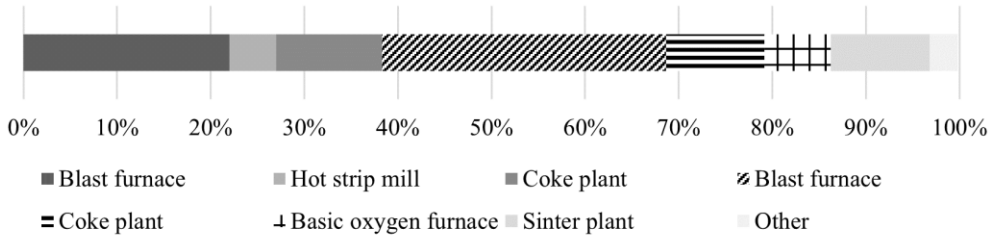


Figure 4. Main direct emitters: split power plant emissions.

Table 5. Emissions: Total and as a share of total emissions.

		Share of Total Emissions							
	Total Emissions	**Direct Emissions**	**Blast Furnace**	**Hot Strip Mill**	**Coke Plant**	**Power Plant**	**Sinter Plant**	**Upstream**	**By-Product**
GWP (kg CO_{2e})	2.1	90%	20%	4%	10%	43%	9%	27%	−17%
AP (kg SO_{2e})	4.8×10^{3}	40%	3%	3%	4%	7%	23%	69%	−9%
EP (kg PO_{4e})	5.1×10^{4}	28%	1%	4%	5%	5%	12%	85%	−13%
POCP (kg C_2H_{4e})	6.5×10^{4}	71%	5%	1%	2%	2%	55%	36%	−6%
ADPf (MJ)	20.7	1%	0%	0%	0%	0%	0%	110%	−11%
ADPe (kg Sb_e)	1.4×10^{6}	3%	0%	0%	0%	0%	0%	115%	−19%
ODP (kg $R11_e$)	1.6×10^{11}	0%	0%	0%	0%	0%	0%	111%	−11%

Table 6. Share of direct and upstream emissions.

	% of Direct Emissions					% of Upstream Emissions			
	Blast Furnace	**Hot Strip Mill**	**Coke Plant**	**Power Plant**	**Sinter Plant**	**Iron Ore Mix**	**Hard Coal Mix**	**Pellet Feed Mix**	**Alloying Elements**
GWP ((kg $CO_{2\,e}$)	22%	5%	11%	48%	11%	11%	26%	14%	16%
AP (kg $SO_{2\,e}$)	9%	7%	9%	17%	58%	30%	26%	23%	13%
EP (kg $PO_{4\,e}$)	4%	13%	17%	17%	44%	28%	29%	18%	16%
POCP (kg $C_2H_{4\,e}$)	7%	1%	2%	3%	79%	26%	33%	20%	13%
ADPf (MJ)	0%	0%	0%	0%	0%	3%	73%	4%	4%
ADPe (kg $Sb_{\,e}$)	0%	0%	0%	0%	0%	3%	1%	2%	91%
ODP (kg $R11_{\,e}$)	0%	0%	0%	0%	0%	18%	0%	18%	64%

Significant direct emissions are both indirectly resulting from the power plant (48%; patterned (Figure 4)) and the blast furnace (22%; dark gray), which has a high energy demand, being comparable with the results of previous studies [9,15]. Other relevant emission shares are attributable to the sinter plant, the coke plant, and the hot strip mill (Figure 4).

As shown in Figure 4, 48% (patterned) of the emissions (7% basic oxygen furnace + 11% coke plant + 30% blast furnace = 48% power plant) can be completely assigned to the actual emitters. This is due to the process gases, which are conducted through other processes of the power plant to be converted into electricity and steam. The blast furnace accounts for the largest share (30% of the gases emitted and converted in the power plant), 11% can be allocated to the coke plant, and 7% are emitted by the basic oxygen furnace. The results in this study are similar to those of other studies, also naming the power plant, the coke plant, the sinter plant, and the blast furnace as the main emitters [1–3,9,22,23].

Acidification (impact category: acidification potential (AP)) is a process that occurs when more acidifying substances are introduced into an ecosystem, e.g., the soil. This results in poorer growth conditions for plants as well as other negative effects on ecosystems [15,37,40,41]. For AP (4.8^{-3} kg $SO_{2\,e}$ /kg of hot-rolled coil), the direct emissions have a share of 40%, where the main emitter is the sinter plant. The upstream chain has the largest share of total AP emissions, influenced by the iron ore mix. As shown in other studies, the upstream chain is greatly influenced by resources [1]. By-products account for −9% of the total emissions (Tables 5 and 6).

Eutrophication refers to the nutrient enrichment of water and soil caused by increased nitrogen and phosphorus input. This can lead to a reduction in species diversity or drive the growth of algae in waters [15,37,40,41]. For EP (5.1^{-4} kg PO_{4e}/kg of hot-rolled coil), the upstream chain accounts for the largest total emission share. The upstream chain contributes 85% of the total emissions. Direct emissions represent only 28% of the total emissions (Tables 5 and 6). For POCP (6.5^{-4} kgC_2H_{4e}/kg of hot-rolled coil), similar to the GWP, direct emissions account for the largest share of total POCP emissions. The direct emissions are significantly influenced by the sinter plant. POCP emissions for the sinter plant are influenced by the process gases, as the direct inputs represent only a very small percentage of POCP sinter emissions. POCP is mainly influenced by carbon monoxide, sulfur dioxide, and nitrogen oxide emissions from combustion processes, as they occur in the sintering process [15,23]. The upstream chain accounts for 36% of total emissions. By-products show comparatively little emissions, influenced by slag and electricity credits (Tables 5 and 6). The abiotic depletion potential (ADP) describes the reduction in the global stock of non-renewable resources, such as metals and minerals. ADPf represents the

potential for abiotic depletion of fossil fuels (f), and ADPe represents the potential for abiotic depletion of non-fossil resources (e) [15,41]. ADPf (20.7 MJ/kg of hot-rolled coil) is 110% influenced by the upstream chain. As part of the upstream chain, the hard coal mix has a significant influence, of 73% of the total upstream emissions (Table 6). By-products achieve a reduction of −11% through slag, electricity, and tar credits. Direct emissions account for only 1%, not generated by the plant itself but by wastewater treatment. Equivalent to ADPf, the upstream chain also leads to ADPe (1.4×10^6 kg Sb_e/kg of hot-rolled coil) for total emissions of 115%, driven almost completely by the alloying elements (Tables 5 and 6). The direct emissions correspond to a 3% share of the total emissions, influenced by water management. Two main groups of substances are responsible for the depletion of ozone: chlorofluorocarbons (CFCs) and nitrogen oxides (NO_x). The ozone depletion potential of a substance results from its ozone depletion potential (ODP) value [15,41]. For ODP (1.6–11 kg R11 $_e$/kg of hot-rolled coil), the absolute emissions are driven through the upstream chain with a proportion of 111% (Table 5), influenced by alloying elements, the iron ore mix, and the pellet feed mix (Table 6). By-products show a reduction of 11% in total emissions, achieved through slag credits. Direct emissions are negligible (Table 5).

Comparability with Other Study Results

Not all comparative studies considered regarding the production of hot-rolled coil show comprehensive LCIA results, leading to a complete comparison in terms of the GWP. At this point, the present study's authors refer to Section 1.2 (LCA), where four of several other studies have been presented in more detail. These four studies, by Neugebauer and Finkbeiner [20], VDEh Stahlinstitut [15], Chisalita et al. [1], and Burchart-Korol [9], all named their system boundaries as cradle-to-gate, focused on an integrated steel mill, and presented the results either in 1 t or 1 kg of produced steel, which, at this point, allows the results to be scaled uniformly to 1 kg of steel and thus provides for a rough comparison of the GWP results (Figure 5). As can be seen in Figure 5, the absolute (partly downscaled) GWP of the five studied values is between 1.7 kg CO_{2e}/kg of steel (lowest value of reported studies) [20] and 2.5 kg CO_{2e}/kg of steel (highest value of reported studies) [9]. The arithmetic mean over the four other studies analyzed, presented in Figure 5, is 2.1 kg CO_{2e}/kg of steel, which corresponds exactly to the values of Chisalita et al. [1] and the present study.

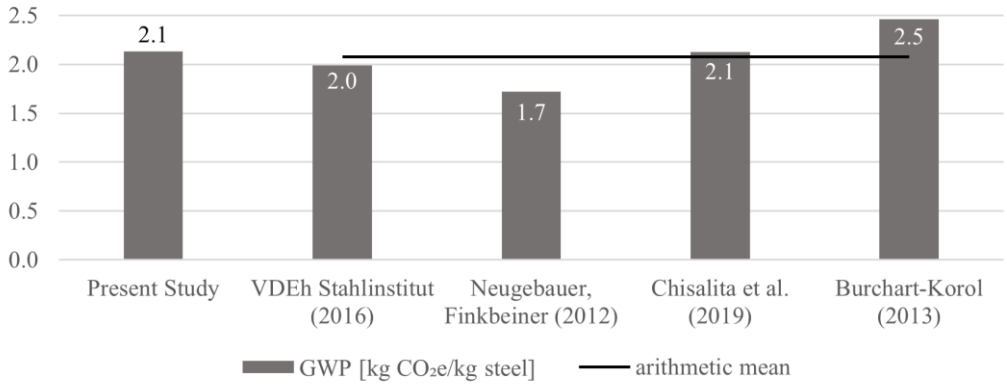


Figure 5. Comparison of GWP results.

To describe the GWP result of 1 kg hot-rolled coil for non-steel experts, a comparison with other construction materials, reinforcement materials (polyacrylonitrile (PAN) carbon fibers), and metals is given. In the construction sector, steel as reinforcement in concrete is currently an often used and popular building material [42]. Compared to the other construction products listed here, steel shows the highest GWP per kg product, with 2.1 kg CO_{2e} [43]. Bribián et al. [44] analyzed the emissions of 1 kg of product during material manufacturing, its transport from production to the building site, its use in construction and demolition, and the final disposal of the product [43]. Habert [44] compared CO_2

emissions for Portland cement production. The given values were reported in g/kg of cement, which leads to a mean of 0.814 kg CO_{2e}/kg of cement [44]. However, on comparing the steel with other materials, such as copper, aluminum, or innovative reinforcement alternatives, such as (polyacrylonitrile (PAN) carbon fibers, it can be seen that the GWP of hot-rolled steel (2.1 kg CO_{2e}) per kg of product is relatively low [45–47]. Das (2011) [47] analyzed carbon fiber-reinforced polymer composites, as they gain more importance in vehicles and as construction reinforcements, substituting them with steel. Results showed, that carbon fiber production is about 14 times more energy intensive than normal steel production, which also showed the high GWP value of 31 kg CO_{2e} per kg of material [47]. Nunez and Jones [45] did a cradle-to-gate LCA for primary aluminum production. The GWP for alumina is 10.8 kg CO_{2e} per kg of primary ingot (Figure 6).

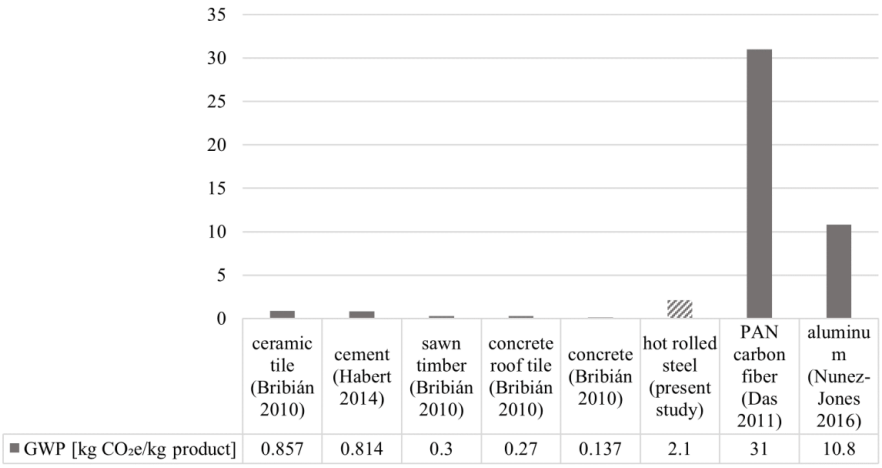


Figure 6. Comparison of GWP results.

4. Discussion and Data Verification

Even if the data basis can be regarded as good and continuous measurements of the values have been carried out, data verification is presented below, showing how uncertainties in the input materials used (upstream), the individual plants (direct emissions), and the credits (by-products) affect the overall results.

The measured primary data are fully integrated into the primary emissions since these are the processes and plants at the production site in Germany. In terms of GWP, direct emissions greatly influence the overall result. Due to the measured and reported primary data, the GWP emission data are reliable. Reliability differs for the upstream data, as the accuracy is based on the secondary data taken from the GaBi database and not directly from the suppliers themselves. For the impact categories acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), fossil abiotic resource consumption (ADPf), and elementary abiotic resource consumption (ADPe), the environmental impacts of the upstream chain dominate the total emissions (Tables 5 and 6). For this reason, hypothetical data uncertainty of the GaBi data for assumed upstream chains of 10% is calculated (Table 7).

Table 7. Data set uncertainty upstream.

Impact Category	Upstream—Δ	Total Emission Result—Δ
ADPe	10%	11.5%
ADPf	10%	11.0%
AP	10%	6.9%
EP	10%	8.5%
GWP	10%	2.7%
ODP	10%	11.1%
POCP	10%	3.6%

Table 7 shows that data uncertainty of +/− 10% in the upstream chain impacts the total emission results from +/− 2.7% (GWP) to +/− 11.5% (ADPe).

To reduce indirect emissions, the influencing upstream emissions need to be cut down. Furthermore, the greenhouse gas balances of the remaining input materials, such as iron pellets and alloying elements, also need to be reduced. Even if it is still expandable, the producer is already analyzing its supply chain and has already developed a code of conduct [48]. By 2030, the producer aims to reduce emissions from its own production and the purchased energy by 30% compared with its reference year 2018. However, if the producer's sustainability strategy is to be pursued further [14], new, innovative approaches are indispensable for reducing direct emissions and allowing the producer itself to intervene. Approaches and opportunities for innovative solutions can already be found in the global steel industry [14,49–51].

5. Limitations

Even though this study is the first German update and completely describes LCA, some limitations could be considered in future studies: the effects of a circular economy strategy at the global level and the increased use of secondary steel. If the demand for secondary materials increases, this can lead to a price increase. The amount of secondary material is closely linked to production based on the primary material, which cannot be increased independently and indefinitely. The study and its data relate only to Germany and the respective integrated steel mill. It does not take a closer look at transnational transport systems or mining processes (relevant processes for upstream/indirect emissions), which were named relevant by other studies [28]. Additionally, only a selection of CML indicators was analyzed in this study and toxicity and human health were not considered, designated as a crucial problem by other authors [2,28]. Further research and studies can cover these gaps.

6. Conclusions

The goal of this cradle-to-gate LCA of steel, concerning ISO 14040/44, was to create an actual picture of the environmental profile for the steel production process and to identify the main emitters in the direct production process and the upstream processes. The study was performed with GaBi SP39, using the CML 2016 database and primary data from the actual production year 2018, supported by thyssenkrupp Steel Europe AG. The functional unit was set to 1 kg of hot-rolled coil manufactured in Germany, based on the measured primary data. The cradle-to-gate system boundaries of this LCA included the integrated steel plant as well as upstream processes and associated processes of wastewater treatment. The equipment and machinery used for the production of steel was not included. The life cycle inventory results were distributed over direct emissions, the upstream chain, and by-products, resulting in a sum of total emissions. Direct emissions only included emissions from the plants at the integrated steel mill site. The emissions produced in the production of raw materials used were listed as upstream emissions and included raw material (auxiliary) and energy processes and the treatment processes at suppliers. Credit notes were listed

for by-products that replaced primary raw materials. The LCIA resulted in a GWP of 2.1 kg CO_{2e}/kg of hot-rolled coil, being influenced by 90% of direct emissions, 27% of the emissions resulting from the upstream chain and −17% from credit. The significant parameters of the GWPs' direct emissions were the blast furnace (22%) and indirectly the power plant (48%). This was due to the process gases, which were conducted through other processes (blast furnace, coke plant, and basic oxygen furnace) of the power plant, to be converted into electricity and steam. For AP, EP, ADPe, and ADPf, the upstream chain accounted for the largest total emission share. For the POCP, direct emissions accounted for the largest share (71%), significantly influenced by the sinter plant. To strengthen plausibility and to better illustrate the results, this study has been compared with other LCA studies on steel. This LCA study shows that the direct emissions in the sinter plant and the blast furnace and, indirectly, in the power plant (driven by process gases of BOF, coke plant, and BF) could be examined more closely. Nevertheless, it should be noted that the material and energy flows of the integrated steel mill have already been thoroughly optimized and further great efforts are being made to increase the potential. A bigger optimization potential could lie in the upstream chain, i.e., by reducing the environmental impacts of suppliers and raw material producers and by this, the purchase and supply chain of the producer itself.

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Data Availability Statement: The used primary data directly represent the production line of thyssenkrupp Steel Europe AG in 2018. Due to confidentiality reasons, these data are and will not be publicly available. Secondary data have been taken from Sphera databases, which are chargeable databases; see also http://www.gabi-software.com/international/index/ (accessed on 17 January 2021).

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