Cost and Life Cycle Analysis for Deep CO_2 Emissions Reduction of Steelmaking: Blast Furnace-Basic Oxygen Furnace and Electric Arc Furnace Technologies

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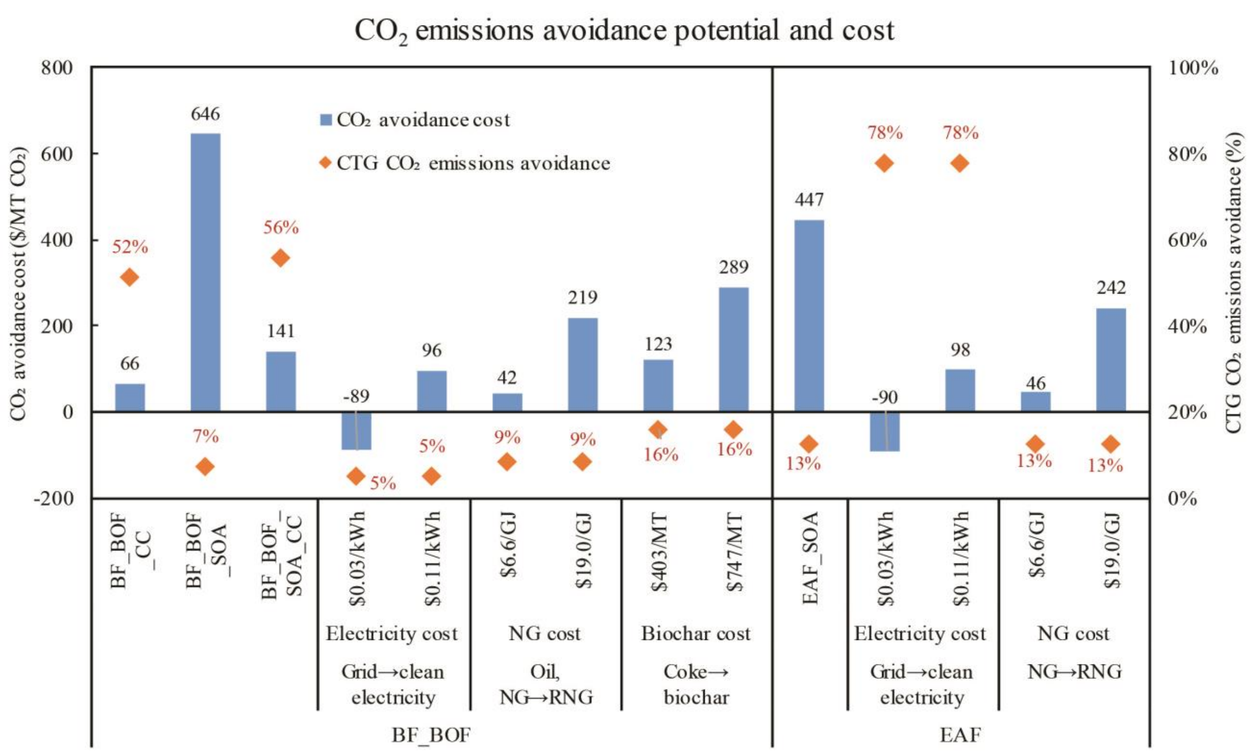
ABSTRACT

Iron and steel manufacturing is the largest contributor to CO_2 emissions among heavy industries worldwide. This is mostly due to the use of coal in blast furnace-basic oxygen furnace (BF-BOF) process for virgin (primary) steel production. The electricity generation mix used in the electric arc furnace (EAF) process to recycle scrap steel also contributes to the CO_2 emission associated with secondary steel production. To decarbonize iron and steel sector, we investigated decarbonization options for BF-BOF and EAF processes, including energy efficiency, carbon capture and storage, and the use of clean energy sources, in various BF-BOF and EAF process configurations. For each decarbonization approach, we evaluated the CO_2 reduction potential via life cycle analysis (LCA) and estimated the associated cost through techno-economic analysis (TEA). A typical U.S. BF-BOF for virgin steel production has a cradle-to-gate (CTG) CO_2 emissions of 1,990 kg/MT steel with a levelized cost of steel (LCOS) of \$439/MT steel, while a typical U.S. EAF process for secondary steel production in the United States has a CTG CO_2 emissions of 270 kg/MT steel with a LCOS of \$365/MT steel. Combining renewable energy sources and carbon capture, BF-BOF CTG CO_2 emissions can be reduced to 16 kg/MT steel, and EAF configurations can achieve similar deep reductions to reach 25 kg/MT steel. The corresponding LCOS with these decarbonization levels is estimated to increase to \$542/MT steel and \$348/MT steel, respectively. The estimated CO_2 avoidance costs vary from -\$90/MT CO_2 to \$646/MT CO_2, depending on the various decarbonization technologies and energy prices.



KEYWORDS

Steelmaking, decarbonization, techno-economic analysis, life cycle analysis, CO_2 emissions, energy switching

1. INTRODUCTION

Iron and steel manufacturing is the largest contributor to CO_2 emissions and second largest energy consumer among heavy industries worldwide (IEA, 2020a). The iron and steel industry accounts for 83% of the coal demand in the U.S. manufacturing sector (EIA 2018 and 2020), where coal is used as a primary fuel as well as a feedstock for coke production. In a coke oven, coal is heated to produce coke, which has a higher carbon content and lower impurities, and is an important raw material for pig iron production (Babich and Senk, 2019; Mayer et al., 2019). This large coal consumption, as well as high demand for other energy sources, results in high greenhouse gas (GHG) emissions in iron and steel manufacturing (Ryan et al., 2020). In 2019, the direct GHG emissions from U.S. iron and steel manufacturing were 72 million metric tons (MMT) CO_2 equivalent, or 6% of the total U.S. GHG emissions from manufacturing sectors (GHGRP, 2019). To achieve the goal of net-zero CO_2 emissions by 2050 (IEA, 2020b), the iron and steel manufacturing sector needs a deep reduction of CO_2 emissions (Arens et al., 2017). That reduction can be achieved through increased energy efficiency, carbon capture and storage (CC), and the use of cleaner energy (Milford et al., 2013). However, these approaches may increase crude steel production cost given the investment cost of energy-efficient technologies, the increased energy consumption of CC, and the higher price of clean energy. Thus, this work discusses the CO_2 emissions reduction potential of different approaches with cost tradeoffs to determine the optimal decarbonization solution.

In the U.S. steel industry, the two major manufacturing technologies are the blast furnace–basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF) (Jamison et al., 2015). In 2019, a total of 87.8 MMT of steel was produced in the U.S.: 30% from BF-BOF and 70% from EAF (World steel Association, 2020). BF-BOF consumes mostly iron ore, though scrap (recycled steel) can constitute up to 30% of the raw material; EAF uses primarily scrap without iron ore (Cavaliere, 2019). U.S. BF-BOF facilities are over 30 years old (Hasanbeigi and Springer, 2019), on average, with an energy consumption of around 23 GJ/metric ton (MT) steel, of which 85% is coal (Jamison et al., 2015). Because U.S. EAF facilities use scrap as the primary feedstock, their energy consumption is much lower: 6.1 GJ/MT steel (including energy consumption for finishing processes at 3.8 GJ/MT) of which 59% is electricity (Hasanbeigi and Springer, 2019). The different technologies and energy consumption profiles of the BF-BOF and EAF processes require different CO_2 reduction options.

BF-BOF plants, sometimes called integrated mills, consist of multiple processes such as coke making, iron ore agglomeration (Cui et al., 2021), blast furnace, basic oxygen furnace, refining, and casting processes. Energy efficiency improvements, such as multifunctional energy systems (Jin et al., 2009), solid waste utilization (Griffin and Hammond, 2019), and heat-energy recovery (Chen et al., 2018), are potential ways to reduce energy consumption and CO_2 emissions. The U.S. Department of Energy's (DOE's) *Bandwidth Study* estimated the energy consumption of a typical BF-BOF process in the U.S. as the baseline (Jamison et al., 2015). This study concluded that the energy efficiency improvements can reduce energy consumption by 10% achieved through state-of-the-art (SOA) BF-BOF technology, such as coke dry quenching, enhanced combustion control, waste gas heat recovery, steam recovery, ladle management, and bottom stirring (Jamison et al., 2015). Carbon capture and storage is another CO_2 emissions reduction approach in steel production (Rigamonti and Brivio, 2022). Biermann et al. studied an integrated steel mill to estimate the CO_2 capture cost. Their results showed that the lowest capture cost, \$33/MT CO_2, can be achieved by partial CO_2 capture from blast furnace gas, with 36% carbon avoidance. To achieve 76% carbon avoidance, the capture cost increases to \$51/MT CO_2 (Biermann et al., 2019). The International Energy Agency (IEA) compared three CO_2 capture cases that showed the CO_2 avoidance cost to be \$56–\$81 per metric ton when the CO_2 avoidance ratio is 47%–60%(IEA, 2013). Another widely studied approach for industrial steel CO_2 emissions reduction is switching from fossil energy to renewable sources of energy (Kumar et al., 2017). Mandova et al. showed that by using biomass, a BF-BOF mill can achieve a maximum CO_2 emissions reduction rate of 42% (Mandova et al., 2018).

The second type of steel mill, EAF mills, are known as “mini mills” as they have only one primary conversion process. The DOE bandwidth study estimated the energy consumption of EAF technology at 2.3 GJ/MT for crude steel production—90% less than the current typical BF-BOF process (Jamison et al., 2015). Birat et al. reviewed the global energy consumption of EAF and showed that the best EAF route in practice had an energy intensity of 2.2 GJ/MT crude steel, of which 1.6 GJ/MT is related to electricity consumption and 0.6 GJ/MT is related to fossil fuel consumption for preheating (Birat, 2010). The typical CO_2 emissions reduction approach in EAF mills is to increase energy efficiency and use renewable energy sources (both electricity and fuels) rather than fossil energy sources (Echterhof, 2021). The direct CO_2 emissions from EAF mills are more than 90% lower than those of BF-BOF mills, and CO_2 capture cost increases greatly when CO_2 emissions are low owing to economic of scales (Herron et al., 2014). Thus, CC technology is not used to reduce CO_2 emissions in EAF mills.

The CO_2 emissions reduction in BF-BOF and EAF configurations has been previously studied in terms of increased energy efficiency, with and without CC, and with and without the use of renewable energy sources, respectively. However, none of the decarbonization methods can achieve deep decarbonization individually; a combination of several methods is needed to reach the net-zero emissions target.

The previous steel decarbonization studies were based on various plant parameters and analysis boundaries, thus did not employ a uniform framework to evaluate and compare different decarbonization options. Consequently, information from these studies could not be simply compared to investigate decarbonization options for steel manufacturing. A systematic, comprehensive, and quantitative analysis for steel decarbonization options with consistent system boundary and baseline is thus needed. This study provides a comprehensive life cycle analysis (LCA) and techno-economic analysis (TEA) of six U.S. BF-BOF and four U.S. EAF decarbonization methods to achieve deep CO_2 reduction.

The six BF-BOF configurations analyzed include two types of system designs: current-practice U.S. blast furnace technologies (BF-BOF) and state-of-the-art (SOA) blast furnace technologies (BF-BOF-SOA). For each of these technologies, we analyzed three system designs: the two base cases (BF-BOF and BF-BOF-SOA), cases with CC (BF-BOF-CC and BF-BOF-SOA-CC), and cases in which CC is combined with a change in all energy sources from fossil to renewable (BF-BOF-all and BF-BOF-SOA-all). The four EAF configurations also include a current technology case and state-of-the-art technology case, and for each we analyzed the base cases (EAF and EAF-SOA) and the decarbonization cases with all energy sources changed from fossil to renewable (EAF-all and EAF-SOA-all). The technology readiness level of these configurations and their available year is listed in Table S1 of the supporting information (SI). The

LCA was conducted using GREET® (Greenhouse gases, Regulated Emissions and Energy use in Technologies) 2020. GREET is a life-cycle model developed by Argonne National Laboratory to evaluate energy and emissions impacts of fuels and products (Wang et al., 2020). TEA was conducted using discounted cash flow analysis—the same methodology used in DOE's *Ironmaking Process Alternatives Screening Study Volume I: Summary Report* (Greene, 2000).

In this study, we derived the mass and energy conversion of all evaluated BF-BOF and EAF configurations information from various literature sources, such as DOE reports (Jamison et al., 2015), industrial reports (The Athena Sustainable Materials Institute, 2002), and others. The mass and energy conversion data were incorporated in the GREET model to evaluate the CTG CO_2 emissions, covering all stages from iron ore recovery to steel production. The mass and energy flow data were also used as input for equipment scaling, and capital and operating costs evaluation, which are used in the discounted case flow analysis to calculate the LCOS.

2. METHODOLOGY

Increased energy efficiency, carbon capture and storage, and use of renewable energy are three methods that can be used to reduce CO_2 emissions from iron and steel manufacturing processes. This methodology section reviews the BF-BOF and EAF steel production technologies using these three methods and includes a discussion of LCA boundaries and assumptions as well as detailed information for TEA analysis. The basic assumptions and conditions for the analysis are listed below.

a) The energy and mass conversion data represents U.S. steel industry average value (i.e., does not represent a specific plant).

b) The steel plants are assumed to operate under steady state (i.e., the transient state energy and mass conversion during startup and shut down is not considered);

c) The life cycle analysis focuses on the feedstock and fuel consumptions, and does not account for the embodied emission during plant construction, which is likely negligible when allocated to per MT of steel, given the large production throughput over the long plant life time;

d) The techno-economic analysis uses the average U.S. historical fuel cost, thus the impact of regional and time-dependent price variations are not covered in this study.

2.1 Steel production technology

2.1.1 BF-BOF technology and CO_2 reduction methods

Figure 1 shows the mass flow rate and CTG CO_2 emissions of a current-practice baseline U.S. BF-BOF steel mill. The energy consumption data is from a previous work by Jamison et al. (2015), for a typical BF-BOF process in the United States. The material flow rates of iron ore, scrap, limestone, and lime are based on previous studies for a baseline steel production plant in the United States (The Athena Sustainable Materials Institute, 2002). The CO_2 emissions are evaluated based on energy consumption, material consumption, and the carbon balance using GREET model. The BF-BOF process includes two materials preparation processes: ore agglomeration (pelletizing and sintering) and coke making (He and Wang, 2017). In the ore agglomeration process, iron ore is crushed and ground to remove impurities and pelletized to form uniformly sized round iron ore pellets. In the sintering process, the ore pellets are mixed with iron fines, coke breeze (fine coke), and limestone to form hardened lumps of sinter as feedstock for the blast furnace. The coke breeze supplies energy for the sintering processes. In the coke oven, coking coal is heated to high temperatures in an airless environment to drive off volatile chemicals, increase carbon content, and produce lump coke as the energy supply for the blast furnace (Xu et al., 2020). The tar and benzol produced from the coke oven are sold to the market as by-products (IEA, 2013). Although not all coke is produced on-site in U.S. BF-BOF plants, the process is included in this analysis to make the analysis boundaries consistent with the energy data source (American Coke and Coal Chemicals Institute, 2020).

After the materials preparation, ironmaking reactions take place in the blast furnace (Suopajärvi et al., 2018). Pellets and sinter (from ore agglomeration), lump coke (from the coke oven), and limestone are added to the top of the blast furnace. In the lower section of the blast furnace, coke is gasified to produce CO through reactions R1 and R2 using hot blast air (24 w% O_2) as the gasification agent (IEA, 2013). The CO reacts with iron oxides as the reducing agent to form hot metal (pig iron) through reactions R3 to R5.

$$C + O_2 \rightarrow CO_2 \qquad \Delta H^0 = -393\ kJ/mol \qquad \text{(R1)}$$

$$C + CO_2 \rightarrow 2CO \qquad \Delta H^0 = +172\ kJ/mol \qquad \text{(R2)}$$

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2 \qquad \Delta H^0 = -47\ kJ/mol \qquad \text{(R3)}$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2 \qquad \Delta H^0 = +19\ kJ/mol \qquad \text{(R4)}$$

$$FeO + CO \rightarrow Fe + CO_2 \qquad \Delta H^0 = -11\ kJ/mol \qquad \text{(R5)}$$

The hot metal produced in the blast furnace is routed to the BOF to be purified and converted to liquid steel. Up to 30% scrap can be also fed to BOF (Suopajärvi et al., 2018). Finally, the liquid steel is refined and cooled in the refining and casting stages to produce crude steel (Kapoor et al., 2021). In the BF-BOF configuration, coke oven gas (COG) and blast furnace gas (BFG) are formed in the coke oven and blast furnace, respectively, and are used as fuel in the power generation unit to supply heat and power to the entire system (Peacey and Davenport, 2016).

Figure 1 shows the material flow rates of iron ore, scrap, limestone, and lime from a typical steel production plant in the United States, as evaluated by the Athena Sustainable Materials Institute (The Athena Sustainable Materials Institute, 2002). Table 1 shows the energy consumption of the six BF-BOF configurations covered in this study. The BF-BOF case represents the typical current technology (current-practice baseline) in U.S. iron and steel manufacturing, which uses 22.7 GJ energy (after by-product displacement) to produce 1 metric ton of crude steel. The energy consumption of the BF-BOF (also shown in Figure 1) is calculated from a U.S. onsite energy consumption database, based on the U.S. Energy Information Agency's (EIA's) Manufacturing Energy Consumption Survey (MECS) data, which includes offsite electricity as well as steam generation and transmission losses (Jamison et al., 2015).

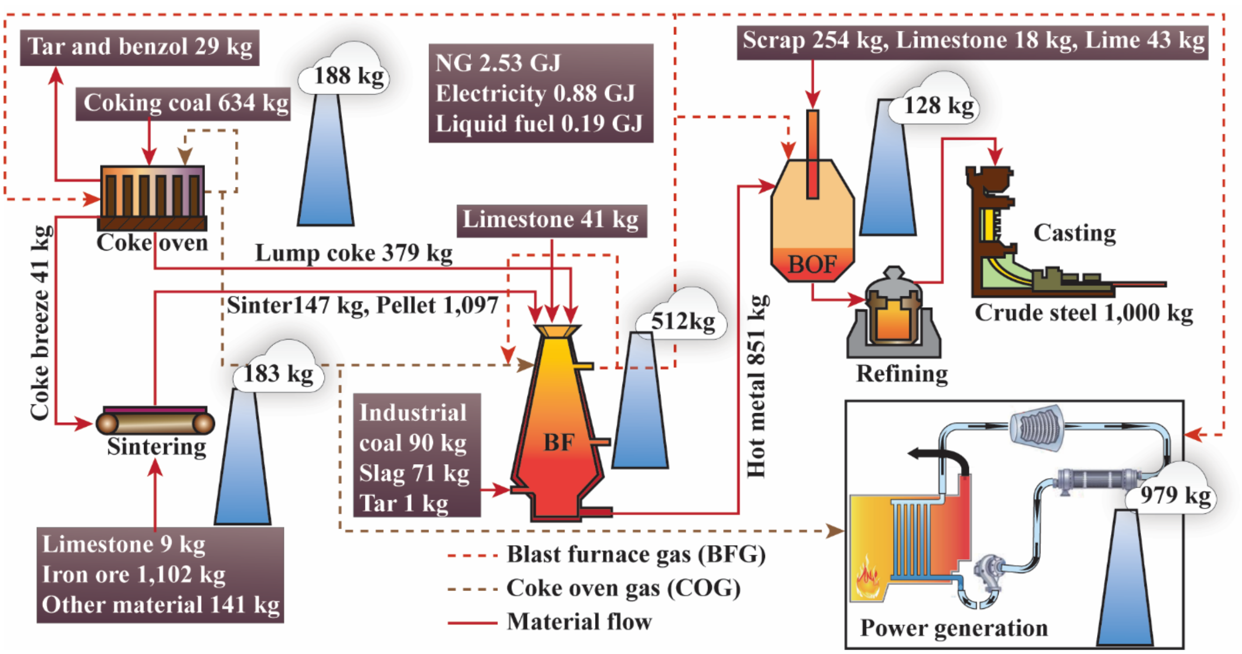


Figure 1. Mass flowrate (red arrows) and CTG CO_2 emissions (clouds) of the current practice baseline of the BF-BOF process in the U.S.

Table 2 shows direct CO_2 emissions from the baseline BF-BOF with additional NG consumption for carbon capture. In the baseline case, the flue gas from coke oven, BF-hot stoves and steam boiler has a CO_2 concentration above 10 vol%. These flows are used as high concentration CO_2 sources for carbon capture (Herron et al., 2014). The carbon capture method is mono-ethanol-amine (MEA) with 90% carbon capture ratio from these sources. Thus, the total CO_2 captured from the BF-BOF baseline case is 1,376 kg/MT steel, which, when compared with the total carbon emissions (1,995 kg/MT) in the base case, implies a carbon capture ratio of 69%.

According to case B of IEA's *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)* (IEA, 2013), the heat required for the MEA carbon capture process is supplied by natural gas (NG) combustion. The NG consumption is 3.0 GJ for each metric ton of CO_2 captured (IEA, 2013). The total electricity consumption for carbon capture and compression (to 153 bar) is 0.4 GJ for each metric ton of CO_2 captured. The electricity consumption for carbon capture and compression is estimated at 43 MJ/MT CO_2 and 354 MJ/MT CO_2, respectively (IEA, 2013; Zang et al., 2021).

Table 1. Energy consumption of six BF-BOF configurations for crude steel production

Groups	**BF-BOF**			**BF-BOF-SOA**		
Energy consumption (GJ/MT steel)	BF-BOF (current practice baseline)	BF-BOF-CC	BF-BOF-all	BF-BOF-SOA	BF-BOF-SOA-CC	BF-BOF-SOA-all
Residual oil	0.152	0.152	0.000	1.316	1.316	0.000
Gasoline	0.003	0.003	0.003	0.003	0.003	0.003
Diesel	0.038	0.038	0.038	0.038	0.038	0.038
NG	2.530	7.150	0.000	0.378	4.727	0.000
RNG	0.000	0.000	7.267	0.000	0.000	6.008
Coking coal	18.15	18.15	16.33	17.01	17.01	15.31
Industrial coal	2.039	2.039	0.000	2.574	2.574	0.000
Biochar	0.000	0.000	3.194	0.000	0.000	3.656
Grid electricity	0.875	1.416	0.000	0.446	0.955	0.000
Clean electricity	0.000	0.000	1.405	0.000	0.000	0.927
By-product	-1.130	-1.130	-0.852	-1.350	-1.350	-1.089
Total	22.66	27.82	27.39	20.42	25.27	24.85
Relative to baseline (%)	100%	123%	121%	90%	112%	110%

Table 2. Direct carbon emissions and CO_2 captured from BF-BOF baseline case

	Coke oven	Sintering	BF hot stoves	BF other	BOF	Steam boiler	NG for CO_2 capture	Total
Direct CO_2 emissions (kg/MT steel)	157	166	404	32	32	968	236	1,995
CO_2 concentration (v%)	15%	5%	27%	6%	6%	25%	3%	--
CO_2 captured (kg/MT steel)	141	0	364	0	0	871	0	1,376
CO_2 capture ratio (%)	7%	0%	18%	0%	0%	44%	0%	69%

Coal, NG, residual oil, and electricity are the major energy inputs for the current BF-BOF plant. Switching energy sources from fossil energy to renewable energy or low carbon energy, such as bioenergy, can reduce steel production carbon intensity and reduce (fossil) CO_2 emissions (Luh et al., 2020). For example, biochar has the potential to replace all the industrial coal for combustion use in the BF-BOF technology and can replace 10% of the coke used in the blast furnace (Mandova et al., 2018; Mousa et al., 2016). Given that residual oil and NG are used primarily as fuel for combustion without participating in the major reactions, both of them can potentially be replaced by renewable natural gas (RNG) (Cavaliere, 2019). In addition, grid electricity can be switched to clean (low or zero carbon emissions) electricity from lower-carbon energy sources such as nuclear, biomass, and wind/solar energy to reduce CO_2 emissions (Arens et al., 2021). The BF-BOF-all case in Table 1 shows the resultant energy consumption with all the energy switching options. The total energy consumption of BF-BOF-all case is 0.4 GJ/MT crude steel lower than that of the BF-BOF-CC case, because 10% of the coke used in the blast furnace is replaced by biochar.

Currently, the U.S. BF-BOF facilities are, on average, over 30 years old. Thus, a group of state-of-the-art BF-BOF technologies (BF-BOF-SOA) are listed in Table 1 to reflect recent BF-BOF technology improvements (Jamison et al., 2015). The BF-BOF-SOA case uses the most efficient technologies or equipment for ore agglomeration, coke making, blast furnace, and basic oxygen furnace. All processes of BF-BOF-SOA case have lower energy consumptions than the BF-BOF case(Jamison et al., 2015). As shown in Table 1, the total energy consumption of the BF-BOF-SOA case is 20.4 GJ/MT crude steel (by accounting for credit of by-product displacement). BF-BOF-SOA case shows 10% reduction of energy consumption from current BF-BOF (22.7 GJ/MT). More detailed energy consumption information for the six BF-BOF configurations is shown in Table S2 of the Supporting Information (SI).

2.1.2 EAF technology and CO_2 reduction methods

"Mini-mill" steelmaking with EAF as the major reaction unit accounts for approximately 26% of world crude steel production and 70% of U.S. steel production (Hasanbeigi and Springer, 2019). Unlike BF-BOF that uses iron ore as the primary feedstock, EAF produces steel from scrap (recycled steel), direct reduced iron (DRI), pig iron, and additives, without iron ore input. In the United States, scrap is used as feedstock in almost all U.S. EAF plants (USGS, 2020a). Only four metallic iron plants in the U.S. produce a limited amount of reduced iron (DRI) (one DRI plant in Louisiana, and three hot-briquetted iron (HBI) plants in Indiana, Ohio, and Texas).

For a baseline case of U.S. EAF steel production, the energy consumption, materials flowrate, and CO_2 emissions are derived from the study of Jamison et al., The Athena Sustainable Materials Institute, and the GREET model. In the EAF process, scrap is melted with a certain amount of added carbon (e.g., graphite) in order to lower the metallic iron melting point, and therefore reduces electricity consumption (Cavaliere, 2019). The process of iron-carbon melting is very complex and includes heat transfer from the melted liquid metal to the scrap and from the surface to internal layers of scrap pieces (Gajic et al., 2016). The energy demands of EAF (shown in Table 3 as current-practice baseline) are 1.8 GJ/MT of electricity and 0.5 GJ/MT of NG in the current typical U.S. EAF case (Jamison et al., 2015). The EAF-all case in Table 3 shows the energy consumption when NG is replaced by RNG and grid electricity by clean electricity.

The two EAF-SOA options in Table 3 reflect recent technology improvements in EAF (Jamison et al., 2015). The EAF-SOA case uses the most efficient EAF technology available today. As shown in Table 3, the total energy consumption of the EAF-SOA case is 1.9 GJ/MT crude steel, which is 17% lower than the energy consumption of the current EAF technology. The EAF-SOA-all case shows the RNG and clean electricity application potential in the EAF-SOA case.

Table 3. Energy consumption of four EAF configurations for steelmaking

Groups	**EAF**		**EAF-SOA**	
Energy consumption (GJ/MT steel)	EAF (current-practice baseline)	EAF-all	EAF-SOA	EAF-SOA-all
NG	0.546	0	0.189	0
RNG	0	0.546	0	0.189
Grid electricity	1.779	0	1.744	0
Clean electricity	0	1.779	0	1.744
Total	**2.325**	**2.325**	**1.933**	**1.933**
Relative to baseline (%)	**100%**	**100%**	**83%**	**83%**

2.2 LCA analysis and fuel switching CO_2 emissions

Using the same process configurations described above, we evaluated CO_2 emissions from steel production using the GREET model (2020). The CO_2 emissions analysis from steel production can be conducted in three scopes: scope I—direct emissions; scope II—CO_2 emissions for the electricity supply; and scope III— all the upstream emissions of process inputs, such as fuel/material extraction, transportation, and emissions displacement of by-products (Birat, 2010). Figure 2 shows the cradle-to-gate (CTG) LCA analysis boundaries used in this study, which include all the above scopes. We have considered four major analysis steps of materials/fuel extraction and transportation and electricity generation and transmission, materials pretreatment, ironmaking, and steelmaking steps. The LCA analysis is based on the functional unit of kg CO_2 per MT of crude steel produced (kg/MT steel) (Cruz et al., 2021).

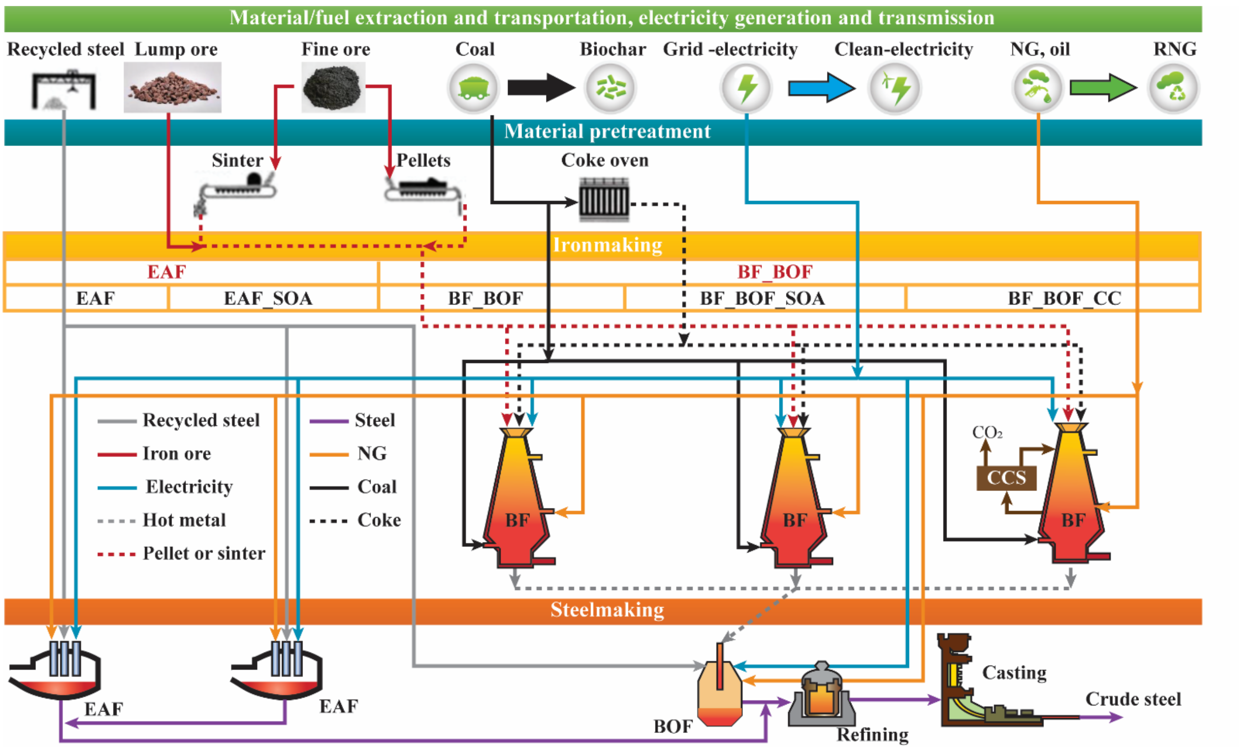


Figure 2. LCA analysis boundary for BF-BOF and EAF cases

Figure 2 illustrates the main configurations of five cases for steel production from BF-BOF and EAF processes. The CO_2 emissions associated with energy switching are accounted for in the materials/fuel extraction, transportation, electricity generation and transmission steps (detailed information is shown in Table 4). All the data is from GREET 2020, where the liquid fuel includes low-sulfur diesel, gasoline, and residual oil, with extraction and transportation CO_2 emissions of 12.3, 16.1, and 9.3 kg CO_2/GJ liquid fuel, respectively. The NG fuel carries 5.9 kg CO_2/GJ emissions from upstream extraction and transportation processes. It can be replaced by renewable natural gas, of which the CO_2 emission varies with different sources and production technologies. For the present study, we show results for RNG from combined waste, which has -57.2 kg CO_2/GJ emissions from the production process, based on GREET 2020. Industrial coal carries 1.5 kg

CO_2/GJ emission for upstream extraction and transportation processes; it can be replaced by biochar to reduce CO_2 emission. One GJ of biochar can be produced from forest residue with a yield of 25%, using 0.14 GJ heat and 0.04 GJ power (Crombie et al., 2015, Cong et al., 2018). The upstream CO_2 emissions of the biochar are -86.3 kg CO_2/GJ after accounting for the biogenic carbon (Wang et al., 2020).

Table 4. CO_2 emissions for extraction and transportation of various materials and fuels and for generation of electricity from GREET 2020

	Liquid fuel			**Gas fuel**		**Solid fuel**	
Extraction transportation	Diesel	Gasoline	Residual oil	NG	RNG	Coal	Char
GREET 2020 pathway	Petroleum LS diesel	Petroleum gasoline blendstock	Petroleum residual oil	NG as stationary fuels	RNG combined waste to NG	Coal to power plant	Pyrolysis IDL
CO_2 emissions (kg/GJ)	12.3	16.1	9.3	5.9	-57.2	1.5	-86.3
	Electricity Source					**Materials**	
Extraction transportation	U.S. grid	Bio-electric	Nuclear-electric	Hydro-electric	Wind	Limestone	Lime
GREET 2020 pathway	Electric U.S. mix	Electric biomass fired power	Electric nuclear	Electric hydroelectric	Electric wind power	Ag-inputs $CaCO_3$	Ag-inputs lime in U.S.
CO_2 emissions (kg/GJ)	118	6.5	2.0	0.0	0.0	8.4	1,085

The direct CO_2 emissions from material pretreatment, ironmaking, and steelmaking include fuel combustion emissions and process emissions (detailed information shown in Table 5). The fuel combustion emissions factors are from GREET 2020, and the process emissions of sintering (27.6 kg CO_2/GJ) and blast furnace (21.9 kg CO_2/GJ) are from the simulation by the previous study (The Athena Sustainable Materials Institute, 2002). The LHV, density, and carbon ratio of fuels are shown in Table 6.

Table 5. CO_2 emission factors of various fuels

	Liquid fuel			**Gaseous fuel**			**Solid fuel**	
Fuel combustion	Diesel	Gasoline	Residual oil	NG	BFG	COG	Coal	Char
CO_2 emissions (kg/GJ)	73.9	68.8	80.6	56.3	278.6	44.1	94.8	85.3
Process emissions	**Sintering**			**Blast furnace**				
CO_2 emissions (kg/MT steel)	27.6			21.9				

Table 6. Fuel properties used for life cycle and technical-economic analysis

Material parameter	**LHV (GJ/MT-fuel)**	**Density (kg/L)**	**Carbon content (wt%)**
Coal fuel	22.65	--	58.57%
Coking coal	28.61	--	74.70%
Residual oil	39.47	0.99	86.80%
Gasoline	43.45	0.74	86.30%
Diesel	42.61	0.85	87.10%
Coke	31.34	0.00	86.67%
NG	47.14	0.00	72.40%

2.3 TEA analysis and fuel switching cost

TEA analysis evaluates the LCOS using a discounted cash flow analysis and process-level information from *Ironmaking Process Alternatives Screening Study Volume I: Summary Report* (Greene, 2000). The discounted cash flow analysis is broadly used for levelized cost evaluation of steel production. The LCOS is the steel price that makes the net present value of the steel plant zero when the plant life is assumed to be 25 years with a discount rate of 10%. The construction period of a new steel plant is two years, with 75% invested during the first 12 months and 25% spent in the second 12 months. The start-up time is 12 months, and revenues are assumed to be 75% those of a normal operating year (Greene, 2000).

Capital expenditures are the sum of the total installed cost (TIC) and contingency (5% of the TIC) (IEA, 2013). TIC is evaluated using equation 1 (Manzolini et al., 2020), where $C_{ref,i}$ is the reference equipment cost. The BF-BOF equipment cost listed in Table 7 is from (IEA, 2013) and the EAF equipment cost listed in Table 7 is from (Greene, 2000). $S_{ref,i}$ is the reference equipment size, S_i is the real size of the equipment used in this study, and f is the scaling exponent. Detailed information for the TIC is shown in Table 7.

$$TIC = \sum_{i=0}^{n} C_{ref,i} \times (S_i / S_{ref,i})^f \quad (1)$$

Table 7. Equipment installed cost for BF-BOF and EAF technologies

	Reference scale	Units (MT/year)	Reference installed cost (US$ million)	Scaling exponent
BF-BOF				
Coke oven	2,277,702	Coal	400	0.80
Sintering	4,445,559	Sinter	220	0.80
Blast furnace, hot stoves, and hot metal desulphurization	3,894,263	Hot metal	622	0.80
Basic oxygen furnace and steel refining	4,323,327	Crude steel	459	0.80
Continuous slab caster	4,000,000	Crude steel	195	0.80
Lime production	591,361	Crude steel	16	0.80
Air separation unit	4,323,327	Crude steel	130	0.80
Power plant	4,323,327	Crude steel	362	0.80
Steam generation plant	4,323,327	Crude steel	139	0.80
Raw material handling	4,323,327	Crude steel	247	0.80
Pre-operating expenses	4,323,327	Crude steel	21	0.80
Land preparation, site development, and waste disposal	4,323,327	Crude steel	144	0.80
Buildings and site infrastructure	4,323,327	Crude steel	196	0.80
Project engineering	4,323,327	Crude steel	201	0.80
CO_2 capture and compression	4,323,327	Crude steel	590	0.80
EAF				
Electric arc furnace and refining	4,920,000	Crude steel	591	0.80
Land preparation, site development, and waste disposal	4,920,000	Crude steel	119	0.80

The annual operations and maintenance (O&M) cost includes the fixed O&M cost, variable O&M cost, and “other O&M” cost (e.g. slag processing, on-site haulage, disposal, and landfill). The detailed calculation processes for fixed and other O&M cost are shown in Table 8, and the material price used to calculate the variable O&M cost is shown in Table 9. In Table 8, the miscellaneous cost includes services related to logistics, engineering, analysis, infrastructure, and information. The LCOS of each system was evaluated to demonstrate the impacts of the selected technology and carbon capture option on the steel price. For TEA analysis, the base cases use market prices in 2019 of the incumbent energy sources: electricity price of \$0.07/kWh (Zang et al., 2021), NG price of \$3.7/GJ (EIA, 2019a), coking coal price of \$161/MT (EIA, 2019b), and industrial coal price of \$68/MT (EIA, 2019b). To show the impacts of renewable energy prices on the LCOS, a clean electricity price of \$0.03-\$0.15/kWh (Wiser and Bolinger, 2019), an RNG price of \$6.6-\$19.0/GJ (American Gas Foundation, 2019), and biochar price of \$403-\$747/MT (Bushell, 2018) have been used.

Table 8. Fixed and other O&M costs for BF-BOF and EAF technologies

	Maintenance (% installed cost)	**Personnel (\$/MT steel)**	**Miscellaneous (\$/MT steel)**
BF-BOF			
Coke oven	5.0%	8.52	5.10
Sinter production	5.0%	8.81	1.67
Blast furnace/hot stoves and hot metal desulphurization plant	4.0%	8.26	3.20
Basic oxygen steelmaking plant and refining	5.0%	10.68	3.90
Continuous slab caster	8.0%	9.31	1.89
Lime production	8.0%	0.74	0.60
Air separation unit	2.5%	0.91	
Power plant	2.5%	1.09	
Steam generation plant	2.5%	0.39	
CO_2 capture and compression	2.5%	0.57	
Other personnel cost	(\$/MT steel)		
Central engineering	8.02		
Management and admin staff	12.94		
EAF	**(\$/MT steel)**		
EAF personnel cost	6.32		
EAF other O&M cost	34.97		
Refining O&M cost	6.35		

Using these prices of fossil energy and renewable energy, the LCOS of current steel and future low-carbon steel can be estimated. The CO_2 emission amount is quantified from the CTG LCA analysis by combining CO_2 emissions from different processes. Then the CO_2 avoidance cost

($C_{CO_2,A}$) is calculated by using the change in LCOS (ΔC_{steel}) divided by the change in CO_2 emissions (ΔE_{CO_2}), as shown in equation 2. By comparing the CO_2 avoidance cost from increased of energy efficiency, CC, and energy switching, this study can quantify the impact of different CO_2 emissions reductions.

$$C_{CO_2,A}(\$/MT\ CO_2) = -\Delta C_{steel}\ (\$/MT\ steel)/\Delta E_{CO_2}(MT\ CO_2/MT\ steel) \quad (2)$$

Table 9. Materials prices used to calculate the variable O&M cost of BF-BOF and EAF technologies

Material	Price	Unit	Reference
Coking coal	160.77	$/MT	(EIA, 2019b)
Industrial coal	67.65	$/MT	(EIA, 2019b)
Residual oil	0.97	$/gal	(EIA, 2020)
Electricity	0.07	$/kWh	(Zang et al., 2021)
Natural gas	3.71	$/GJ	(EIA, 2019a)
Gasoline	2.67	$/gal	(EIA, 2020)
Diesel	3.04	$/gal	(EIA, 2020)
Iron ores	66.14	$/MT	(USGS, 2020a)
Purchased scrap	249.22	$/MT	(USGS, 2020b)
Dolomite	27.67	$/MT	(IEA, 2013)
Burnt dolomite	109.48	$/MT	(IEA, 2013)
Crude tar	0.97	$/gal	(EIA, 2020)
Benzol	0.97	$/gal	(EIA, 2020)
Coke	107.09	$/MT	(EIA, 2019b)
Graphite used in EAF	86.34	$/MT	(Greene, 2000)
EAF electrodes	1,530.77	$/MT	(Greene, 2000)
Lime charged	114.47	$/MT	(Greene, 2000)
O_2 gas to EAF	0.06	$\$/Nm^3$	(Greene, 2000)
RNG-min	6.60	$/GJ	(American Gas Foundation, 2019)
RNG-max	19.00	$/GJ	(American Gas Foundation, 2019)
Clean electricity-min	0.03	$/kWh	(Wiser and Bolinger, 2019)
Clean electricity-max	0.15	$/kWh	(Wiser and Bolinger, 2019)
Biochar-min	403.00	$/MT	(Bushell, 2018)
Biochar-max	747.00	$/MT	(Bushell, 2018)

3. RESULTS AND DISCUSSION

3.1 Cradle-to-gate energy consumption and CO_2 emission reduction potential

With a detailed analysis of BF-BOF subprocess energy consumption, the overall process energy flow of a typical U.S. BF-BOF process can be summarized as shown in Figure 3. The width of each flow line represents the heat content, i.e., the lower heating value (LHV) of each flow based on the mass flowrate. Figure 3 shows the major energy consumption of all equipment of a typical U.S. BF-BOF plant. For the typical U.S. BF-BOF plant, coal is the primary energy input: 18.2 GJ of coking coal and 2.0 GJ of industrial coal for the production of 1 metric ton of crude steel. The other energy inputs of the BF-BOF process are 0.9 GJ/MT of electricity, 0.2 GJ/MT of liquid fuel (a mixture of residual oil, gasoline, and diesel), and 2.5 GJ/MT of NG. It is worth noting that 0.8 GJ/MT of tar and 0.3 GJ/MT of benzol are produced from the BF-BOF system as by-products, and both have CO_2 emission displacement credit. After the by-product displacement, the total energy consumption of the BF-BOF process is 22.7 GJ/MT, as shown in Table 1.

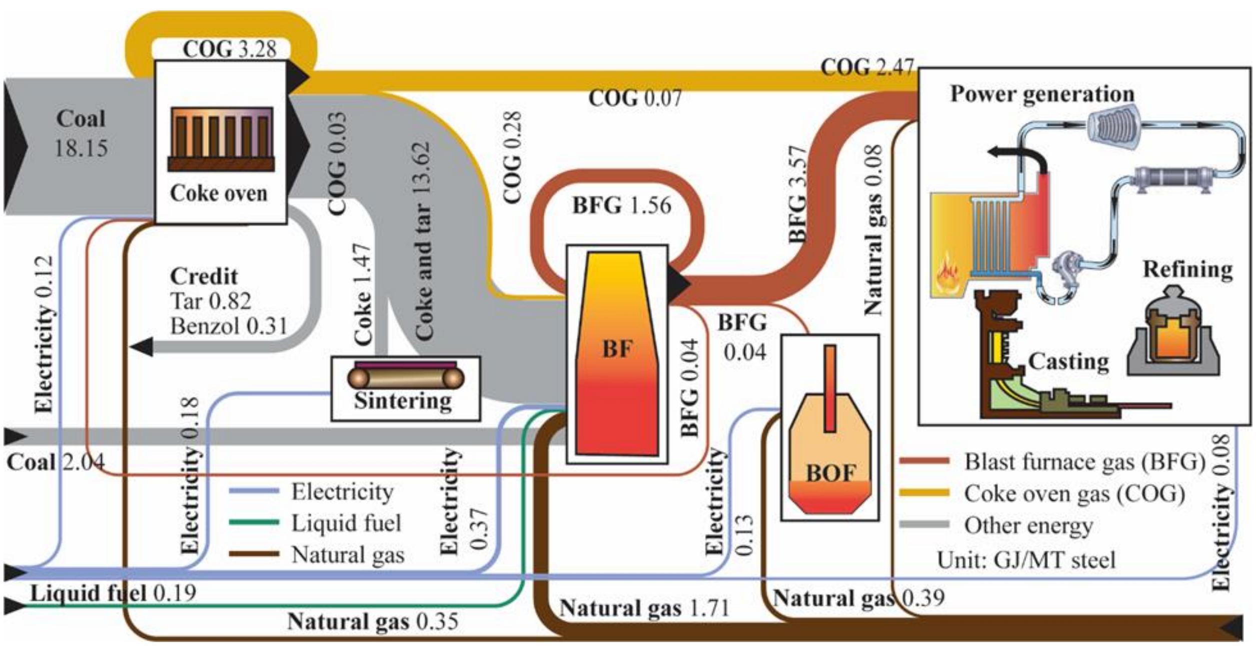


Figure 3. Energy Sankey diagram of a typical U.S. steel mill using BF-BOF technology. All values are in the unit of GJ per metric ton of crude steel production. The width of flow line indicates the quantity of energy based on lower heating value, the red flow represents blast furnace gas, the

yellow flow shows the coke oven gas and the blue, green, brown, and gray flows represent energy flows of electricity, liquid fuel, natural gas, and other energy, respectively.

The overall process carbon flow of the current-practice baseline U.S. BF-BOF process can be summarized as shown in Figure 4(a). The width of the flows shown in Figure 4(a) represents the carbon content of each flow based on the mass flowrate shown in Figure 1. The numbers shown in Figure 4 indicate kg carbon per metric ton of crude steel produced. For the current-practice baseline U.S. BF-BOF plant, coal is the primary carbon source: 474 kg of carbon from coking coal and 53 kg of carbon from industrial coal for the production of 1 metric ton of crude steel. The other carbon input to the BF-BOF is 39 kg C/MT steel from natural gas, 4 kg C/MT steel from liquid fuel (a mixture of residual oil, gasoline, and diesel), and 22 kg C/MT steel from other material input, such as limestone. It is worth noting that 18 kg/MT of carbon in tar and 7 kg/MT of carbon in benzol have CO_2 emission displacement credit, and tar and benzol are produced from the BF-BOF system as by-products. After the by-product displacement, the total carbon input to the BF-BOF process is 567 kg C/MT steel.

For the entire BF-BOF system, heat and steam are supplied by combusting coke oven gas (COG) and blast furnace gas (BFG). The carbon content of the COG is 12 kg C/GJ COG based on carbon balance. It is assumed that the carbon input to the coke oven is coking coal, while the carbon outputs of the coke oven are coke, tar, benzol, and COG. The carbon content of the BFG is 76 kg C/GJ BFG based on carbon balance. The carbon input sources to the blast furnace are natural gas, coal, coke, tar, and limestone, and the carbon output of the blast furnace is BFG. Figure 4(a) also shows the direct carbon emissions from each process. The power generation process has the largest carbon emissions, 264 kg C/MT, which discharges 967 kg of direct CO_2 emissions for 1 metric ton of crude steel produce.

Figure 4(b) summarizes the mass and carbon flow of the current-practice baseline U.S. EAF plant. Natural gas and graphite/electrode (shown as "other sources") are the primary carbon source for steel production from EAF. The carbon content of the natural gas is 8.4 kg C/MT steel, while the carbon content in the graphite/electrode is 7.0 kg C/MT steel. The EAF process discharges 56.5 kg of direct CO_2 emissions calculated from the carbon balance.

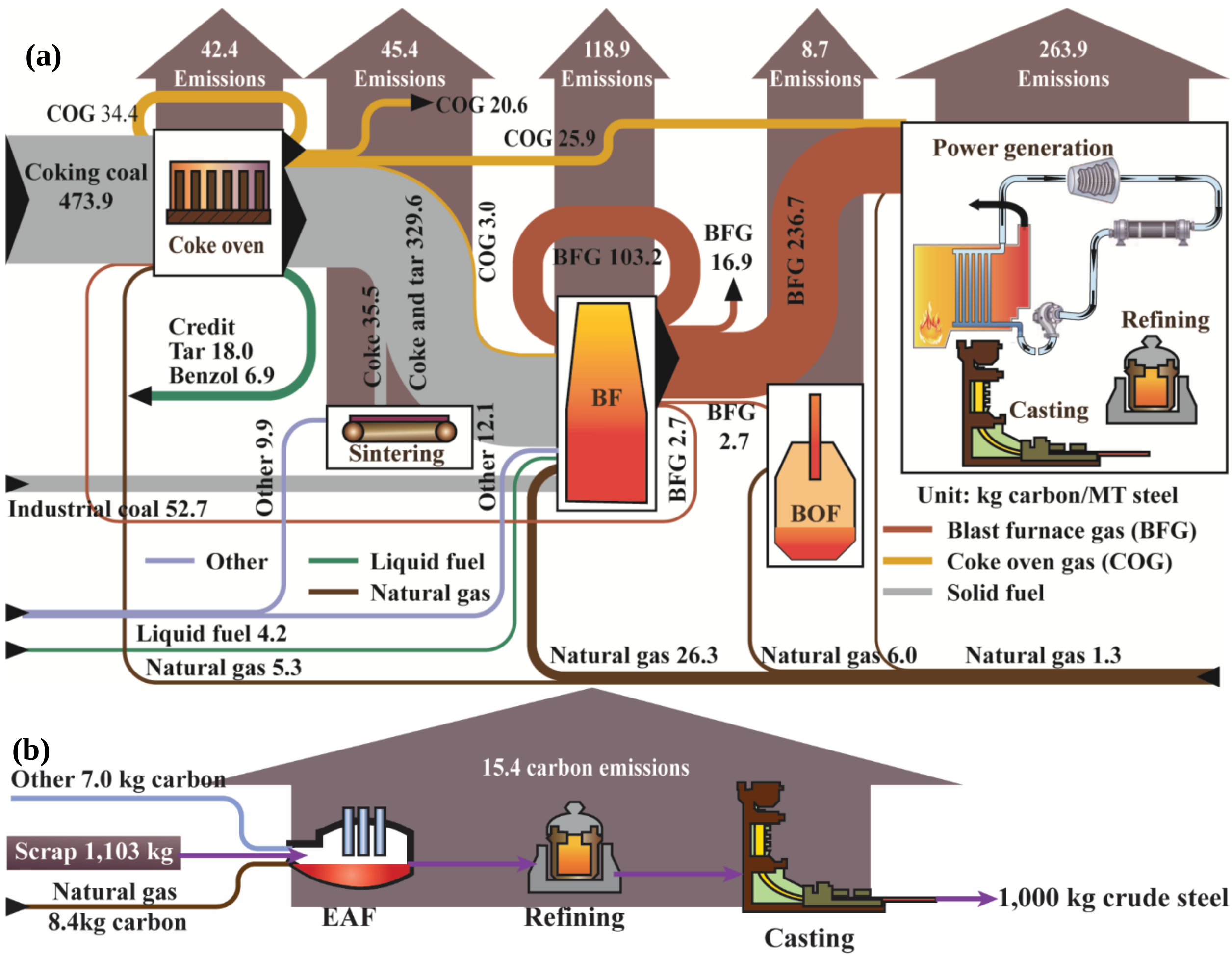


Figure 4. The CTG carbon Sankey diagram of (a) BF-BOF current-practice baseline (b) EAF current-practice baseline in the U.S. All the values indicate kg carbon per metric ton of crude steel production. The width of the flow line indicates the quantity of carbon. The red flow represents blast furnace gas, the yellow flow shows the coke oven gas, and the blue, green, brown, and gray flows represent carbon flows of other materials, liquid fuel, natural gas, and solid fuel, respectively.

Figures 5(a) and 5(b) show the CTG CO_2 emissions from different BF-BOF technologies. For the current-practice baseline U.S. BF-BOF plant, the CTG CO_2 emissions are 1,990 kg/MT steel. The power generation process has the largest CO_2 emissions: 979 kg/MT steel (49% of the total) resulting from combustion of COG, BFG, and fuel for power generation and steam production, and the upstream fuel production emissions. The 49% also accounts for the burdens for the refining and casting processes. The 49% power generation CO_2 emissions share is similar to that found in the study by Birat, which showed that 47% of total CO_2 emissions are from power generation (Birat, 2010). The blast furnace has the second-largest CO_2 emissions: 512 kg/MT steel (26% of the total), because 1.2 GJ BFG/MT steel and 0.2 GJ COG /MT steel are combusted to supply heat for the blast furnace.

After identifying the material and energy inputs and quantifying CO_2 emissions, the potential CO_2 reduction can be estimated by switching the fossil carbon source to a renewable carbon source. Figure 5(a) shows the CTG CO_2 emissions when the energy source is changed from grid electricity to clean electricity (wind power) (indicated by grid → clean electricity) and from oil and NG to RNG (oil, NG → RNG). It also shows the emissions when using biochar to replace 10% of the coke consumption (maximum amount allowed without modifying BF process) and 100% of the industrial coal consumption in the blast furnace (coke → biochar). The change in electricity source has the potential to reduce CO_2 emissions by 104 kg/MT steel, and the use of RNG and biochar has the potential to reduce CO_2 emissions by 174 and 318 kg/MT steel, respectively. The BF-BOF-all-no CC case combines all the energy switching options without using carbon capture and storage. The CO_2 emissions from the BF-BOF-all-no CC case is 1,396 kg/MT steel—30% lower than the current-practice baseline of BF-BOF.

The BF-BOF-CC case uses NG and grid electricity to supply the energy for carbon capture, while the BF-BOF-CC-R case uses RNG and clean electricity as the energy supply for carbon capture. For both cases, 1,376 kg of CO_2 can be captured from BF-BOF plants, with energy consumption of 3.0 GJ NG/RNG per MT CO_2 and 0.4 GJ grid/clean electricity per MT CO_2. When the energy inputs for carbon capture are NG and grid electricity, the CTG CO_2 emissions for BF-BOF-CC are reduced by 1,025 kg/MT steel (51% of the total). In contrast, when the energy inputs are from renewable sources of RNG and clean electricity, CTG CO_2 emissions for BF-BOF-CC are reduced by 1,326 kg/MT steel (67% of total). The case of BF-BOF-all, which combines carbon capture and all energy switching options, has the lowest CO_2 emissions in the BF-BOF group; it has an emission of 16 kg/MT steel, a 99% reduction from the current-practice base case shown in Figure 5(a).

The CTG CO_2 emissions for the BF-BOF-SOA group (with the most efficient blast furnace and basic oxygen furnace) are shown in Figure 5(b), with the energy consumption in Table 1. The CTG CO_2 emissions of the BF-BOF-SOA case are 1,842 kg/MT steel, which is 7% lower than that of baseline BF-BOF case as a result of its lower energy consumption. The BF-BOF-SOA-CC case captures 1,295 kg CO_2 for each MT crude steel produced. The amount of CO_2 captured in the BF-BOF-SOA case is 6% lower than that of the BF-BOF case because the lower fuel consumption of BF-BOF-SOA results in the lower amount CO_2 emission. With carbon capture, the CTG CO_2 emissions of the BF-BOF-SOA-CC are 877 kg/MT steel, which is 52% lower than BF-BOF-SOA case and 9% lower than the BF-BOF-CC case. With all energy switching and carbon capture options, the CTG CO_2 emissions of BF-BOF-SOA-all are 84 kg/MT steel (96% lower than the current-practice baseline of BF-BOF), as shown in Figure 5(b).

These results indicate that increasing energy efficiency has a limited CO_2 emissions reduction potential of 7.4%, while CCS has a more significant CO_2 emissions reduction potential of 21.7%. The decarbonization potential of fuel switching ranges from 5.2% to 15.1%.

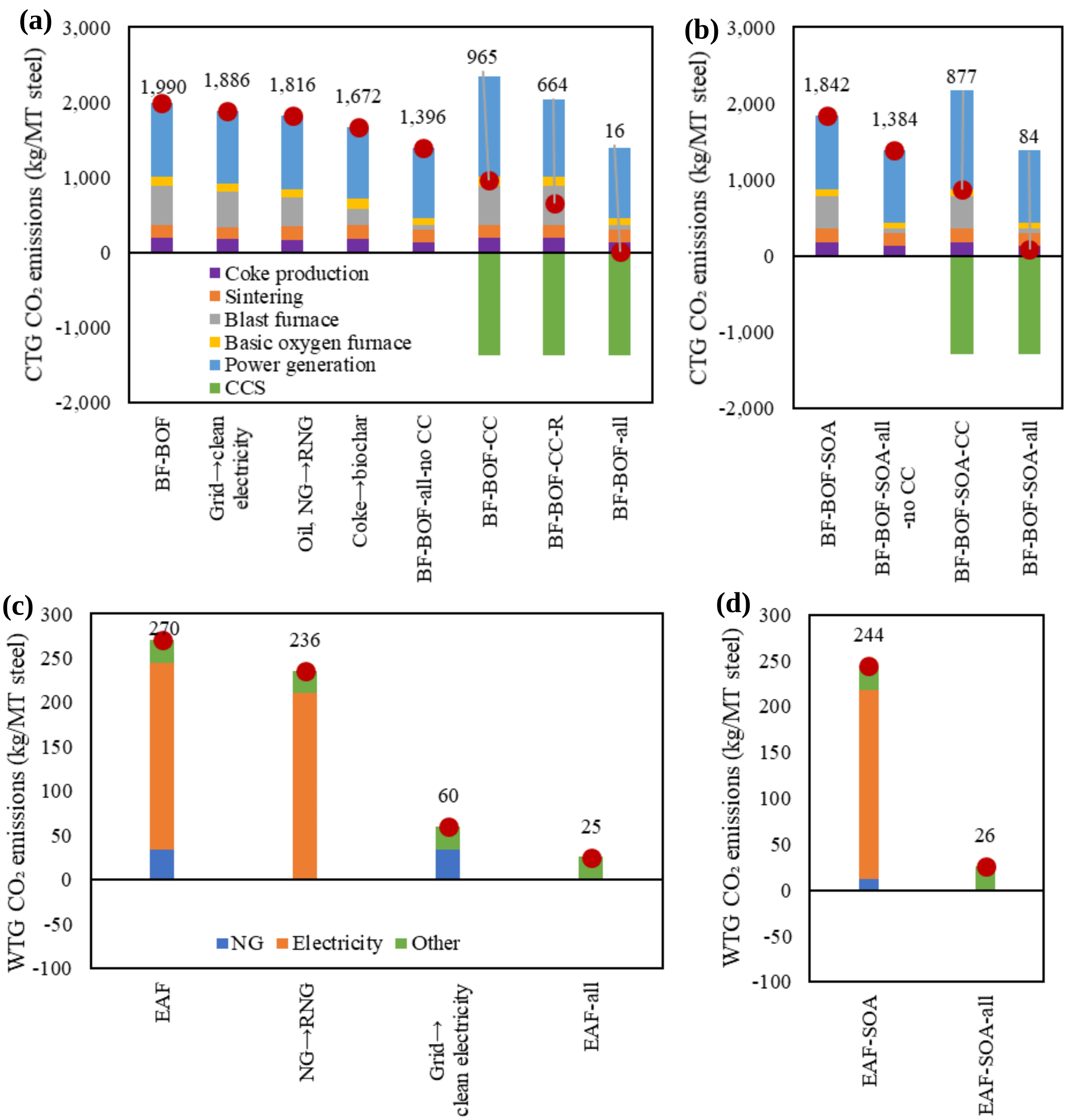


Figure 5. LCA results of BF-BOF and EAF. (a) CTG CO_2 emissions of current BF-BOF group, (b) CTG CO_2 emissions of the BF-BOF-SOA group, (c) CTG CO_2 emissions of current EAF group, and (d) CTG CO_2 emissions of the EAF-SOA group. The "power generation" is the internal power generation in the BF-BOF processes.

About 70% of the steel plants in the United States use EAF technology to process scrap and a small amount of DRI feedstock. The CTG CO_2 emissions for EAF and EAF-SOA are shown in Figure 5(c)-(d), with energy consumption shown in Table 1. Unlike the BF-BOF process, which consists of six major subunits or reaction processes, the EAF pathway has only one main reaction unit: the electric arc furnace. Thus, the CTG CO_2 emissions from the EAF cases come only from the consumption of NG, electricity generation, and process emissions due to the graphite use. Graphite is used as the electrode as well as a carbon source to reduce the electricity consumption in the electric arc furnace. The CTG CO_2 emissions of EAF are 270 kg/MT steel—86% lower than the CTG CO_2 emissions in the BF-BOF case. The NG → RNG and grid → clean electricity columns in Figure 5(c) show the CTG CO_2 emissions when NG is replaced by RNG and grid electricity by clean electricity (wind power). The use of RNG and clean electricity has the potential to reduce CO_2 emissions by 34 kg/MT steel and 210 kg/MT steel, respectively. When the combination of RNG and clean electricity is used, the CTG CO_2 emissions of EAF can be reduced to 25 kg/MT steel that is 91% lower than the CO_2 emissions from current-practice baseline of EAF. Figure 5(d) shows the CTG CO_2 emissions for state-of-the-art EAF (EAF-SOA) technology (with energy consumption data shown in Table 1). The CTG CO_2 emission of EAF-SOA is 244 kg/MT steel, which is 10% lower than the current-practice baseline EAF steel production plant in the U.S. After all energy switching options (to RNG and clean electricity), the CTG CO_2 emissions of EAF-SOA-all are 26 kg/MT steel. If RNG and clean electricity are used in combination, the CTG CO_2 emissions of EAF can be reduced by 89%.

3.2 LCOS of steel and cost of CO_2 avoidance

The TEA analysis in this study uses 2019 U.S. dollars based on materials market prices in 2019, shown in Table 9. Given that the typical U.S. BF-BOF steel mill has been running for more than 30 years, the calculation of the LCOS from current BF-BOF baseline case does not include capital expenditures. For the BF-BOF case, the fixed O&M cost is $338 million per year and includes the cost of maintenance, direct labor, and indirect labor. The variable O&M cost is $1,051 million per year and includes the cost of fuel and reductant, iron ore, purchased scrap, fluxes, consumables, and other utilities. The "other O&M" cost is $24 million per year and includes all other expenses and by-products credit (Table 10). The LCOS (making the net present value zero) of BF-BOF case is $439/MT crude steel, as shown in Figure 6(a). For the BF-BOF cost, the three leading cost sources are fuel and reductant cost, iron ore and scrap cost, and labor cost representing 33%, 33%, and 24% of the LCOS, respectively. The LCOS of $439/MT steel is close to the amounts found by previous research that showed a cost of $413/MT steel in 2020 using the basic oxygen furnace route (Steelonthenet.com, 2020a). The BF-BOF-CC case in Figure 6(a) shows the LCOS when carbon capture technology is integrated into current-practice baseline BF-BOF plant. The major capital expenditure for carbon capture is $560 million per plant for the CO_2 capture unit and compression equipment with a CO_2 capture ratio of 65%. In Figure 6(a), the LCOS of the BF-BOF-CC case is $506/MT, of which 6% is capital expenditure, 32% fuel cost, 29% iron ore and scrap cost, and 22% labor cost, with the remaining 11% being electricity, other O&M, and by-product credit. As a result of the addition of the carbon capture unit, the fuel and electricity cost of the BF-BOF-CC case is $29/MT higher than the BF-BOF case, while the labor cost of the BF-BOF-CC case is $7/MT higher than the BF-BOF case. The LCOS of the BF-BOF-all is $542/MT when the minimum renewable fuel price is used for the TEA analysis, as shown in Figure 6(a).

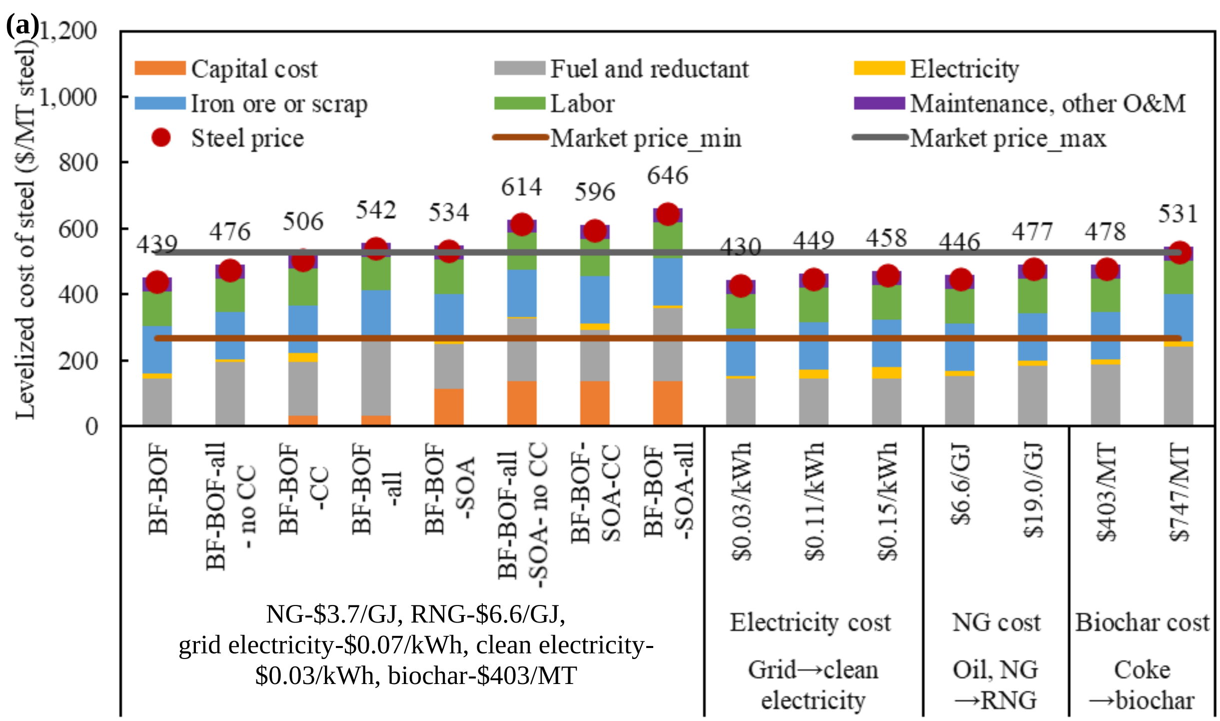
The LCOS for the BF-BOF-SOA and BF-BOF-SOA-CC cases is $534/MT and $596/MT, respectively, or 22% and 36% higher than the current BF-BOF technology. The capital expenditure in the BF-BOF-SOA case and BF-BOF-SOA-CC case is $3.7 billion and $4.6 billion per plant, respectively, as shown in Table 11 and Table 12. The high capital expenditure for the construction of a greenfield steel plant adds $112/MT and $138/MT to the steel production cost for the cases with and without CCS, respectively, and results in higher LCOS compared to the current BF-BOF technology.

Table 10. O&M cost components of the BF-BOF case

Item cost	Cost breakdown (US$ million/y)	Percentage of O&M (%)	Annual OPEX (US$ million/y)
Fixed O&M cost			337.8
Maintenance	110.0	7.8%	
Direct labor	159.3	11.3%	
Indirect labor	68.4	4.8%	
Variable O&M cost			1,050.8
Fuel and reductant	517.4	36.6%	
Iron ore	247.4	17.5%	
Purchased scrap	215.4	15.3%	
Fluxes	34.3	2.4%	
Consumables & other utilities	36.3	2.6%	
Other O&M cost			23.9
Miscellaneous works expense	43.1	3.1%	
Other OPEX	11.4	0.8%	
Slag processing	6.2	0.4%	
On-site haulage	0.2	0.0%	
Disposal and landfill	3.9	0.3%	
By-product credit	-40.9	-2.9%	
Total O&M	1,412	100.0%	1,412

Table 11. Capital expenditure for the greenfield BF-BOF-SOA case

BF-BOF-SOA Plant section	**Cost breakdown (US$ Million)**
Coke oven	489
Sintering	252
Blast furnace, hot stoves, and hot metal desulphurization	588
Basic oxygen furnace and steel refining	451
Continuous slab caster	185
Lime production	13
Air separation unit	124
Power plant	266
Raw material handling	122
Spare parts and first fill	110
Pre-operating expenses	20
Land preparation, site development and waste disposal	137
Buildings and site infrastructure	186
Project engineering	191
Utility	417
Total installed cost	3,551
Contingency (5% of total installed cost)	178
Total investment cost (US$ Million)	3,728



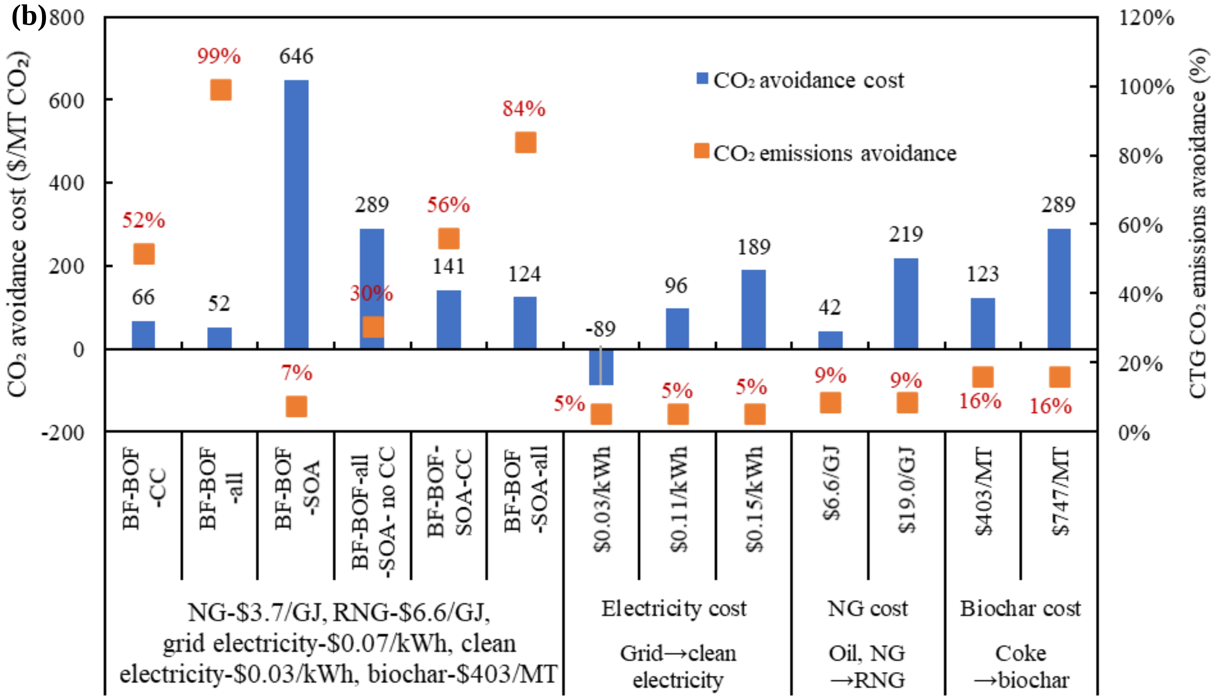


Figure 6. TEA results of BF-BOF (a) LCOS and (b) CO_2 avoidance cost relative to the base line case of BF-BOF. BF-BOF-all-no CC, BF-BOF-all, BF-BOF-all-SOA-no CC and BF-BOF-SOA-all use RNG, clean electricity, coal and biochar as energy sources to produce crude steel. BF-BOF, BF-BOF-CC, BF-BOF SOA and BF-BOF-SOA-CC use NG, grid electricity, and coal as energy sources to produce crude steel. The other bars show the impacts of renewable energy's price modified from the current-practice baseline of BF-BOF.

Figure 6(a) also shows the impacts of electricity, natural gas, and biochar cost on the LCOS. For the BF-BOF baseline, the costs of electricity, natural gas, coking coal, and industrial coal are $0.07/kWh, $3.7/GJ, $161/MT, and $68/MT, respectively. When clean electricity is used to replace grid electricity, the clean electricity cost changes to somewhere between $0.03/kWh and $0.15/kWh (Wiser and Bolinger, 2019). Figure 6(a) shows a sensitivity analysis with three LCOS using $0.03/kWh, $0.11/kWh, and $0.15/kWh as clean electricity costs. When the electricity cost increases from $0.03/kW to $0.15/kW, it constitutes 2% to 8% of the LCOS, and the LCOS changes from $430/MT to $458/MT. Given that the RNG cost is $6.6 to $19.0/GJ, or 78% to 147% higher than the market cost of NG ($3.7/GJ), the LCOS of steel made using RNG is $446-$477/MT, 2%-9% higher than the LCOS of steel made using the current BF-BOF technology.

Meanwhile, the high cost of biochar ($403-$747/MT) results in an LCOS increase to $478-$531/MT, which is 9%-21% higher than the current BF-BOF technology. Figure 6(a) summarizes the range of crude steel market prices in the U.S. from 2019 to 2020, with a minimum crude steel market price of $268/MT and a maximum crude steel market price of $529/MT (USGS, 2020b).

Table 12. Capital expenditure for the BF-BOF-SOA-CC case.

BF-BOF -SOA-CC	**Cost breakdown (US$ Million)**
Coke oven	489
Sintering	252
Blast furnace, hot stoves, and hot metal desulphurization	588
Basic oxygen furnace and steel refining	451
Continuous slab caster	185
Lime production	13
Air separation unit	124
Power plant	344
Steam generation plant	132
Raw material handling	235
Pre-operating expenses	20
Land preparation, site development, and waste disposal	137
Buildings and site infrastructure	186
Project engineering	191
CO_2 capture and compression	561
Utility	417
Total installed cost	4,324
Contingency (5% of total installed cost)	272
Total investment cost (US$ Million)	4,596

Under the current baseline case assumptions, these results indicate that all the fuel switching options lead to higher steel cost, due to the current higher cost of low carbon and renewable energy sources (e.g., RNG, biochar) relative to fossil energy sources. The energy efficiency increase results in a moderate steelmaking LCOS, based on the current technology level. CCS shows the lowest LCOS due to concentrated CO_2 emission from BF-BOF that enables low-cost CO_2 capture. It is worth mentioning that the CCS option did not consider CO_2 transportation and storage cost since the present study represents a generic case for steel production with no specific CO_2 storage site or distance for transportation. In general, for a specific steel plant, the decarbonization options need to be evaluated by considering accessibility to low carbon energy sources, availability to CO_2 pipeline for transportation, proximity to CO_2 storage site, etc. Figure 6(b) compares the CO_2 avoidance cost of different technology and energy switching options, accounting for all CO_2 avoidance from cradle to gate boundaries. The LCOS ($439/MT steel) and CTG CO_2 emissions (1,990 kg/MT steel) of the current-practice baseline BF-BOF technology are used as the reference. For each technology and energy switching option, the change of LCOS ΔC_{steel} and the change of CO_2 emissions ΔE_{CO_2} are calculated relative to the baseline case. The CO_2 avoidance cost is evaluated using ΔC_{steel} divided by ΔE_{CO_2}, shown in Equation 2. For example, the CO_2 reduction cost of BF-BOF-CC is $66/MT CO_2, i.e., the cost of incorporating carbon capture into the current BF-BOF plant. This result is in the range of the IEA report (IEA, 2013), while lower than the CO_2 capture cost of $80-$110/MT from the study by Herron et al., 2014. This is because the present study assumes that waste heat from steel production configurations reduces the NG consumption in the boiler. In contrast, the study by Herron et al., 2014 designed a standalone boiler to supply heat for the carbon capture process without using waste heat.

The LCOS of BF-BOF-SOA is $96/MT steel higher than the current BF-BOF cost, but the CO_2 emissions reduction is only 148 kg/MT steel. The BF-BOF-SOA has the highest CO_2 avoidance cost, $646/MT CO_2, due to the high capital expense required. The BF-BOF-SOA-CC case combines carbon capture with the most efficient BF-BOF-SOA technology. Although the LCOS of BF-BOF-SOA-CC is $157/MT steel higher than the current BF-BOF technology, it has a larger CO_2 emissions reduction potential of 1,113 kg/MT steel, leading to a CO_2 avoidance cost of $141/MT CO_2. Figure 6(b) also shows the CO_2 avoidance cost for energy switching options.

The cost of renewable energy sources is the key parameter that impacts the CO_2 avoidance cost. In Figure 6(b), the CO_2 reduction costs of using clean electricity, RNG, and biochar are in the range of $-89/MT to $189/MT, $42/MT to $219/MT, and $123/MT to $289/MT, respectively. A cost of $-89/MT means that when the clean electricity price is $0.03/kWh, the application of clean electricity in the BF-BOF case can reduce both CO_2 emissions and LCOS.

These results show that CO_2 avoidance cost for CCS is much lower than increasing energy efficiency. The CO_2 avoidance cost of fuel switching is largely dependent on renewable energy prices, which could be reduced potentially with technology energy efficiency improvement.

Figure 7(a) shows the LCOS of various EAF cases. The current-practice EAF case has an LCOS of $365/MT crude steel, which is 17% lower than the current BF-BOF technology. In Figure 7(a), scrap, electricity, maintenance, and other O&M costs account for 70%, 9%, and 18% of the LCOS, respectively. The calculated LCOS of EAF at $365/MT is close to estimates by previous studies that calculated the EAF steelmaking route cost as $385/MT (Steelonthenet.com, 2020b). Because the state-of-the-art technology of EAF-SOA includes a capital investment of $17/MT steel, the LCOS of EAF-SOA is 4% higher than current EAF technology. Figure 7(a) shows the impact of the energy switching on LCOSs of steel produced from EAF technology. When RNG and clean electricity are used for steel production, the LCOS changes from $367/MT to $373/MT and from $346/MT to $405/MT (in Figure 6), respectively. The LCOS of EAF-all is $17/MT lower than that of the current EAF technology, assuming that the clean electricity price in the EAF-all case is $0.03/kWh, which is $0.04/kWh less than that used in the current EAF plant. All the LCOSs of the EAF technologies are in the range of crude steel market price variation, indicating that increased energy efficiency and use of clean energy sources can achieve deep CO_2 emissions reduction with attractive crude steel production cost.

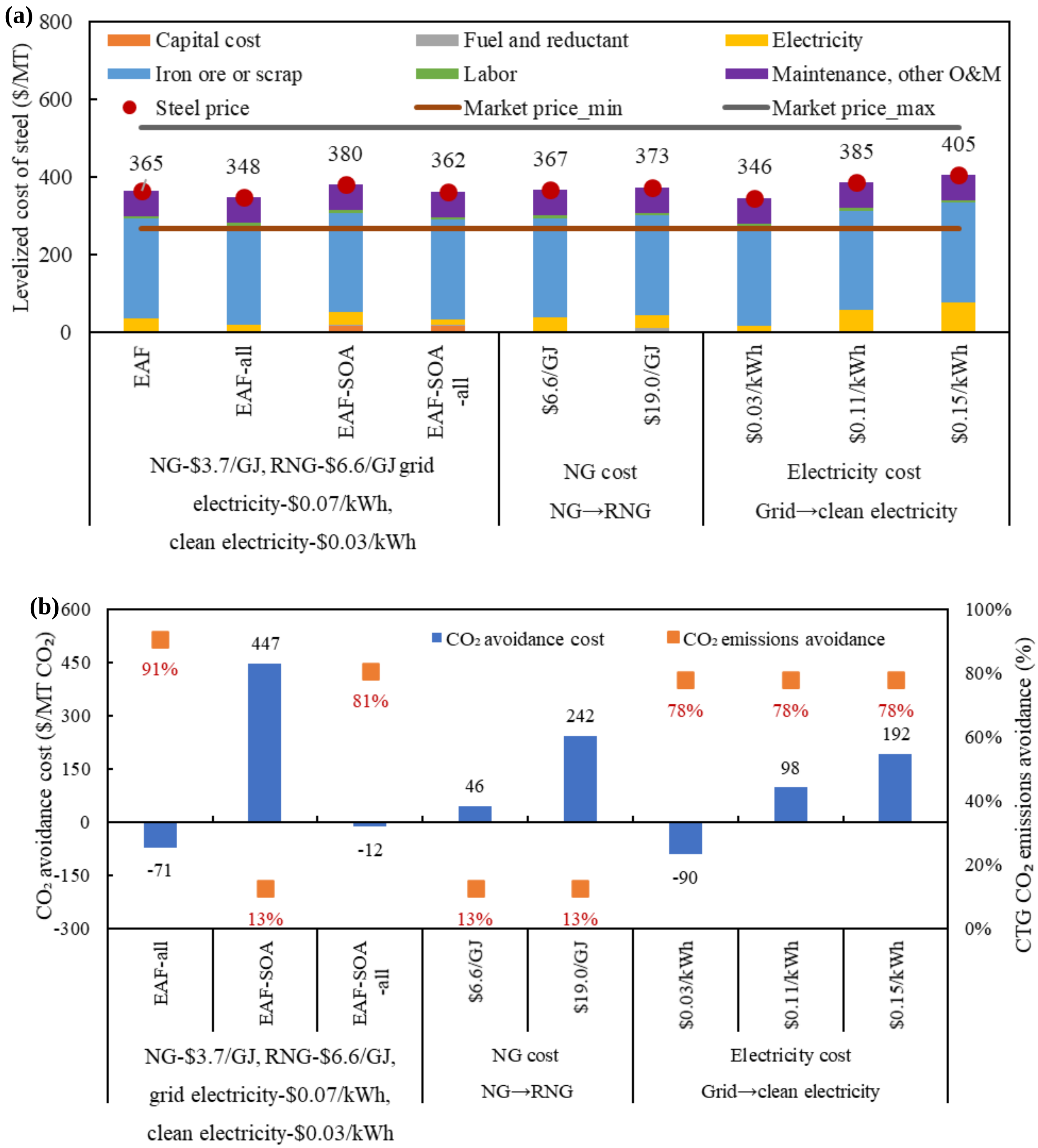


Figure 7. TEA results of EAF (a) LCOS and (b) CO_2 avoidance cost. EAF-all and EAF-SOA-all use RNG and clean electricity as energy sources to produce crude steel. EAF and EAF-SOA use NG and grid electricity to produce crude steel. While all the other bars show the impacts of renewable energy's price modified from the current-practice baseline of EAF.

Figure 7(b) compares the cost of CO_2 avoidance energy consumption and energy switching options. The LCOS ($365/MT steel) and CTG CO_2 emissions (270 kg/MT steel) from the current EAF technology are used as the reference to calculate the change (in LCOS ΔC_{steel} and in CO_2 emissions ΔE_{CO_2}) based on different technology and energy switching options. The CO_2 avoidance cost of EAF-SOA is $447/MT, because the amount of CO_2 avoided is only 34 kg/MT steel. For the current EAF technology, the CO_2 avoidance cost when using RNG and clean electricity adds $46/MT to $242/MT and $-90/MT to $192/MT, respectively, which is similar to the CO_2 avoidance cost for the current BF-BOF technology shown in Figure 6(b).

The steel made in BOF technology with a low levels of "tramp" elements is destined for flat products, while the steel produced from the EAF is served for billet and bloom[*] products (Zhu et al., 2019). The U.S. DOE report of *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Advanced High Strength Steels Manufacturing* estimated the total advanced high-strength steel (AHSS) production in the U.S. to be 1.2 million metric tons, with 80% of it produced using BOF configurations (DOE Advanced Manufacturing Office, 2017). In order to meet the material property requirements of different applications, BOF technology can not be completely replaced by EAF technology given the former technology yields products with higher quality than the latter. The volatility of scrap cost, iron ore cost, and energy prices contribute to the differences in LCOSs between BOF and EAF. The sensitivity analysis of the TEA results are shown in Figure 8 and Figure 9.

* Flat products are finished rolled steel products like steel strip and plate. A billet is a semi-finished steel product with a square cross section up to 155 mm x 155 mm. A bloom is a semi-finished product with a square cross section larger than 155 mm x 155 mm.

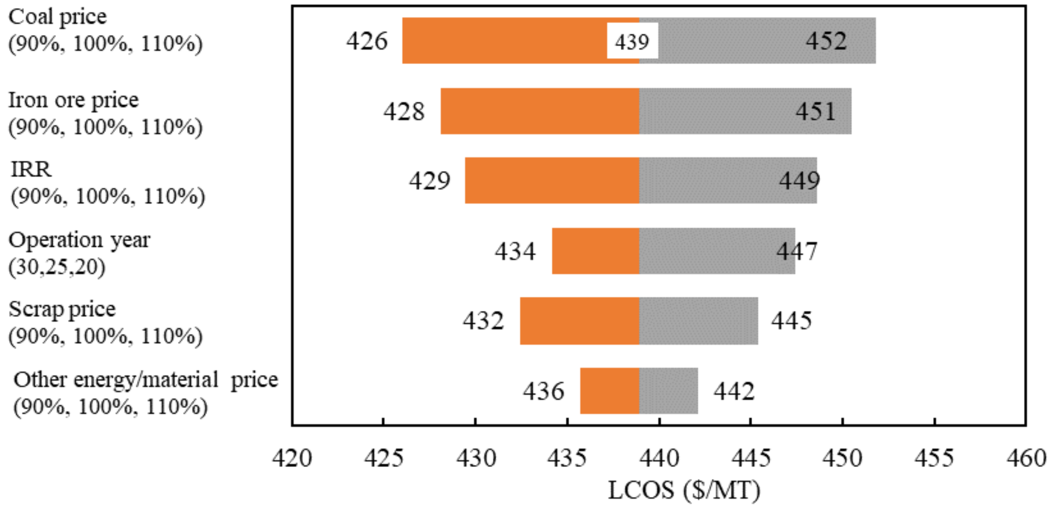


Figure 8. Sensitivity analysis results of BF-BOF configuration.

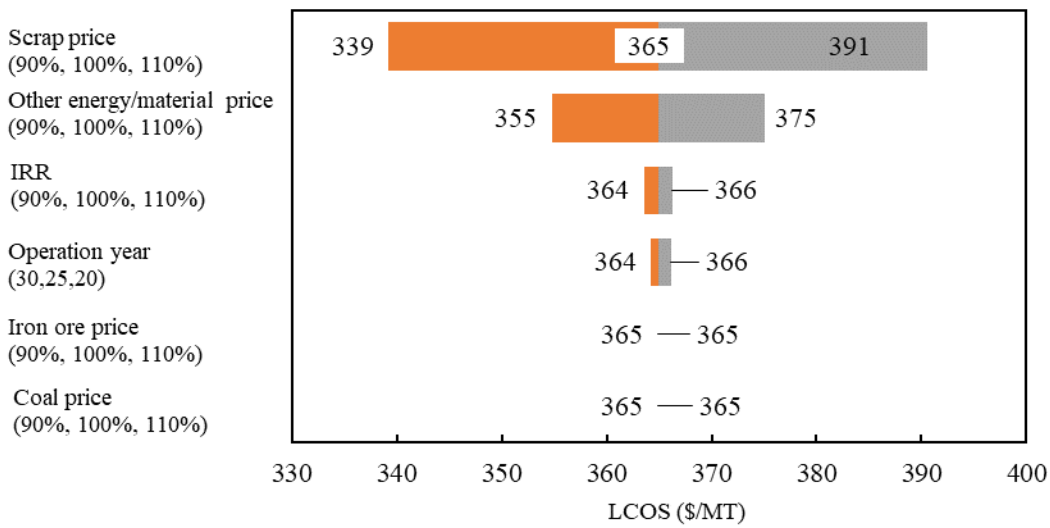


Figure 9. Sensitivity analysis results of EAF configuration.

4. CONCLUSIONS

Iron and steel manufacturing is the largest CO_2 emission source and the second-largest energy consumer among heavy industries worldwide. To decarbonize steel manufacturing, a detailed assessment is required to understand a) the current energy consumption and greenhouse gas emission profiles associated with steelmaking, b) the decarbonization options and the potential CO_2 reduction potential; and c) the economic impacts of various decarbonization pathways.

This study provided a systematic analysis with a consistent system boundary and harmonized assumptions to evaluate various decarbonization options. Six BOF-BOF and four EAF configurations for steel decarbonization were analyzed, including plant energy efficiency improvement, energy source switching, and CCS, covering all steps from iron ore recovery to final steel production. The CTG CO_2 emissions analysis indicates that the CO_2 emissions of BF-BOF and EAF configurations can be reduced by more than 90% compared with the baseline cases by combining carbon capture and energy switching from fossil fuels to renewable energy sources.

The LCOS (levelized cost of steel) was estimated via techno-economic analysis using a discounted cash flow analysis model. The LCOS of the U.S. BF-BOF baseline case is $439/MT steel, and that of the U.S. EAF baseline case is $365/MT steel. The application of the carbon capture increases the LCOS of BF-BOF to $506/MT and the combination of carbon capture and renewable energy sources increases the LCOS of BF-BOF to $542/MT. The LCOS of BF-BOF-SOA case increases to $534/MT as a result of the high capital investment of the greenfield BF-BOF-SOA facility.

The CO_2 avoidance costs vary from -$90/MT CO_2 to $646/MT CO_2 depending on various technologies and energy prices. The CO_2 avoidance cost associated with RNG use is $42/MT CO_2 to $242/MT CO_2, and that of the application of clean electricity is $-90/MT CO_2 to $192/MT CO_2, impacted by the price of renewable energy sources. The CO_2 avoidance cost of carbon capture is $66/MT, and that of BF-BOF-SOA and EAF-SOA is $646/MT CO_2 and $447/MT CO_2, respectively, depending on the capital investment.

The present study investigates the decarbonization options that can be applied to the current BF-BOF and EAF processes, which the dominant iron and steel manufacture processes in the United States. Our study benchmarks the U.S. steel sector emission baseline, lays out potential decarbonization options for these existing facilities and quantifies the decarbonization amount and cost. We are aware of other low carbon or emerging technologies for steel production, such as DRI-EAF using natural gas or hydrogen to reduce the CO_2 emissions in virgin steel making. We evaluated these emerging DRI technologies and discussed the potential of further decarbonization in a separate paper (Zang et al, 2023). These two studies together provide insights to steel industry technology developers and stakeholders/investors to manufacture low carbon steel, and inform policy makers and the public. Our research will shed light on ion/steel manufacture decarbonization directions by identifying decarbonization opportunities with quantification of emission reduction potential; and provide quantitative decarbonization cost information that help reduce investment risks and accelerate low carbon manufacture technology deployment.

5. SUPPORTING INFORMATION

Additional details on process-level energy consumption of BF-BOF cases and technology readiness level are shown in the Supporting Information.

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7. ABBREVIATIONS USED

CTG	Cradle to gate
MMT	Million metric tons
AHSS	Advanced high strength steel
BF	Blast furnace
BOF	Basic oxygen furnace
EAF	Electric arc furnace
MT	Metric ton
DOE	U.S. Department of Energy
SOA	State of the art
CC	Carbon capture
IEA	International Energy Agency
LCA	Life cycle analysis
TEA	Technology-economic analysis
GREET	Greenhouse gases, Regulated Emissions and Energy use in Transportation
COG	Coke oven gas
BFG	Blast furnace gas
MECS	Manufacturing Energy Consumption Survey
MEA	Mono-ethanol-amine
NG	Natural gas
RNG	Renewable natural gas
DRI	Direct reduced iron
HBI	Hot-briquetted iron
TIC	Total installed cost
O&M	Operations and maintenance
LHV	Lower heating value
NETL	National Energy Technology Laboratory

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