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Oxygen enrichment combustion to reduce fossil energy consumption and emissions in hot rolling steel production

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ABSTRACT

The reheating furnace operation in the hot mill is natural gas- and electricity-intensive. Oxygen enrichment combustion for reheating furnaces has been proposed to curb and replace natural gas use. In this study, heat transfer in steel slabs in the combustion environment of a push-type reheating furnace was simulated using a computational fluid dynamics (CFD) model. Two oxygen enrichment methods that optimized for performance were selected— a medium oxygen enrichment (MOE) case and an oxy-fuel (OF) case. A life cycle analysis (LCA) characterized the energy and emission profiles of an integrated iron and steel manufacturing process using the two oxygen enrichment cases for the hot mill. These conditions were evaluated for energy use and carbon intensity and compared with a baseline case. Results show that with oxygen enrichment, natural gas consumption can decrease by 19.6%–26.8%, total energy consumption (natural gas and electricity) can decrease by 15.1%–20.7% in the hot mill. Emissions of greenhouse gases can decrease by 11.1%–15.2% in the two optimized cases with 14%–27% reductions in regulated criteria pollutants (nitrogen oxides, carbon monoxide, particulate matter, volatile organic compounds, black carbon, organic carbon, and volatile organic carbons). There is a tradeoff between reducing natural gas consumption and increasing electricity demand from a life cycle perspective. Although the OF case resulted in higher energy- and emissions-related benefits, the MOE case showed the more desirable heat flux uniformity, which is key to maintaining product quality. The analysis suggests that oxygen enrichment in the reheating furnace process can have a significant impact on hot mill environmental performance and become a contributing factor in transitioning to low-carbon steel manufacturing.

1. Introduction

Steel production is energy intensive. On average, it takes 20 GJ (GJ) to produce 1 ton (t) of crude steel — and release 1.85 t of carbon dioxide (CO_2) emissions (Worldsteel, 2019). A significant portion of the energy demand (Orcajo et al., 2015) and GHG emissions (Hu et al., 2014) is attributed to blast furnace and basic oxygen furnace systems upstream of the steelmaking process. CO_2 emissions in iron and steelmaking varies from 1080 to 2142 $kgCO_2$ per t of crude steel, with the range primarily due to the industrial process structure in a given country (Hasanbeigi et al., 2016). Downstream, the hot rolling process is the most energy intensive. This is mainly attributable to reheating furnace operation (Kun and Szemmelveisz, 2014), followed by casting (Caneghem et al., 2010). Reheating furnaces consume about 70%–80% of the total energy required for hot rolling mills (Thekdi, 2011) and contribute the majority of CO_2 emissions (Worl et al., 2019). Steel manufacturing sector aimed to reduce fossil energy consumption and reduce CO_2 and other environmental emissions to achieve energy efficient, resilient, and sustainable production (ArcelorMittal Ghent).

The steel manufacturing process consists of several major production steps: iron ore production, sinter plant, blast furnace, basic oxygen furnace, continuous casting, and hot rolling (Fig. 1). The reheating furnace is a major operation in hot rolling that processes 100–300 t of steel per hour (Thekdi, 2011). Its operations are complex and, especially with newer advanced steels, require great operational dexterity. The

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Nomenclature

Athena	Athena Sustainable Materials Institute Materials Institute
BAT	Best Available Techniques
BC	Black carbon
CFD	Computational fluid dynamics
CH_4	Methane
CO	Carbon monoxide
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies modeling software
HPC	High performance computing
LCA	Life cycle analysis
MOE	Medium oxygen enrichment
NO_x	Nitrogen oxides
O_2	Oxygen
OC	Organic carbon
OF	Oxy fuel
PM	Particulate matter
SO_x	Sulfur oxides
SRI	Steel Recycle Institute
VOCs	Volatile organic carbons

furnaces typically heat the steel slabs to 1050°C–1300 °C (Tan et al., 2013), then the steel is cooled with water and rolled to meet specific size and quality demands (Kun and Szemmelveisz, 2014). Natural gas is a primary fuel in the reheating furnace operation. The natural gas stream is blended with air and injected into the furnace via a set of burners positioned at the top and bottom of the preheating, heating, and soaking zones (Fig. 2).

Air streams are split into primary and secondary streams, and each stream of natural gas and air has a unique flow rate. The major process parameters—fuel mix, mass flow rate, and position of burners—affect the uniformity of the heating of the steel slabs, which is essential to achieving desirable product quality. Reheating furnace temperatures in all zones must be dynamically controlled to ensure within-tolerance slab heating rates, slab thermal profiles, and target temperatures to maintain product quality. Jang et al. (2008) indicated that the key challenges in reheating furnace operation are balancing many factors to reach the target temperatures consistently and homogeneously and maintaining desired metallurgical properties while trying to minimize fuel usage. Uneven heating can lead to surface and internal defects, resulting in losses from product rework, wasted energy resources, downtime, and equipment repair/replacement.

Recently, researchers have begun to investigate increasing the oxygen in the furnace input flow to improve fuel efficiency (Worl et al., 2019). Worl and colleagues found that at an oxygen level above atmospheric concentration, higher flame temperatures and better radiative heat transfer to slabs can occur. How the fuel technology affects operation parameters, heat uniformity, total fuel consumption, and product quality are not clear. A full understanding of the interactions of these factors and the impact on environmental emissions is lacking.

Life cycle analysis (LCA) is a recognized framework that quantifies the environmental impacts of material inputs and outputs over a product's entire life cycle to support making decisions that will benefit the environment. A method for defining "consecutive and interlinked stages of a product (or service) system, including acquisition of raw materials, design, production, transportation/delivery, use, end-of-life treatment and final disposal" in ISO 14044 (ISO, 2016), an LCA compiles the inputs and outputs of materials and energy for all stages of a product's life in a defined system in order to assess environmental impacts.

Burchart-Korol and colleagues (2011a, 2011b) identified LCA as the most holistic way to compare and select alternative metallurgical technologies in iron-making processes and assess their environmental impacts. Their subsequent work, which found the blast furnace to be the major source of GHG emissions and the iron ore sintering process the largest contributor to dust and gas emissions in integrated steelmaking, analyzed how using raw material substitutions can reduce those emissions (Burchart-Korol, 2013). Caneghem et al. (2010) found that a steelmaking plant in Ghent achieved an eco-efficiency improvement of 33% while increasing steel production from 1980 to 2005 by 17%, primarily by switching from ingot casting to continuous casting and using improved practices. Jing et al. (2019) developed two approaches to assessing life cycle GHG emissions from integrated steel manufacturing in China. Several life cycle modeling software packages or databases include steel manufacturing. Two of them, Ecoinvent SimaPro Analyst (SimaPro) (Ecoinvent SimaPro Analyst, 2019) and GREET (GREET, 2019), include all production stages of the hot rolled steel life cycle, but the reheating furnace is lumped into hot mills. BAT (Remus et al., 2013) includes multiple stages of steel manufacturing, but not hot mills. The Steel Recycling Institute (SRI) (2014) and Athena (2002) present aggregated life cycle results for hot rolled steel. None of the prior LCA work or models can either address or simulate reheating furnace technologies and their life cycle impacts.

This study evaluates life cycle CO_2 and air emissions of hot rolled steel production from a pusher-type reheating furnace with oxygen-enriched combustion air in an ArcelorMittal facility in North America. The process was simulated by a computational fluid dynamics (CFD) model developed for the reheating furnace and optimized for production and energy efficiency. Simulation results provide mass and energy data for the LCA. The goal of this study is to fill the knowledge gap of how fuel

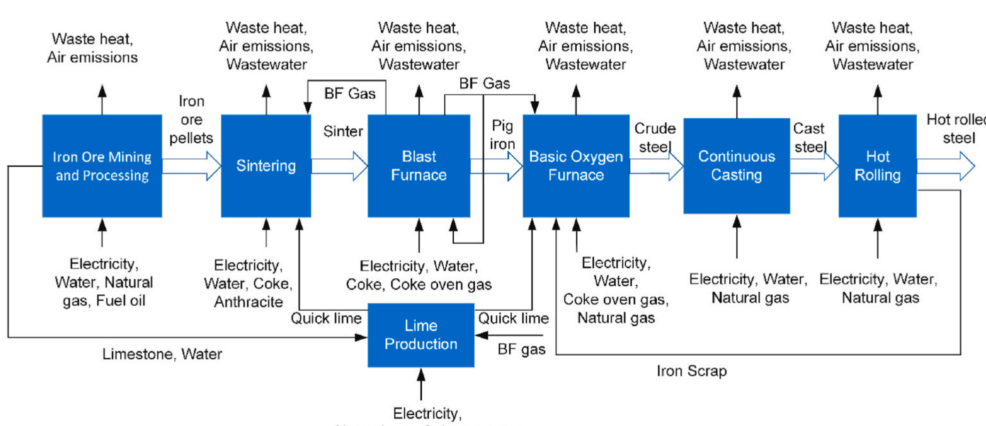

Fig. 1. Schematic of an integrated iron and steel production system used in this study.

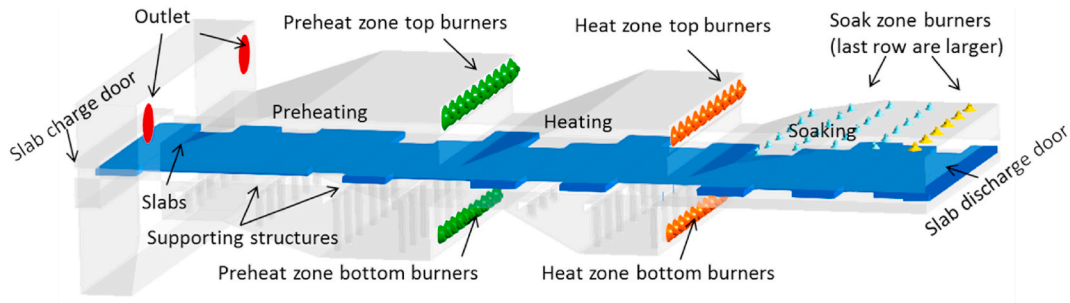

Fig. 2. Three-dimensional schematic of a pusher-type reheating furnace.

technology and operations in the reheating furnace affect environmental emissions of hot rolled steelmaking.

2. Methodology

The modeling and analysis methodology framework is illustrated by the block diagram in Fig. 3. This work is comprised of three major steps: 1) reheating furnace process simulation, 2) life cycle inventory development, and 3) environmental impact assessment and sensitivity analysis.

2.1. Fuel technology

The reheating furnace uses natural gas as the process fuel. This work investigates two oxygen enrichment levels that are optimized for energy efficiency in the reheating furnace operation and compares them with a current operation baseline.

- Baseline: The baseline case supplies an air stream in the preheat zone for combustion.
- Medium oxygen enrichment (MOE): In the MOE level case, a pure oxygen stream is provided and mixed with the air stream.
- Oxy fuel (OF): The OF level case uses pure oxygen for combustion with no air stream.

The natural gas stream contains 95.3% methane (CH_4), 3.3% ethane, 0.9% CO_2, and 0.5% nitrogen gas (N_2). The ratio of natural gas to oxygen and air flow in the MOE case was varied in simulation to achieve optimized performance, as was the ratio of natural gas to oxygen in the OF case.

2.2. Process simulation

A three-dimensional (3D) industrial-scale pusher-type reheating furnace model was developed with the ANSYS Fluent CFD software. The computational domain for the reheating furnace includes three zones: preheating, heating, and soaking, as shown in Fig. 2 above. Slabs enter through the charge door and are moved to the discharge door through the motion of upstream slabs used to push all product through the furnace at a given rate. Simulations were conducted to determine optimum MOE and OF combustion in the preheating zone of the furnace. Parametric case matrices have been developed to simulate a transient reheating furnace with a range of input parameters, including number of burners, burner location in each heating zone, fuel mass flow rate, air flow rate from each burner, charge of temperature, and slab spacing.

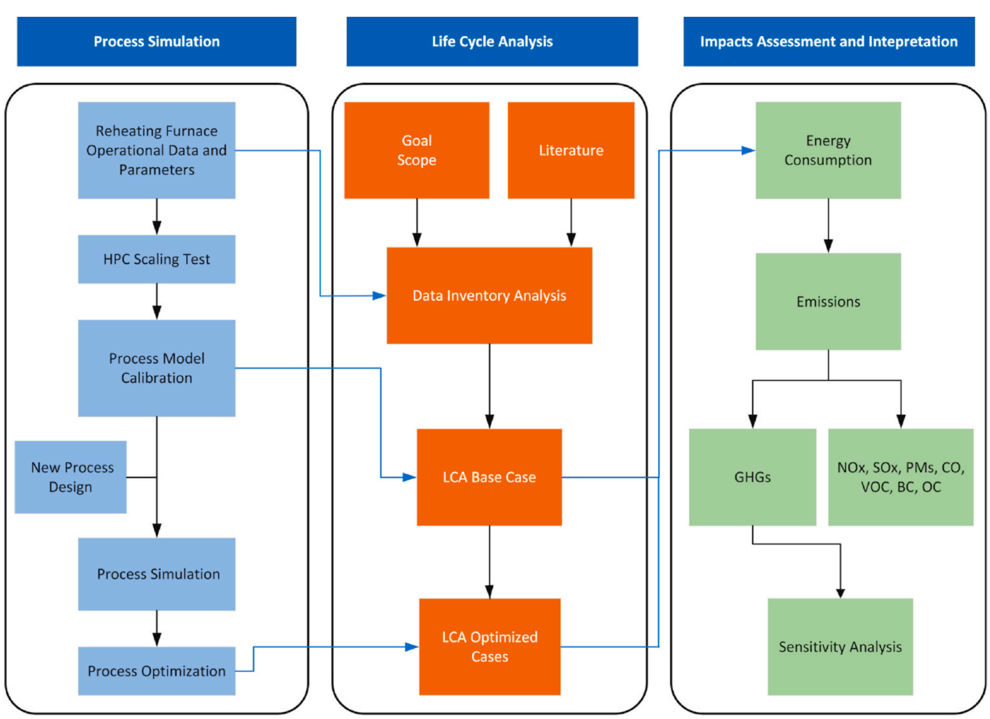

Fig. 3. Modeling and analysis framework.

Slab temperatures were defined using the slab temperature profile obtained from the plant, which provides the temperature of a slab at each position in the furnace. This temperature profile was used as a boundary condition in the CFD simulation. Comparison of the heat flux on the slabs provides the heating uniformity comparison.

The simulated parameters and their range include combustion air temperature (300 K, 640 K, and 900 K), oxygen enrichment level in the preheat and heating zones (4% and 8%), slab layout spacing (50 mm, 75 mm, and 100 mm), and burner fuel rate reductions (15% and 30%). Heat transfer was modeled as stationary radiation through the furnace. The model simulates a total of 105 burners across all zones. The dimensions of the hot rolled steel slab product are 318″ × 55″ × 9.9″, and it weighs 22.78 t. The burner designs were modified for MOE and OF combustion rates. The flow rates of oxygen and air in the MOE and OF combustion cases were adjusted to ensure that the flame shapes generated by the burners were similar to those found in air-fired combustion (the baseline case). The fuel flow rates were further reduced to lower the heat flux to match the slab heating profiles in the baseline case. Optimized cases were then analyzed and selected.

High-performance computing (HPC) is an essential tool providing sufficient speed and scale for a comprehensive CFD analysis. The simulation runs were conducted on the HPC Bebop cluster at Argonne National Laboratory in Lemont, IL, U.S.A., which has 1024 public nodes, 128 GB of memory on each node, and 36–64 cores per compute node, with Intel Omni-Path Fabric Interconnect. This study uses an iterative method to transfer heat flux and temperature between steady-state combustion and a transient heating simulation. The baseline case converged in roughly 6.8 h (10 nodes ~ 320 cores ~ bandwidth partition) for the first steady-state run. Literature regarding a similar method has provided a baseline of 4x the first steady-state run; when compared to our case, this results in ~8.5 h/case (scaled linearly to 32 nodes ~1024 cores). A scaling study was run on two processors (Broadwell and Knight's Landing) organized into partitions of the Bebop cluster for 2000 iterations from the same starting point and data set to determine the performance for a mesh sizing of 9.85M cells, 5.84M nodes, and a pressure-based coupled solver using specific models. This includes the energy equation, k-epsilon realizable turbulence model, the discrete ordinates radiation model, and the non-premixed combustion steady flamelet model. The scaling study found good scaling up to 32 nodes for the Broadwell partition, and good scaling up to around 16 nodes for the Knight's Landing partition. These partitions have 32 and 64 processors per node, respectively. Fig. 4 shows the scaling behavior for each partition studied, with the given processors per node, as compared to the "ideal" 1-to-1 linear scaling. Based on performance, the Broadwell processor was selected for further Fluent model simulations.

2.3. *Life cycle analysis*

2.3.1. *Goal and scope definition*

The goal of this LCA is to assess energy consumption and associated emissions of the hot rolled steel life cycle when one of these new fuel technologies is implemented and optimized in a reheating furnace. The criteria for comparing systems in this study are GHG and regulated air pollutant emissions. The LCA in this study is cradle-to-gate, including iron ore mining, sintering, blast furnace, basic oxygen furnace, casting stage, and hot rolling. Fig. 1 above presented the system boundary of the integrated steel manufacturing process analyzed in this work. As noted, the key environmental impact metrics evaluated are GHG and regulated criteria pollutants: NO_x, carbon monoxide (CO), volatile organic compounds (VOCs), sulfur oxides (SO_x), particulate matter (PM), black carbon (BC), and organic carbon (OC). The functional unit used in this study is the volume of material and energy input/output at each stage per 1 kg of hot rolled steel produced. Material and energy data were based on industrial operation data that considered reuse of waste heat, wastewater recycle, and coproduct production. Steel scrap recycling was considered in the work. Water was not analyzed for the optimization cases because data were not available.

2.3.2. *Life cycle inventory analysis*

A life cycle inventory analysis collects production stage data and models it into flows that are input to and output from the defined system boundary. The inventory includes feedstock materials and energy used in each production stage and non-feedstock material inputs to individual stages in the system. A mass balance is established for feedstock iron ore, sinter, pig iron, crude steel, cast steel, non-feedstock input materials, and final product hot rolled steel. The energy inputs consist of electricity and various fuels (Fig. 1).

- Energy consumption in each production stage is calculated by summing the consumption of individual energy types contributing to the production stage of the iron and steel manufacturing process, expressed by the mass of final product hot rolled steel.
- Energy consumption in the supply chain encompasses manufacturing, storage, and transport of other material inputs to the production stage.

The life cycle energy consumption is the sum of energy consumption in all six production stages (Iron ore mining, sintering, Blast furnace, basic oxygen furnace, casting, and hot rolling) plus the energy consumption to produce all non-feedstock contributing materials, as shown in Equations (1) and (2).

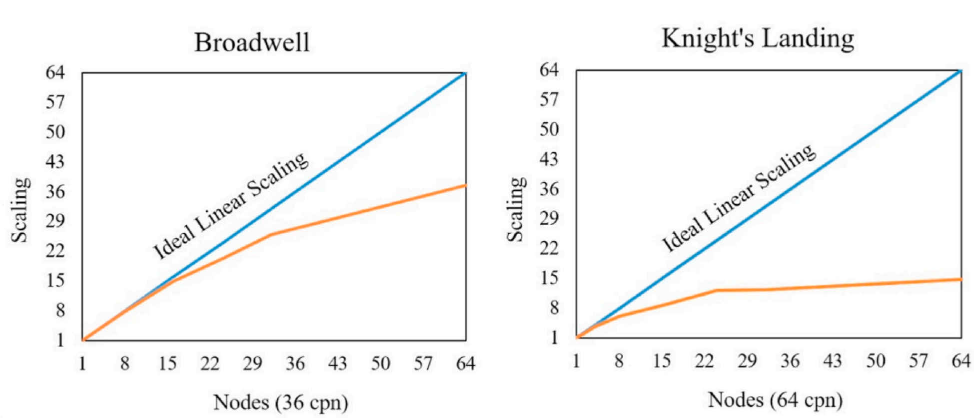

Fig. 4. Scaling of the processors Broadwell and Knight's Landing partitions for the representative testing case (cpn denotes core per node) based on their linear scaling performance. The orange line shows the parallel scaling response of a representative case on the Broadwell nodes and the Knights Landing nodes relative to ideal scaling, which is shown as a blue line. Broadwell, with a scaling that is closer to the ideal scaling, was selected for model simulations.

$$Electricity_{total}\left(\frac{kWh}{kg}\right)=\sum_{i=1}^{n}EP_i\left(\frac{kWh}{kg}\right)+\sum_{i=1}^{n}\left(\sum_{j=1}^{m}SEP_j\right)_i\left(\frac{kWh}{kg}\right) \tag{1}$$

$$Fuel_{total,Q}\left(\frac{MJ}{kg}\right)=\sum_{i=1}^{n}FP_i\left(\frac{MJ}{kg}\right)+\sum_{i=1}^{n}\left(\sum_{j=1}^{m}SFP_j\right)_i\left(\frac{MJ}{kg}\right) \tag{2}$$

Electricity total is the life cycle total electricity consumption to produce 1 kg of hot rolled steel, in kWh.
EP_i is the electricity input at stage i of the iron and steel production process; i can be iron ore mining, sintering, blast furnace, basic oxygen furnace, casting, or hot rolling.
SEP_j is the supply chain electricity input to process j, which produces the materials used at stage i of the iron and steel production process and stores and transports the materials; j can be the production of natural gas, coal, residual oil, and so forth.
$Fuel_{total,Q}$ is the life cycle total consumption of fuel type Q in producing a kg of hot rolled steel, in MJ. Fuel type Q can be coal, natural gas, residual oil, and so forth.
FP_i is the fuel input at stage i of the iron and steel production process; i can be iron ore mining, sintering, blast furnace, basic oxygen furnace, casting, or hot rolling.
SFP_j is the supply chain fuel input to process j, which produces the materials used at stage i of the iron and steel production process and stores and transports the materials; j can be the generation of electricity or the production of natural gas, coal, residual oil, and so forth.

The total GHG gaseous and air emissions of a given production stage account for emissions from the production stage through material conversion, fuel and electricity use, and upstream production, storage, and transport of materials that are used in that stage. Emissions of a gas component from each contributing fuel component Q or electricity in a stage is calculated by multiplying the individual component contributing to the stage by a specific emission factor of the gas component and aggregating to the product. Total emissions of the gas component for the stage are the sum of the individual contributions. Emission factors from various production processes and equipment uses were quantified by U. S. EPA (U.S. EPAb). GHG emissions from the three major gas components—CO_2, CH_4, and N_2O—are calculated by using the global warming potentials as CO_2 equivalents (CO_2 eq) (U.S. EPAa). Equation (3) below shows the total emissions of a component k at production stage i of the iron and steel manufacturing process. The life cycle emissions of a gas component are an aggregation of all production stages.

$$EM_{total,k,i}\left(\frac{g}{kg}\right)=[Emission_k,material\,conversion]_i\left(\frac{g}{kg}\right)+[(EP_i+SEP_i)\times EF_k]\left(\frac{g}{kg}\right)+\sum_{Q=1}^{O}[(FP_i+SFP_i)\times FF_k]_Q\left(\frac{g}{kg}\right)+[Emission_k,upstream\ \ material]_i\left(\frac{g}{kg}\right) \tag{3}$$

$EM_{total,k,i}$ is the total emissions of gas component k at production stage i to produce a kg of hot rolled steel; k can be CO_2, CH_4, N_2O, CO, VOCs, NOx, SOx, PMs, BC, and/or OC.
EF_k is the emission factor of the gas component k for electricity consumption, in g/kWh.
Q is the fuel type.
FF_k is the emission factor of the gas component k for combustion of fuel Q, in g/MJ.
Emission$_k$, *material conversion* is the emissions generated from material conversion in a given production stage for a given emission component, in g/kg hot rolled steel.
Emission$_k$, *upstream material* is the emissions generated in the production, storage, and transport of the materials used in a given production stage for a given emission component, in g/kg hot rolled steel.

Historical reheating furnace and hot mill operation data were obtained from an industrial facility to establish a baseline. The material energy flow data for the production stages upstream of the hot mill were a compilation of data sources, as available datasets were limited. A summary of the system boundaries for six other LCAs of iron and steel manufacturing is available in Appendix Fig. A1. This study relies on data sources that distinguish production stages (non-aggregated) and reflect most recent North America iron and steel mill operations if all possible. The sinter plant and blast furnace data are from BAT (Remus et al., 2013), iron ore mining and operations in surface mines are described by Haque and Norgate (2015), and Burchart-Korol (2013) provides specific process data for basic oxygen furnace and continuous casting. The life cycle data for oxygen production was based on Banaszkiewicz et al. (2013, 2014). Process simulations of new technologies provided data for LCA of optimized cases for reheating furnace in hot mill.

3. Results and discussion

3.1. Life cycle energy consumption and emissions of hot rolled steel

It takes 21.7 MJ to produce a kg of hot rolled steel from cradle to gate with current baseline technologies. That value is slightly higher than values from Athena but lower than those from GREET, SRI, and SimaPro, all of which have the same system boundary (Fig. 5). However, results from Burchart-Korol (2013) depart significantly from the other studies. We found that producing a kg of hot rolled steel produces emissions of 2.4 kg $CO_{2\ eq}$ GHG, which falls within the range of prior cradle-to-gate studies (1.9–6.9 kg $CO_{2\ eq}$ kg^{-1} of hot rolled steel). Coke consumption makes up 56.2% of total energy use and is a major contributor to life cycle GHG emissions in integrated iron and steel manufacturing. The large energy consumption in Burchart-Korol's work is likely attributable to higher energy consumption in the blast furnace in the Poland facility (47 MJ kg^{-1} of hot rolled steel), which is 2.5 times higher than that reported in BAT (18.5 MJ kg^{-1}), GREET (18.6 MJ kg^{-1}), and SimaPro (17.6 MJ kg^{-1}). Life cycle inventory analysis of the baseline integrated steel manufacturing is summarized in Appendix Table A1.

Baseline cradle-to-gate total fossil fuels, electricity, water, and GHG emissions were further examined for each stage of hot rolled steelmaking (Fig. 6). Results show that the blast furnace, sinter production, and hot rolling have the largest impact on GHG emissions in steelmaking because of their high fossil fuel consumption. The blast furnace requires the largest share of fossil fuels (84.1%), followed by the iron ore sinter plant (8.1%) and hot rolling (5.9%). Coke use in the blast furnace operation makes it a major GHG emitter, making up 83.2% of total GHG emissions. The iron ore sinter plant ranked a distant second (8.1%) in GHG emissions, followed by hot rolling (4.7%).

Hot rolling is the major electricity user, consuming a third of the total electricity (29.9%), and is followed by the basic oxygen furnace (22.2%) and the blast furnace (20.2%). In a hot mill, electricity demand is primarily from the operation of rolling stands, coilers, and auxiliary equipment (Orcajo et al., 2015). Hot rolling requires high and dynamic loadings due to the continuous cycle of the mill, which also contributes

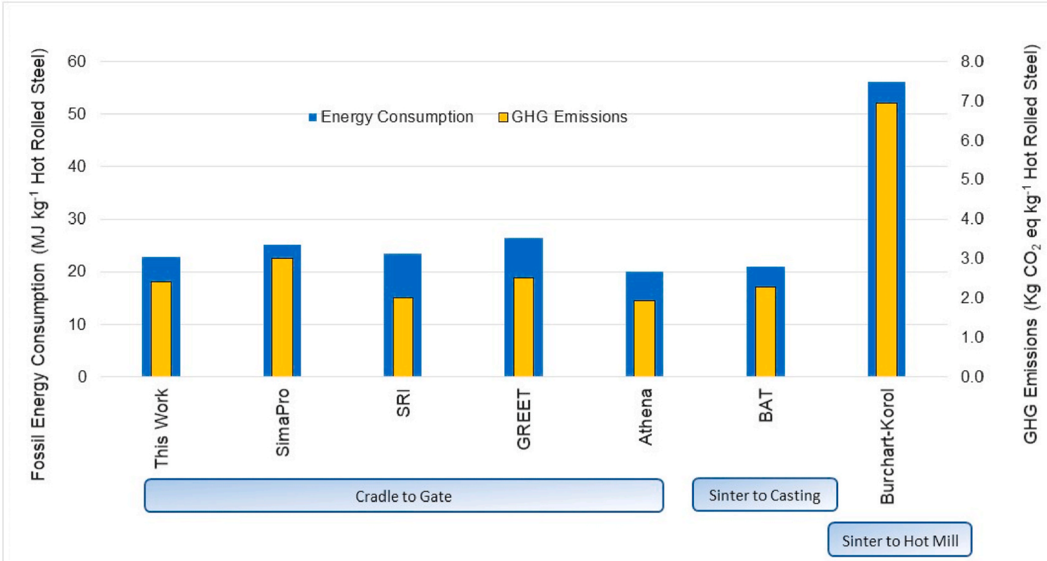

Fig. 5. Energy consumption and GHG emissions of hot rolled steel production in the baseline case from this study compared with literature.

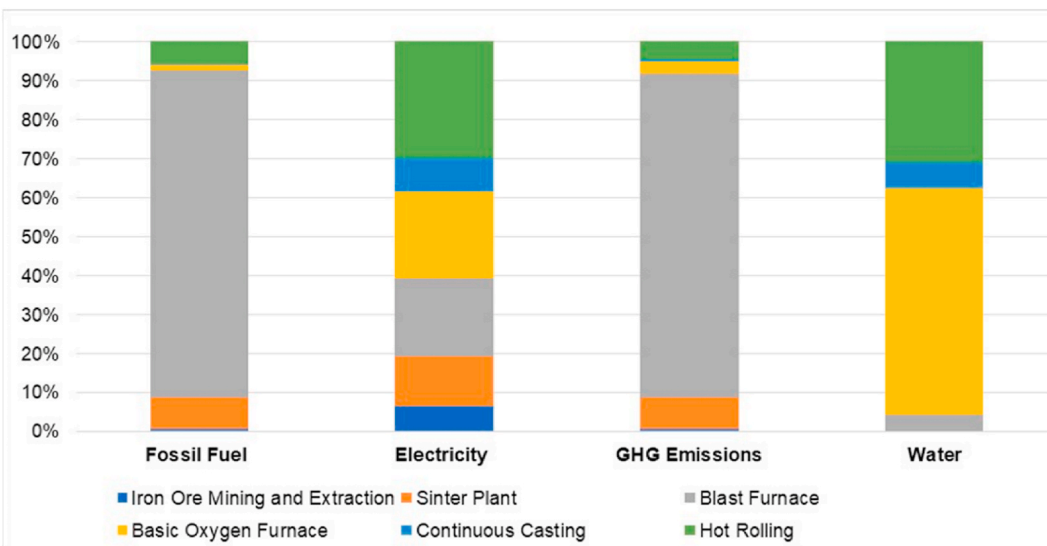

Fig. 6. Contributions of production stages to consumption of fossil fuel, electricity, water, and GHG emissions in hot rolled steel production.

to the high electricity demand (Orcajo et al., 2015). In addition, electricity demand in the hot mill varies with the chemical composition of the steel slab, process conditions, and the targeted condition of the output rolled coil (Kun and Szemmelveisz, 2014). The GHG emissions associated with electricity consumption can be reduced by changing the fuel sources in the electricity mix. As of 2020, 19% of U.S. electricity generation was from coal, 40% was from natural gas, 21% from nuclear energy, and 20% from renewables. Because coal-based electricity contributes to most CO_2 emissions, lower coal power generation could reduce GHG emissions in hot mills. The basic oxygen furnace dominates water consumption (58.2%), followed by hot rolling (31.1%), primarily due to the demand for cooling (Fig. 6).

We further calculated the contribution of each production stage to life cycle air pollutant emissions (Fig. 7). The blast furnace is the dominant emitter of seven out of eight regulated air pollutants: NO_x (85%), SO_x (89%), CO (48%), PM_{10} (86%), $PM_{2.5}$ (83%), BC (72%), and OC (59%). The level of emissions from the blast furnace can be up to 10 times the level of other production stages. Iron ore mining leads VOC emissions (60%) and ranks second in CO emission (43%), which is closely associated with coke combustion. Sintering contributes 8.5% of NO_x and 8.6% of SO_x. Hot rolling is responsible for emitting 20% of the OC, 16% of the BC and less than 10% of PM over the steel life cycle. The air emission profiles of each production stage illustrate that by replacing coke with less GHG intensive fuels in blast furnaces can improve the life cycle environmental profile for steels and reduce emissions of regulated air pollutants, thus improving the air quality in the community surrounding iron and steel manufacturing facilities.

Analysis of the hot mill operational data suggests that the facility used in this study is more energy efficient in fuel usage (1.27 MJ kg^{-1} steel) that those in the literature, which ranged from 2.37 MJ to 6.39 MJ per kg (Fig. 8). The actual fuel consumption in a hot mill is about one fifth to one half of that documented. Electricity usage from the hot mill is also at the low end of the reported data range. As a result, GHG emissions from the hot mill are less than half that reported in previous studies (Fig. 8). SimaPro provides an aggregated energy consumption value for the hot mill. We applied data homogenization by aggregating electricity and fuel to fossil fuels for all four studies.

The resulting total energy consumption numbers are strikingly

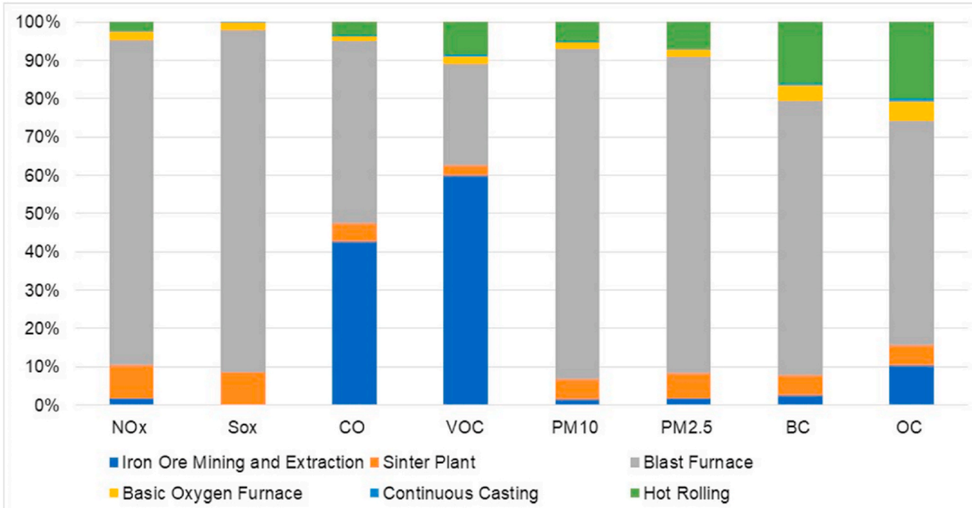

Fig. 7. Contribution of production stages to total life cycle air emissions in hot rolled steel production.

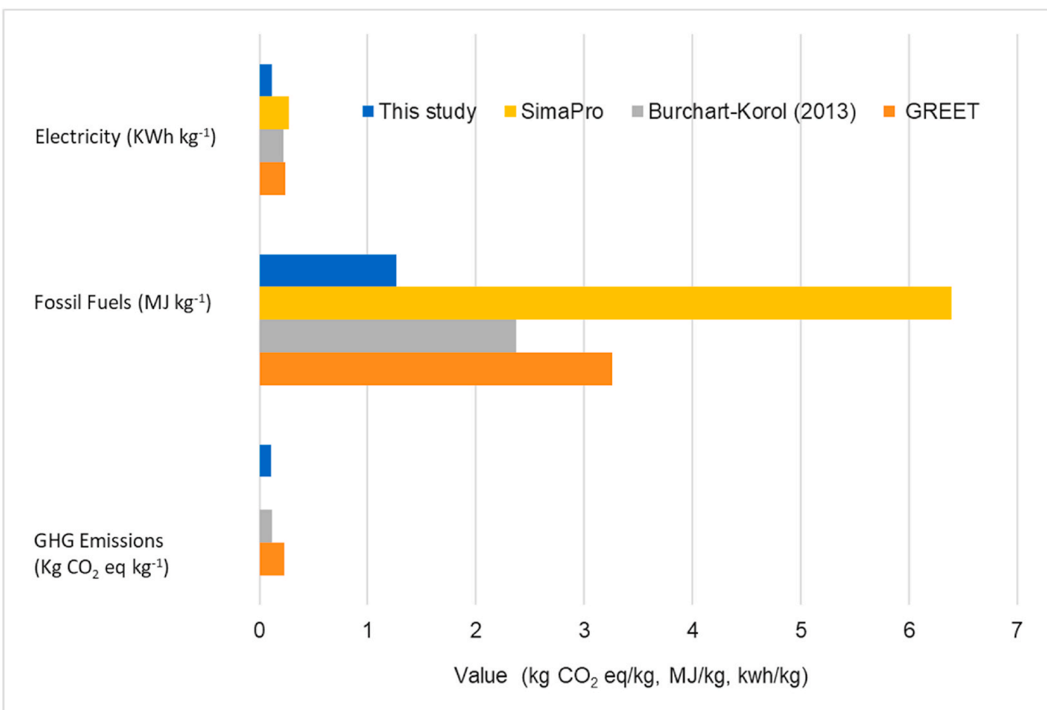

Fig. 8. Comparison of energy consumption and GHG emissions to produce a kg of hot rolled steel in hot mills. Fossil fuels bar includes fuel and electricity use.

different, as expected: 1.64 MJ kg^{-1} from this study, 2.78 MJ kg^{-1} from Burchart-Korol, 4.09 MJ kg^{-1} in GREET, and 6.39 MJ kg^{-1} in SimaPro. The differences could be a result of data year, facility type, fuel type, and/or operation. The operational data we collected for this study were most recent (2018) and came from a push-type reheating furnace facility where there has been a major effort to improve process energy efficiency in the past decade. The furnace types in the other three studies were not available. The Burchart-Korol study used 2011 data for a facility in Poland with natural gas as major fuel. The other two sources did not specify the details. The hot mill investigated in this work likely reflects the most up-to-date hot mill operations in North America. Future work may evaluate hot mills with different furnaces, such as a walking beam reheating furnace, but this study provides the most recent hot rolled steel LCA by analyzing updated hot mill industrial data.

Table 1
Impact of reheating furnace technology scenarios on energy consumption and GHG emissions.

	Baseline	MOE	OF
Hot Mill			
Electricity consumption (kWh kg^{-1})	0.104	0.104	0.104
Fuel consumption (MJ kg^{-1})	1.268	1.020	0.929
GHG emissions (kg $CO_{2\ eq}$ kg^{-1})	0.113	0.101	0.096
Life Cycle			
Electricity consumption (kWh kg^{-1})	0.349	0.356	0.358
Fuel consumption (MJ kg^{-1})	21.663	21.414	21.323
GHG emissions (kg CO_2 eq kg^{-1})	2.417	2.408	2.404

Note: All values are based on producing 1 kg of hot rolled steel.

3.2. Oxygen enrichment technology

3.2.1. Energy and emission profiles of the hot mill with MOE and OF

The optimized cases for the two new technologies—MOE and OF—increase methane combustion efficiency and maintain process performance through increased oxygen fuel and decreased natural gas and air flow. This approach improves radiative heat transfer by maximizing CH_4 combustion while minimizing the partial oxidations that yield CO and H_2. Process simulation cases that optimized for heat efficiency reduced natural gas flow into the reheating furnace from 0.65 kg s^{-1} in the baseline case to 0.43 kg s^{-1} in MOE and even further, down to 0.36 kg s^{-1}, in OF. By replacing natural gas with oxygen and reduced air flow, fuel consumption in the hot mill was reduced by 0.25 MJ kg^{-1} in MOE and by 0.34 MJ kg^{-1} in OF (Table 1), representing a decrease in fuel usage of 19.7% (MOE) and 26.8% (OF). Total fossil energy consumption decreased 15.1% (MOE) and 20.7% (OF) (Fig. 9).

Methane is a major component in natural gas and is more than 28 times more effective than carbon dioxide at trapping heat in the atmosphere (A global warming potential of 28 $CO_{2\ eq}$). In all three cases (MOE, OF, and baseline), methane contributes 88%–95.5% of the total GHG emissions from a hot mill. MOE and OF can reduce GHG emissions by 11.1% and 15.2% in a hot mill, respectively. The level of change in energy consumption and GHG emissions is significant at a national production scale. Currently, the United States produces 69.3 million tons (Mt) of hot rolled steel per year (Association for Iron & Steel Technology (AIST), 2019). If MOE and OF were to be implemented, 17.2–23.5 trillion MJ of energy could be conserved and 0.9–1.2 Mt of GHG emissions avoided annually in hot mills nationwide. Results also indicate that there is a tradeoff between fuel and electricity use from a life cycle perspective. Because the production of oxygen requires electricity (Banaszkiewicz et al., 2014), life cycle electricity use in MOE and OF increased from 0.349 kWh kg^{-1} to 0.356–0.358 kWh kg^{-1}, a 2%–2.5% increase (See Table 1 above.). Despite this increase in electricity use, life cycle net fossil energy consumption and GHG emissions decreased. These results show that oxygen enrichment could have a substantial impact on the environmental profiles of hot rolled steel production. The reduced use of natural gas would also potentially contribute to lower operational cost.

NO_x, SO_x, and CO dominate the pollutant emissions in a hot mill. In the baseline case, NO_x comprises 40% of total criteria pollutants, SO_x 26%, and CO 22%. Simulation results show that oxygen enrichment reduced the amount of flue gases emissions leaving the furnace (Appendix Table A2). The pollutant emissions of NO_x, CO, VOC, $PM_{2.5}$, PM_{10}, BC, and OC decreased 14.8%–17.3% in MOE and 20.3%–23.7% in OF (Fig. 9). There were no changes in SO_x emissions. These reductions can bring substantial changes at production scale. Nationally, implementing the new technologies could reduce NO_x emission by 594–812 t and CO emissions by 362–495 t per year at current hot rolled steel production level (69.3 Mt). Thermal NO_x, the primary form of NO_x in natural gas combustion, is generated from the high-temperature combustion flame (U.S. Environmental Protection Agency and U.S. EPA, 1998). Even though the oxygen content increased in the MOE and OF cases, the amount of NO_x formed decreased, as there is a lower nitrogen concentration in the furnace atmosphere.

3.2.2. Reheating furnace performance

A key performance factor in reheating furnace operation is heat uniformity in the steel slab. The two oxygen enrichment cases increased the oxygen level in the input gas mix by 7% for MOE and by 10% in OF, while natural gas inputs in the preheat zone decreased by 33% for MOE and by 45% for OF. Because nitrogen does not contribute to radiative heating (Oliveira et al., 2014), the changes in furnace atmosphere gas composition led to overall improved radiative heat transfer, which in turn resulted in higher flame temperatures and better heat transfer to steel slabs, as suggested by Liu et al. (2018). The oxygen-enriched cases were able to maintain a desirable heating profile on steel slabs with lower fuel consumption. However, a reduction of nitrogen in the input fuel/oxidant mixture could also lead to overheating of the steel slabs. Overheating the slab is a key factor contributing to surface defects (Tang et al., 2016), while underheating the slabs can deform their shape during rolling, which negatively affects product quality (Sahoo et al., 2019). The heat flux contour plots in Fig. 10 show that the MOE case maintains a performance level similar to the baseline case's. The high heat flux in the MOE case appears at the same position as in the baseline case. However, more heat is transferred through the bottom: 35.8% compared to 33% in the baseline case. In the OF case, less heat is transferred to the bottom of the slabs (27%) compared to the baseline case (33%). While the OF case has the lowest fuel consumption and GHG emissions, the heating uniformity was relatively poor. In some areas at the top of the slab, the heat flux of the OF is much higher than that of the baseline case

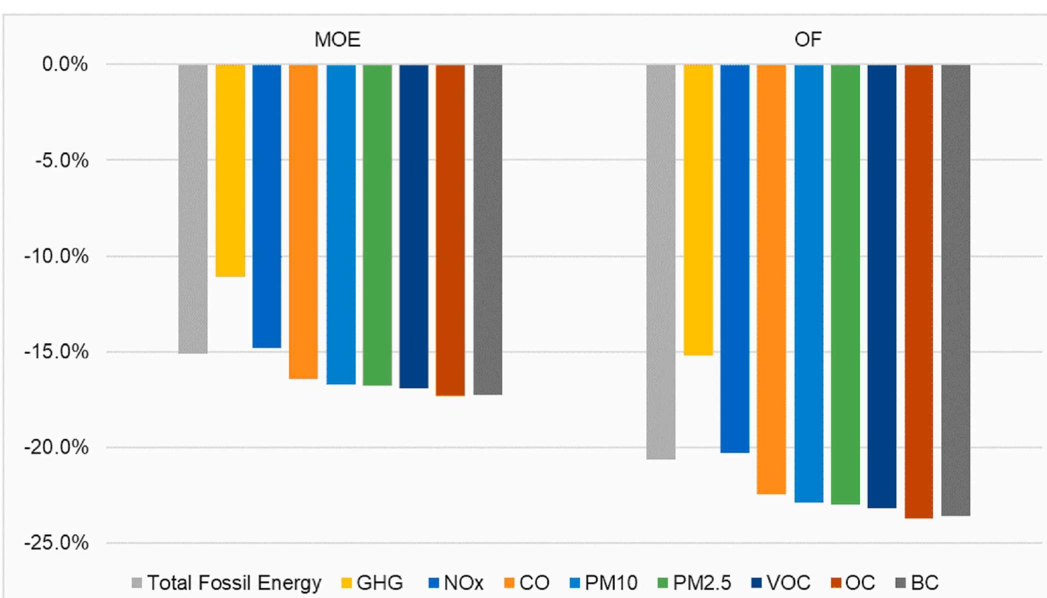

Fig. 9. Changes in total fossil energy use, GHG emissions, and air pollutants emissions (NOx, CO, VOCs, $PM_{2.5}$ and PM_{10}, BC, and OC) in optimized cases (MOE and OF) in the hot mill compared with the baseline. Change in SOx is zero.

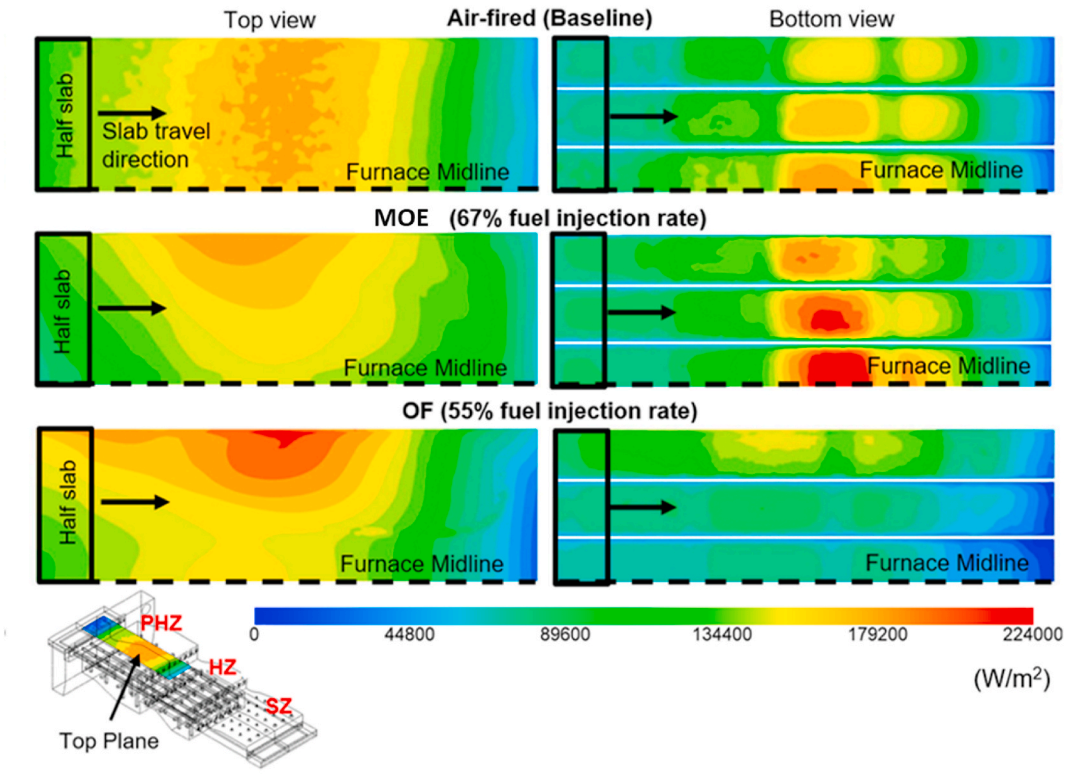

Fig. 10. Heat flux contour plots of each case showing the slab in the preheating zone. The heat flux contour plots represent half of a pusher-type reheating furnace, where the top and bottom planes are set at the slab surface. The small image on the bottom left provides a reference for where the planes of the contour plots are located inside the furnace. PHZ refers to preheating zone, HZ refers to heating zone, and SZ refers to soaking zone.

Table 2
Summary of available heat and combustion efficiencies in the preheating zone and entire reheating furnace.

	Baseline	MOE	OF
Natural gas flow rate in preheat zone (kg s^{-1})	0.65	0.43	0.36
Heat available for combustion in the preheating zone (%)	55%	68%	73%
Heat of reaction source for preheating and heating zones (MJ kg^{-1})	0.56	0.398	0.40
Heat exit at outlet (MJ kg^{-1})	0.40	0.18	0.17
Net heat used in combustion in entire reheating furnace (MJ kg^{-1})	0.16	0.22	0.23
Average outlet temperature (K°)	1333	1301	1319
Heat available for combustion in entire reheating furnace (combustion efficiency) (%)	29%	56%	57%

Note: All values are based on producing 1 kg of hot rolled steel.

(Fig. 10). These results indicate that the OF case is less uniform in its heating profile than the MOE case. From a performance viewpoint, MOE would be preferred.

Oxygen enrichment improved the combustion efficiency of the preheating zone and of the overall reheating furnace. In this study, combustion efficiency is defined as the gross chemical heat release (available heat) minus the heat in the exhausted fuel gas from the reheating furnace and divided by available heat. The preheat zone typically consumes about 50% of the total available heat in the reheating furnace, and the remainder is used in the heating zone and soaking zone. Table 2 presents combustion efficiencies in the preheating zone and in the entire furnace for the optimized cases. With oxygen enrichment, the heat available for combustion in the preheating zone was greatly enhanced, increasing from 55% in the baseline case, 68% in the MOE case, and 73% in the OF case. The total heat used for combustion in the entire reheating furnace in the baseline case is 0.16 MJ kg^{-1} of hot rolled steel. The heat used increased to 0.22 MJ kg^{-1} in MOE and 0.23 MJ kg^{-1} in OF (Table 2). The MOE and OF cases nearly double the overall combustion efficiency in the entire reheating furnace, with levels reaching 56%–57%, compared with 29% in the baseline case.

While the OF case can reach the highest combustion efficiencies, lowest fuel consumption, and lowest GHG emissions, it is also characterized, as noted above, by a less desirable heat flux profile (Fig. 10). In contrast, the MOE case presented improved heat availability and combustion efficiency as well as reduced natural gas input and GHG emissions while maintaining process performance.

3.3. Sensitivity analysis

Based on this integrated iron and steelmaking process LCA, the sensitivity of GHG emissions to fuel sources and types was investigated next. GHG emissions at each production stage were estimated while varying electricity, natural gas, coke oven gas, blast furnace gas, and coke inputs by ±10%.

As shown in Fig. 11, GHG emissions are most sensitive to energy input variations in the blast furnace, basic oxygen furnace, and hot rolling. This is consistent with the proportion of energy inputs to the three stages, as indicated in Fig. 6 above. GHG emissions due to natural gas use are most influenced by the hot rolling stage. A 10% change in natural gas use in hot rolling can yield a 0.26% change in GHG emissions (Fig. 11b). The blast furnace ranked as a distant second. Hot rolling electricity use also has the greatest impact on GHG emissions. A 10% change in electricity consumption can result in a 0.2% change in hot rolling GHG emissions (Fig. efollowed closely by changes in the basic oxygen furnace, the blast furnace, sintering, and casting.

The blast furnace is marked by high blast furnace gas and coke

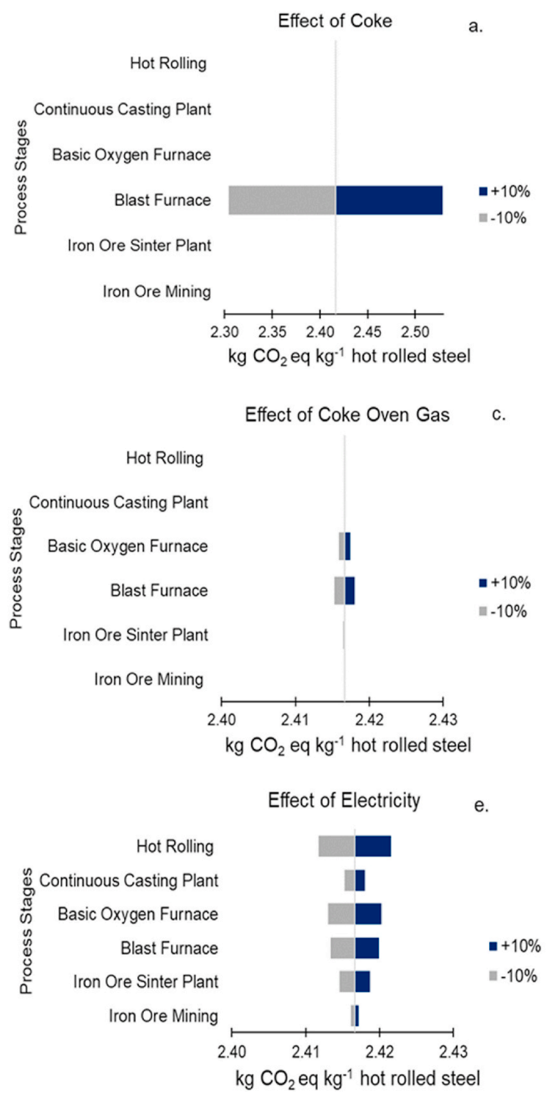

Fig. 11. Effects of ±10% changes in fuel use on total GHG emissions in each process stage of the baseline steel manufacturing case. The total GHG emissions from the cradle-to-gate process is about 2.42 kg CO_2 eq/kg of hot rolled steel. (a) ±10% change in coke input, (b) ±10% change in natural gas input, (c) ±10% change in coke oven gas input, (d) ±10% change in blast furnace gas input, and (e) ±10% change in electricity input.

consumption (Fig. 11d and e), and GHG emissions are most sensitive to changes in coke consumption. A 10% difference in coke consumption in the blast furnace can lead to a ±4.6% change in GHG emissions (Fig. 11d), and a 10% difference in blast furnace gas consumption leads to a ±1.7% change in GHG emissions, accompanied by a smaller change in the basic oxygen furnace (Fig. 11e). In contrast, the effect of changing coke oven gas on the blast furnace appears minimal. GHG emissions have the lowest sensitivity to fuel consumption in the iron ore mining and continuous casting phases. The sensitivity analysis results agreed with previous work in that the blast furnace, basic oxygen furnace, and hot mill are the most energy intensive stages in steel manufacturing (Hu et al., 2014). Data suggest that cutting down coke use in the blast furnace has the biggest impact on GHG emissions, followed by a reduction of blast furnace gas, natural gas, and electricity. Using oxygen enriched fuel in the reheating furnace can be a promising option to achieve the goals of lower GHG emissions and improved environmental sustainability.

4. Conclusion

Process optimization through oxygen enrichment for reheating furnaces provides an opportunity to improve thermal efficiency and reduce environmental emissions. Built on reheating furnace dynamic process simulations, this study employs an LCA to analyze energy and environmental profiles of an integrated iron and steel manufacturing process and investigate the oxygen enrichment combustion technology in a hot mill similar of an ArcelorMittal facility in North America. Hot mill fossil fuel consumption in this work appears significantly lower, and electricity consumption somewhat lower, than hot mills in the literature. Hot mill GHG emissions are about 1/3 of the previously reported values, indicating improvements in energy efficiency and environmental performance in the steelmaking sector.

Life cycle analysis identified the blast furnace, basic oxygen furnace, and hot mill as the most energy use intensive production stages in steel manufacturing. The blast furnace is the largest source of GHG emissions, NO_x, SO_x, PM_{10}, $PM_{2.5}$, BC, and OC. Sintering, hot rolling and the basic oxygen furnace are also major contributors to GHGs. GHG emissions are most sensitive to a change in coke use in the blast furnace, followed by blast furnace gas use in the blast furnace, and natural gas in hot mills. GHG emissions are sensitive to electricity use in most stages.

The results of optimized oxygen enrichment combustion technology simulations reveal substantial energy and emissions benefits for the hot mill. Total fossil energy use can decrease by 15.1% in the MOE case and by 20.7% in the OF case. The GHG emissions can decrease by 11.1% and 15.2% in the MOE and OF cases, respectively, with additional reductions in criteria pollutants. Both the MOE and OF cases improve heat transfer to slabs and doubled heat available for combustion in the reheating furnace; however, only the MOE case meets the heat uniformity criteria for product quality. If implemented in hot mills across the U.S., MOE could bring 17.2 trillion MJ energy savings and avoid 0.9 Mt of GHG emissions annually. This work demonstrated that optimized oxygen enrichment technology for reheating furnaces can contribute significantly to reduced fossil use and GHG emissions—a path to environmentally sustainable production of steel globally.

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CRediT authorship contribution statement

Yusra Khalid: Formal analysis, performed life cycle analysis and sensitivity analysis; interpreted results, Writing – original draft, drafted the manuscript. **May Wu:** Conceptualization, Methodology, designed the concept and methodology for this study; interpreted results, Writing – original draft, drafted the manuscript. **Armin Silaen:** Data curation, Formal analysis, collected and analyzed industry data, and guided process model parameterization, conducted model simulation, developed process 3-D graphics, Writing – review & editing, reviewed the manuscript. **Francisco Martinez:** conducted model simulation, Writing – review & editing, reviewed the manuscript. **Tyamo Okosun:** Formal analysis, Data curation, analyzed and interpreted simulation data; interpreted results, Writing – review & editing, reviewed the manuscript. **Bethany Worl:** conducted model simulation, Writing – review & editing, reviewed the manuscript. **John Low:** performed HPC testing for model compatibility, Writing – review & editing, reviewed the manuscript. **Chenn Zhou:** Conceptualization, Methodology, designed the concept and methodology for this study, Writing – review & editing, reviewed the manuscript. **Kurt Johnson:** Data curation, Formal analysis, provided process knowledge and data for analysis; interpreted results, Writing – review & editing, reviewed the manuscript. **David White:** Data curation, Formal analysis, provided process knowledge and data for analysis, Writing – review & editing, reviewed the manuscript.

Declaration of competing interest

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

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Appendix A. Supplementary data

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