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Research article

Process-level emission analysis and decarbonization pathway for BF-BOF route in Indian iron and steel industry

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ABSTRACT

The blast furnace-basic oxygen furnace (BF-BOF) route contributes 46% to the production of iron and steel in India and is highly energy and emission-intensive. Its decarbonization needs to be prioritized for reducing long-term climate-related impacts. So far, studies have assessed the macro-level carbon emission and energy consumption of the entire industry (encompassing all production routes i.e., BF-BOF, EAF, DRI, SR-BOF, etc.), and lacks the specific plan for decarbonization of plants based on BF-BOF route. Secondly, these studies have focused on just a single input (raw material, energy, fuel, etc.) and the respective output (steel) and lack the analysis of detailed process-wise material and energy flow and consideration of fugitive emissions, which is needed for emission mitigation of entire BF-BOF based plants, which produces 57.37 million tons of crude steel in India. The current study addresses this gap through a case study of a BF-BOF-based plant by comprehensively analyzing the material and energy flow for each production step followed by assessing the respective carbon emissions. Further, a marginal abatement cost curve (MACC) is developed to identify the process-wise cost-effective mitigation measures. The current study shows that the implementation of proposed measures can significantly reduce carbon emissions from 3.3 to 2.43 tCO_2/tcs, making it equal to the global counterparts.

1. Introduction

India is the second largest steel-producing country after China, with annual steel production of 118 million tons in 2021 (Ministry of Steel, 2021). Indian iron and steel industries (IISI) consume energy equivalent to 6–6.5 Giga calorie per tonne of crude steel compared to 4.5–5 Giga calorie per tonne in other countries (Ministry of Steel, 2021). In industry, the iron and steel industry contributes approximately 39% to India's industrial emissions, representing nearly 10% of the nation's total CO_2 emissions (International Energy Agency, 2022). In India, iron and steel production is done in two ways i.e., primary, and secondary routes. The primary route involves using iron ores and scraps as raw materials, while the secondary route involves steel production via recycled steel scrap (Napp et al., 2014). The primary steel production route involves the preparation of raw material, iron and steel making using three processes namely Blast Furnace-Basic Oxygen Furnace (BF-BOF), Direct Reduction Iron-electric arc furnace (DRI-EAF) and smelting reduction (SR-BOF). BF-BOF is the dominant production route, contributing 46% to total steel production. The basic characteristics of Indian iron and steel industry as compared to other countries is shown in Table 1.

In BF-BOF, coke from coal directly reacts with iron pellets/sinter in the blast furnace to form molten iron, which is further decarburized in BOF to produce crude steel (Wang et al., 2020). Major steps in the primary production route are sintering, pelletizing, coking, iron making through BF and steel making & casting through BOF, as shown in Fig. 1.

Following the crude steel production via the primary route, further processing steps including casting, rolling, and finishing are done via continuous caster, rolling mills, annealing, pickling, and surface treatment methods (A Hasanbeigi et al., 2010a,b; Price et al., 2002). In line with India's rapid development, Hall et al. (2020) projected that the nation's demand for steel is expected to increase three times by 2030 and increase fivefold by 2050, which is expected to contribute approximately 35% to the country's total CO_2 emissions by 2050. Thereby, rapid, and deep decarbonization of the iron and steel industry is highly critical to realizing the climate goals of being carbon neutral by 2070 and reducing one billion tons of CO_2 emissions by 2030, as announced by India in Glasgow Summit (2021). Decarbonization requires an in-depth understanding of each, and every process used to make iron and steel. It will help in the assessment of carbon emissions from each

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process, which is required for carving out the mitigation pathway for the entire industry.

Looking at the increasing CO_2 emissions from the iron and steel industry over the last two decades, several researchers from various countries, including China, the European Union, the UK, Canada, and Japan have focused on developing the pathways and technologies for reducing its carbon emissions. Studies by Zhang et al. (2021) and Andrade et al. (2024) highlighted global initiatives and technological innovations aimed at reducing emissions in the steel industry. These include projects like COURSE50 in Japan (Watakabe et al., 2013), hydrogen metallurgy projects in China (Tang et al., 2020), and negative emission technologies utilizing biomass with carbon capture and storage (Yang et al., 2021). Globally, An et al. (2018) used National Energy Technology Model to identify the carbon reduction potential of different technologies for China's iron and steel sector. Arens et al. (2017) and Vögele et al. (2020) provide insights into regional challenges faced by the steel industry for emission reduction, particularly in Germany and the European Union (EU). Andersson and Hellsmark (2024) introduce a framework to analyse the directionality of decarbonization efforts in process industries, with a focus on Sweden's industries. Na et al. (2022) and Tan et al. (2019) focussed on improving energy efficiency in Chinese iron and steel manufacturing processes. Few studies across China (Na et al., 2024; Shen et al., 2021; Tian et al., 2022), compared carbon emissions across different steel production methods and proposed strategies for reducing carbon emissions. These studies map out decarbonization pathways for the entire iron and steel industries by focusing on energy efficiency improvements, technological innovations, and policy frameworks.

In the Indian context, various studies have explored the decarbonization route for the iron and steel industry (Dhar et al., 2020; Elango et al., 2023; Pal et al., 2016). Johnson et al. (2023) employed SESAME Industry and Industrial Fleet models to evaluate emission reduction potential and associated cost of mitigation measures in IISI. Haider and Mishra (2020) and Mallett and Pal (2022) focussed on alternative production routes and energy optimization strategies. Chowdhury et al. (2021) highlighted the potential of mixed production routes and optimization techniques to enhance energy efficiency and reduce environmental impact. The studies also explored the energy efficiency measures within the Indian steel industry (Giri et al., 2021; Krishnan et al., 2013). Pal et al. (2016) generated six scenarios for reduction of emission intensity from Indian steel production. Dhar et al. (2020) analysed supply and demand-side strategies for the steel and cement sectors using energy system and material flow models, to reduce material, energy, and CO_2 intensity. Lau (2024) examined the role of carbon capture and storage (CCS) in reducing carbon emissions in India's steel industry.

So far, Indian iron and steel industry has been treated as a single entity for the creation of decarbonization strategy which includes both primary and secondary steel production (Elango et al., 2023; Johnson et al., 2023; Kim et al., 2022; Mallett and Pal, 2022; Pal et al., 2016). Studies fail to account for the emissions and energy consumption of unique operational route for steel production i.e., BF-BOF route, which produces 57.37 million tons of crude steel (46% of total crude steel production) annually in India. As a result, the emissions provided by the existing studies is aggregated, ignoring the distinct energy requirement and emission production from different routes. Not only do these different production routes have different carbon emissions, but each process within these routes, like sintering, coking, and calcination, uses different amounts of fuel and energy and produces different levels of emissions. The lack of detailed process-wise analysis delays the identification of targeted mitigation strategies, that can effectively help in reducing emissions at critical points in the entire production process. Secondly, exclusion of fugitive emissions remains a notable gap in the existing analyses. Fugitive emissions, which encompass leaks, spills, and other unintentional releases of gases, represent a substantial yet often overlooked source of emissions within the iron and steel industry. These emissions arise from various sources, including coke ovens, blast furnaces, and storage facilities, and can significantly contribute to the industry's overall carbon footprint.

The current study addresses the above-mentioned gaps and contributes to the existing literature in three significant ways. First, it develops a robust carbon flow model that details the carbon emissions throughout the various processes (sintering, coking, iron making, and steel making) within BF-BOF production pathway in the Indian context. Secondly, it provides a mathematical formulation, which calculates specific CO_2 emissions, i.e., CO_2 emissions per ton of crude steel for each process. It enables comparison of emissions between different iron and steel plants with varying steel making capacities, which will also help in identifying inefficiencies in any production stage/process across different steel plants. Thirdly, it accounts for fugitive losses within BF-BOF production route, which will help in estimating carbon emissions from any leakages within the production plant. Addressing these gaps represents a significant contribution to the existing studies, specific to the Indian iron and steel industry decarbonization.

Reducing emissions requires proper selection and implementation of mitigation measures. Implementation of all mitigation measures at once is not possible due to their high cost, operation, and maintenance requirements. Marginal abatement cost curves (MACC) are a widely adopted method for this purpose i.e. for the selection of appropriate mitigation measures. MACC has been heavily relied upon by institutions like the European Union (EU)(Blok et al., 2001) and the US EPA(US EPA,

Table 1
Comparison of iron and steel industry across different countries.

Dimensions	India	China	Japan	United States	Germany	Sweden
Production (in million tons of crude steel)	124.72 in FY23 (2nd largest)	1019.1 in FY23 (largest producer)	91.65 in FY21	85.8 in FY21	36.9 in FY22	4.3 in FY23
Production pathway	BOF-46%, IF-31%, EAF-23%	BOF-90.1%, EAF-9.9%	BOF-74.4%, EAF-25.6%	BOF-30.8%, EAF-69.2%	BF-BOF-70%, EAF-30%	BF-BOF-67%, EAF-33%
Energy intensity	25–27 GJ/tcs	17.58 GJ/tcs	21.35 GJ/tcs	21.92 GJ/tcs	18.20 GJ/tcs (without coking plant)	19.75 GJ/tcs
Carbon emission intensity	2.5 tCO_2/tcs	2 tCO_2/tcs	1.77 tCO_2/tcs (163.09 $MtCO_2$ in FY21)	1.88 tCO_2/tcs	1.41 tCO_2/tcs (without coking plants)	1.32 tCO_2/tcs
Technology in place	MoS-NEDO (Japan) partnership for energy-efficient technologies (3 projects)	Low-emission retrofitting; mandates replacing smaller blast furnaces with larger units	Highly efficient technologies: Coke dry quenching (CDQ), top-pressure recovery turbines (TRT), BOF gas recovery, next-gen coke ovens	Optimized coke oven batteries, waste heat recovery	Pulverized coal injection (PCI), BOF gas recovery, high scrap use in EAF	NG-DR, HYBRIT® heat recovery from coke oven & blast furnace
References	(Ministry of Steel, 2024, 2023, 2020)	(Shen, 2024; WSA, 2024)	JISF (2024)	(United States Steel Corporation, 2023; WSA, 2024)	German Steel Association (2022)	(HYBRIT, 2024; Jernkontoret, 2023)

2013) for assessing the costs of emission reductions across various sectors, including agriculture, industry, transport, building, etc. MAC curves are also being utilized in the iron and steel industry to identify and prioritize mitigation measures for reducing greenhouse gas emissions(Gu et al., 2023; Johnsson et al., 2020; Wu et al., 2016; Zhang et al., 2018b). While MACC has been designed for the entire Indian iron and steel sector, it could not capture the complexities of costs and emission reduction potential of process-wise mitigation measures in the BF-BOF route of IISI.

1.1. Objectives

Concerning this, the proposed study aims to comprehensively evaluate material and energy flow and carbon emissions at a process level, along with consideration of the fugitive losses for the Indian iron and steel industry based on the BF-BOF route. The second objective is to develop a marginal abatement cost curve tailored for BF-BOF route for proposing cost-effective mitigation strategies for the decarbonization of IISI by 2050.

2. Material and methodology

2.1. Case study

The present study focuses on the BF-BOF route integrated iron and steel industry located in India, referred to as ISI-A. ISI-A has an installed capacity of 4.36 million tons of crude steel production. With a capacity utilization of 87.87% during the period of investigation, it produced 3.83 million tons of crude steel. The production process includes a coke oven plant, sintering plant, blast furnace (BF), steel melting and casting plant which includes a basic oxygen furnace (BOF) and casting plant. The enterprise also has its own oxygen and calcining plants. The mill section of ISI-A encompasses three distinct facilities: a slabbing mill, a hot strip mill, and a cold rolling mill. Power requirements are supplied through grid imports. ISI-A's specific energy consumption is 6.5 Gcal/tcs, aligns with the range observed in other integrated iron and steel plants in India (as shown in Table S6 of the supplementary index). The comparison includes a total of eight plants with a combined capacity of 39.1 million tons of crude steel production (out of 54.28 million tons produced via the BF-BOF route in India). This indicate that ISI-A is a suitable case study for studying emissions in BF-BOF production route in India, as its performance reflects those of typical large-scale BF-BOF operations in the country. The three distinct system boundaries were delineated for ISI-A (Fig. 2), which encompasses the entire production process of the iron and steel industry, which is discussed in section 1 of the supplementary index (SI). Material and energy flow and respective carbon emissions for ISI-A are calculated via the following steps. Some of the assumptions in creating material and energy flow and respective carbon emissions for ISI-A are as follows.

1. The emission factor for self-produced products like oxygen and nitrogen is considered based on the emission generated by the oxygen plant for every cubic meter of the respective product produced.
2. Carbon emission credits for unsold inventory of by-products, such as coal chemicals, are excluded from the CO_2 emissions calculations, whereas CO_2 emission credits for sold by-products are included in the enterprise's total CO_2 emission calculations.
3. Internal consumption of by-product gases like COG and BFG is subtracted from the total emission of the plant.
4. Indirect emissions for electricity consumption are calculated using the Indian grid emission factor, provided by Central Electricity Authority, India (CEA, 2022).

2.2. Material and energy flow intensity

Material and energy flow (MEFA) intensity for each process of the iron and steel industry was calculated, as per the methodology prescribed by (Sun et al., 2020a, 2020b; Zhang et al., 2022). Material intensity refers to the total material consumption per ton of the product, which can be expressed as:

$$M = \vdots \begin{bmatrix} M1 \\ M2 \\ \vdots \\ Mx \end{bmatrix} = \begin{bmatrix} M11 & \cdots & M1n \\ \vdots & \ddots & \vdots \\ Mx1 & \cdots & Mxn \end{bmatrix} \tag{1}$$

Where M is being measured as the physical quantity and indicates a matrix representing the material flow, x indicates the material flow index, including iron-ores, coal, coke, and dolomite, n refers to the plant index, which includes various processes such as coking, sintering, pelletizing, ironmaking, steelmaking, hot rolling, etc. M_i is the row vector representing the input of material flow i in each plant and M_{ik} Depicts the input of material flow i for plant k. Based on this, the material flow of the entire plant is calculated and is expressed as follows:

$$M_k = \sum_{i=1}^{x} m_{ik} \tag{2}$$

Similarly, the energy flow intensity for the current plant is calculated representing the total energy consumption per unit of product. It is calculated as follows:

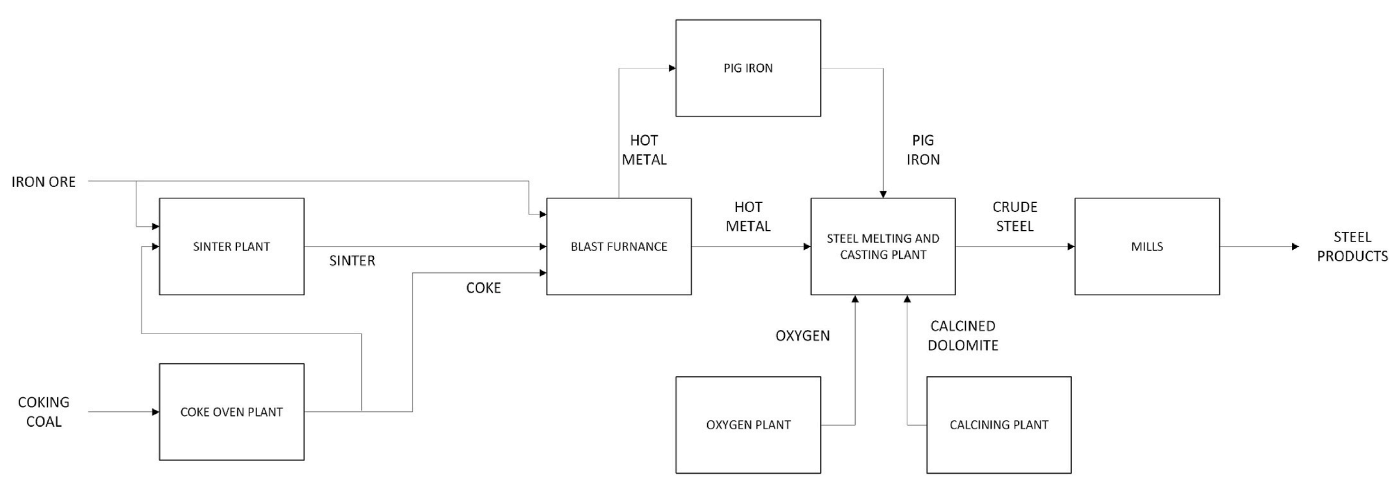

Fig. 1. Single line flow diagram of BF-BOF steel production route.

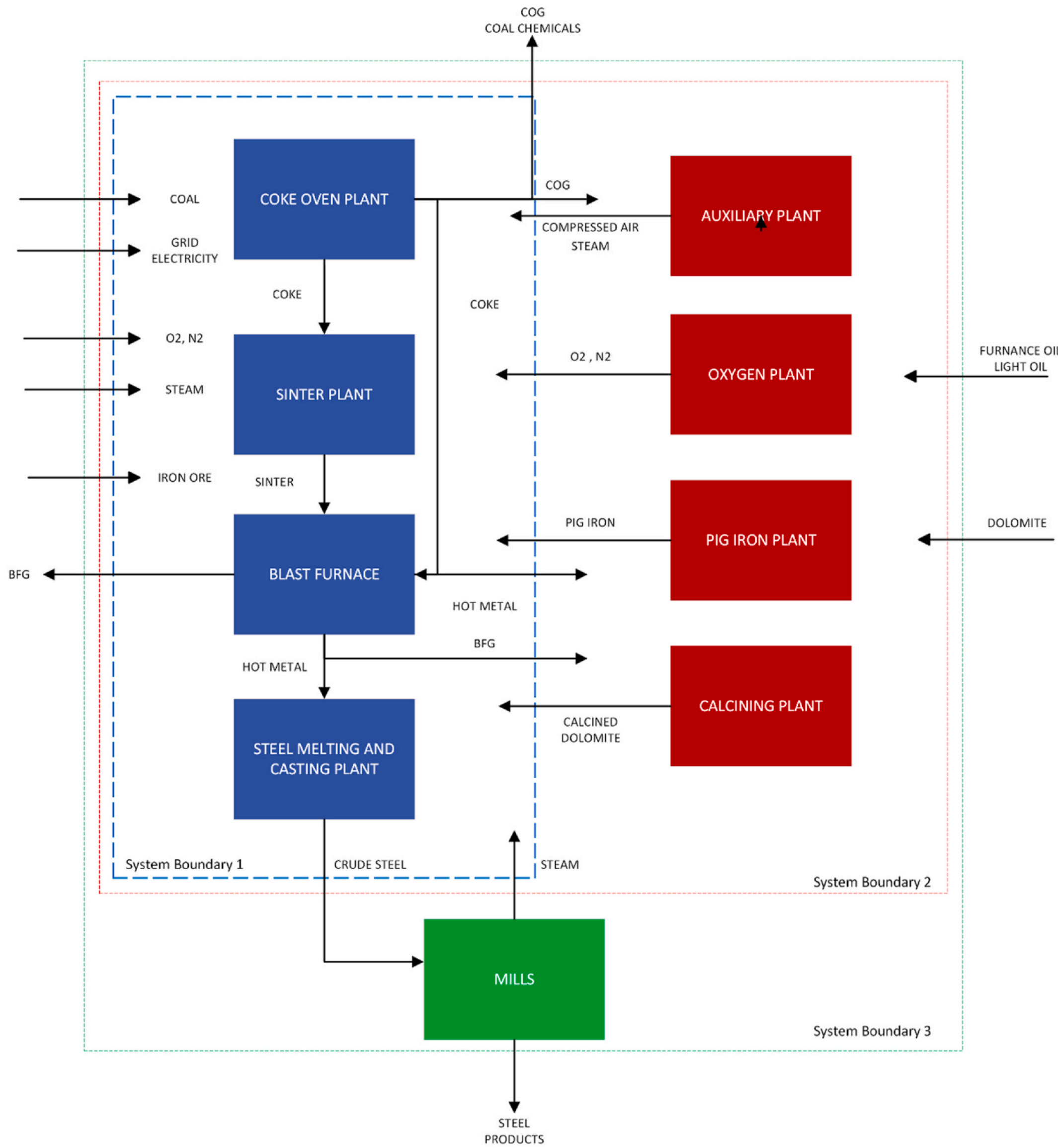

Fig. 2. System boundary diagram for ISI-A.

Table 2
List of best available technologies (BAT) suitable for Indian BF-BOF steel route production.

Process	Technology
Coking	Coke dry quenching (CDQ)
	Coal moisture control (CMC)
Sinter	Heat recovery from sintering and sinter cooler
Blast Furnace	Pulverized coal injection
	Top-pressure recovery turbines (TRT)
	Recovery of BF gas
	Preheating of fuel and air for hot blast stove
BOF	Recovery of BOF gas and sensible heat
	Flue gas waste heat recovery
Casting	Continuous casting
Hot rolling	Recuperative or regenerative burner
	Process control in hot strip mill
	Waste heat recovery from cooling water
Cold Rolling	Heat recovery on the annealing line
	Automated monitoring and targeting systems

$$E = \vdots \begin{bmatrix} E1 \\ E2 \\ \vdots \\ Ea \end{bmatrix} = \begin{bmatrix} E11 & \cdots & E1n \\ \vdots & \ddots & \vdots \\ Ea1 & \cdots & Ean \end{bmatrix} \quad (3)$$

Here, E is a physical quantity and represents the energy flow matrix. a represents the energy flow index, which includes blast furnace gas (BFG), coke oven gas (COG), furnace oil, electricity, steam, oxygen, nitrogen, etc. E_i represents the row vector of energy flow i consumed in all plants and E_{ij} Represents the energy flow i consumed in plant j. MEFA was further used to calculate the carbon emission of all processes of ISI-A.

2.3. CO_2 calculation

Further, the carbon balance approach is used to calculate the carbon emissions of each process, quantifying the carbon content of input materials and fuels, and the carbon content of products and by-products generated during production (WSA, 2022). The methodology to calculate process-wise carbon emission of ISI-A is adopted from Zhang et al. (2022), which is mentioned as follows:

$$C = O \circ EF \quad (4)$$

Where C represents the matrix of carbon emission in the form of CO_2 from each process of the plant. O represents the matrix for the difference in input and output of material and energy flow and EF is a conversion coefficient matrix i.e., CO_2 emissions per unit of material and energy flow, which is listed in Table S1. $\circ$ is a Hadamard product, which is an element-wise multiplication of two vectors/matrix to form a new vector/matrix.

For instance, CO_2 emissions for the coke oven process were calculated based on the difference between the material and energy inflows (COG, BFG, electricity, etc.) and material and energy outflows (coke, COG, and coal chemicals). Similarly, it was performed for other processes such as sintering, blast furnaces, steel melting and casting plants, etc. Based on this, the CO_2 emissions were categorized into three distinct components: direct emissions (fuel), indirect emissions (electricity consumption), and emission credits (ISO 14404, 2013). Credit emission relates to exported material and energy from the plant to other units outside the plant.

Using the above equations and MEFA, carbon-element flow analysis is carried out for ISI-A. Following analysing the carbon emissions of ISI-A, the process-wise CO_2 intensity i.e., CO_2 emissions per ton of product produced is calculated using the following equation:

$$\boldsymbol{CO_2\ intensity\ of\ a\ process}\left(\frac{\boldsymbol{ton\ CO_2}}{\boldsymbol{ton-product}}\right)=\frac{\boldsymbol{CO_2\ emision\ of\ the\ process}}{\boldsymbol{Production\ of\ the\ process}} \quad (5)$$

Process where multiple outputs are produced, CO_2 emission is calculated based on the primary product of the process. For instance, the CO_2 intensity of the coke oven plant is calculated by dividing the total CO_2 emission from the coke oven plant by the total coke produced. The next step includes specific CO_2 emission of a process i.e., CO_2 emission per ton of crude steel, which was calculated using equation (6):

$$\boldsymbol{Specific\ CO_2\ emission\ of\ a\ process}\left(\frac{\boldsymbol{tCO_2}}{\boldsymbol{tcs}}\right)=\boldsymbol{CO_2\ intensity\ of\ a\ process}\left(\frac{\boldsymbol{tCO_2}}{\boldsymbol{ton-product}}\right)\times\boldsymbol{Production\ ratio}\left(\frac{\boldsymbol{ton-product}}{\boldsymbol{tcs}}\right) \quad (6)$$

Here production ratio is the proportion of a process's output that goes into making the final product. For instance, if a process has a high production ratio, it means that a lot of its output is used in making the final product, while a low production ratio indicates that only a small portion of its output contributes to the final product. The production ratio is calculated using the given equation.

$$\boldsymbol{P_k}=\sum_{i}^{N_k}\left(\boldsymbol{P_{k+i}}\times\frac{\boldsymbol{O_{k,k+i}}}{\boldsymbol{T_{k+i}}}\right) \quad (7)$$

Where P_k is the production ratio of process k , $O_{(k,k+i)}$ is the output of process k used in process $k+i$, N_k is the number of processes connected to process k, P_{k+i} is the production ratio of the process i that is connected ahead of process k, and $T_{(k+i)}$ is the total production of process $k+\ i$. The production ratio for the final process, denoted as P_{final}, is equal to one.

Finally, the specific CO_2 emission within each system boundary is calculated, using the following equation:

$$\boldsymbol{Specific\ CO_2\ emission\ within\ system\ boundory}\left(\frac{\boldsymbol{tCO_2}}{\boldsymbol{tcs}}\right)=\sum_{i=1}^{n}\boldsymbol{Specific\ CO_2\ emission\ of\ process\ i} \quad (8)$$

where n is the number of processes within the system boundary.

2.4. Constructing a marginal abatement cost (MAC) curve

Constructing a MAC curve first requires the selection of mitigation measures, followed by assessing the cost of implementing these measures in the plant vs. the CO_2 abatement benefit provided by them (Ibrahim and Kennedy, 2016). It is calculated as follows.

Step 1: Selection of mitigation technologies

Constructing a MACC for the iron and steel industries in India requires the selection of mitigation technologies suitable for the Indian subcontinent. The Ministry of Steel has proposed the best available technologies (BAT) tailored to the Indian context (Ministry of Steel, 2015). Table 2 lists the process-wise BAT, supplemented with additional technologies. The additional technologies considered during the current study are already being implemented in other countries such as China and Japan (Elango et al., 2023; Wu et al., 2016; Zhang et al., 2018b). Secondly, these technologies are also considered suitable for the Indian iron and steel sector by the Japan Iron and Steel Federation (JISF, 2023).

Step 2: Net present value (NPV)

The net present value is calculated using capital cost and the sum of the net benefits over the technology's lifetime, each discounted to their present value using a discount factor (10%), where net benefit includes the net savings from annual O&M change and energy saving benefit (Ibrahim and Kennedy, 2016). Table S4 lists the investment cost, annual O&M cost change, energy-saving benefit, lifetime, and CO_2 abatement of the above-mentioned mitigation measures/technologies. It is calculated as follows:

$$\boldsymbol{NPV}=\boldsymbol{CI}+\sum_{t=0}^{L}(\boldsymbol{O\&M}-\boldsymbol{EB})\times\frac{(\boldsymbol{1}+\boldsymbol{i})^{t}-\boldsymbol{1}}{\boldsymbol{i}\times(\boldsymbol{1}+\boldsymbol{i})^{t}} \quad (9)$$

Where NPV represents the net present value expressed in $/tonne; CI denotes the capital investment cost expressed in $/tonne for the mitigation measure; O&M indicates the annual operation and maintenance (O&M) cost change expressed in $/tonne for the mitigation measure relative to existing BF-BOF technology; EB refers to the annual energy savings benefit (due to fuel savings) expressed in $/tonne for the mitigation measure compared to existing BF-BOF technology; L is the lifetime of the technology in years; and i is the discount rate.

Step-3: Cost-effectiveness of mitigation measures

The following equation is used to calculate the cost-effectiveness of the mitigation measure:

$$Cost\ effectiveness\ of\ technology\left(\frac{\$}{kgCO_2}\right) = \frac{Net\ Present\ Value\ \left(\frac{\$}{tonne}\right)}{CO_2\ abatement\ \left(\frac{kgCO_2}{tonne}\right)} \tag{10}$$

Assumptions: In constructing the MACC for this study, the following assumptions are made. i) The baseline emissions are based on CO_2 emissions from the BF-BOF route for Indian industry. ii) Annual changes in O&M and fuel costs are measured relative to the BF-BOF process. iii) Cost data and technology lifetimes are derived from existing literature, by considering 2015 as baseline year (He and Wang, 2017; Talaei et al., 2020; Wu et al., 2016; Zhang et al., 2018b). iv) The analysis only considers financial savings from reduced fuel or energy consumption, excluding other co-benefits such as improved air quality or health benefits. v) A discount rate of 10% is used for the analysis, based on the previous studies (Kuramochi, 2016; Wu et al., 2016).vi) Discount rates of 5%, 8%, 15%, 20%, and 30% is used for sensitivity analysis.

The discount rate for assessing the economic viability of mitigation technologies in iron and steel industry varies significantly in the studies so far. Higher discount rates (10%–30%) are preferred for shorter payback period and to account for barriers to CO_2 emissions reduction technologies (Brunke and Blesl, 2014; A Hasanbeigi et al., 2010a,b; Rodrigues da Silva et al., 2018). While lower discount rates (4%–10%) are preferred to account for long term benefits and sustainability (Long et al., 2020). 10% is the widely used discount rate by research studies in the iron and steel industry as it reflects a balanced perspective between higher and lower discount rates (Kuramochi, 2016; Wu et al., 2016). Additionally, we have also analysed the change in mitigation cost by considering different discount rates (5%, 8%, 15%, 20%, and 30%), which helped in providing the holistic perspective of change in emission abatement cost of mitigation technologies. It will help in selecting the most suitable discount rate, that can be considered by the policymakers and industry stakeholders for designing decarbonization strategies for IISI.

3. Results and discussions

3.1. Material and energy flow analysis

Fig. 3 represents the material and energy flow (MEFA) for the entire ISI-A, including all the processes with their respective input-output. The thickness of the flow line denotes the amount, whereas the arrowhead and tail denote the direction of the material and energy flow. Here, material flow refers to the input and output of each process within the steel plant. For instance, material flow for a coke oven plant includes coking coal as material input, blast furnace gas (BFG) and coke oven gas (COG) as by-product gas input, steam, and electricity as energy output while coke, COG, and coal chemicals as output. Similarly, material flow for sintering plants includes iron ore, coke, and return sinter as material input, COG and BFG as by-product gas inputs, and electricity as energy input while sintering as material output.

Fig. 3 shows that blast furnace process involves high material and energy flow with 0.26 million tons of non-coking coal, 2.28 million tons of coke, 2.52 million tons of iron ore, 3.9 million tons of sinter, 28,308 thousand cubic meter of COG and 2,914,843 thousand cubic meters of BFG, 103.34 GWh electricity, 201192 thousand cubic meter of nitrogen and 192,565 thousand cubic meters of oxygen are used as input to produce 4.25 million tons of hot metal and 7,428,352 thousand cubic meters of BFG as output. After the blast furnace, the second highest

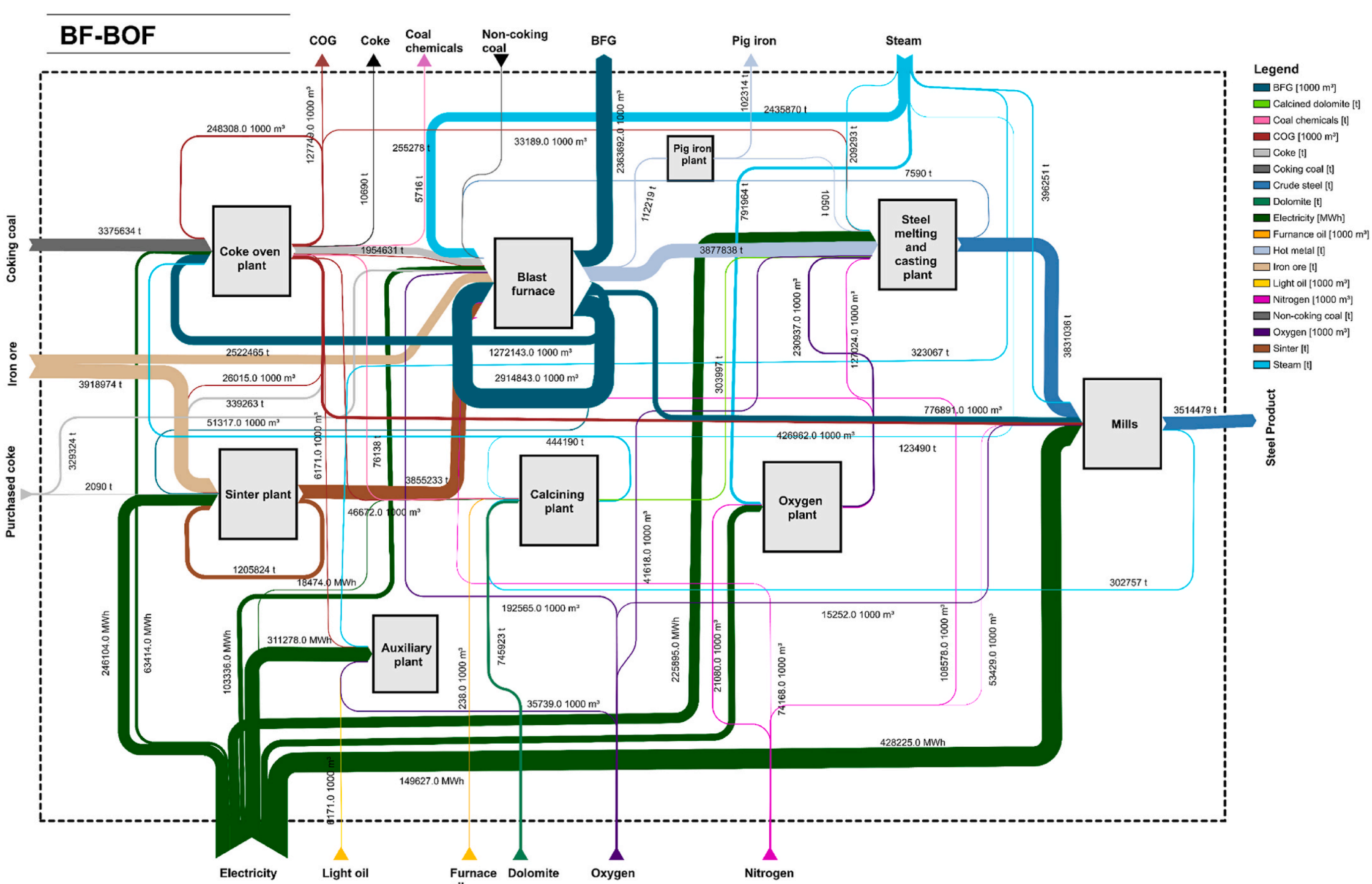

Fig. 3. Material and energy flow diagram for ISI-A.

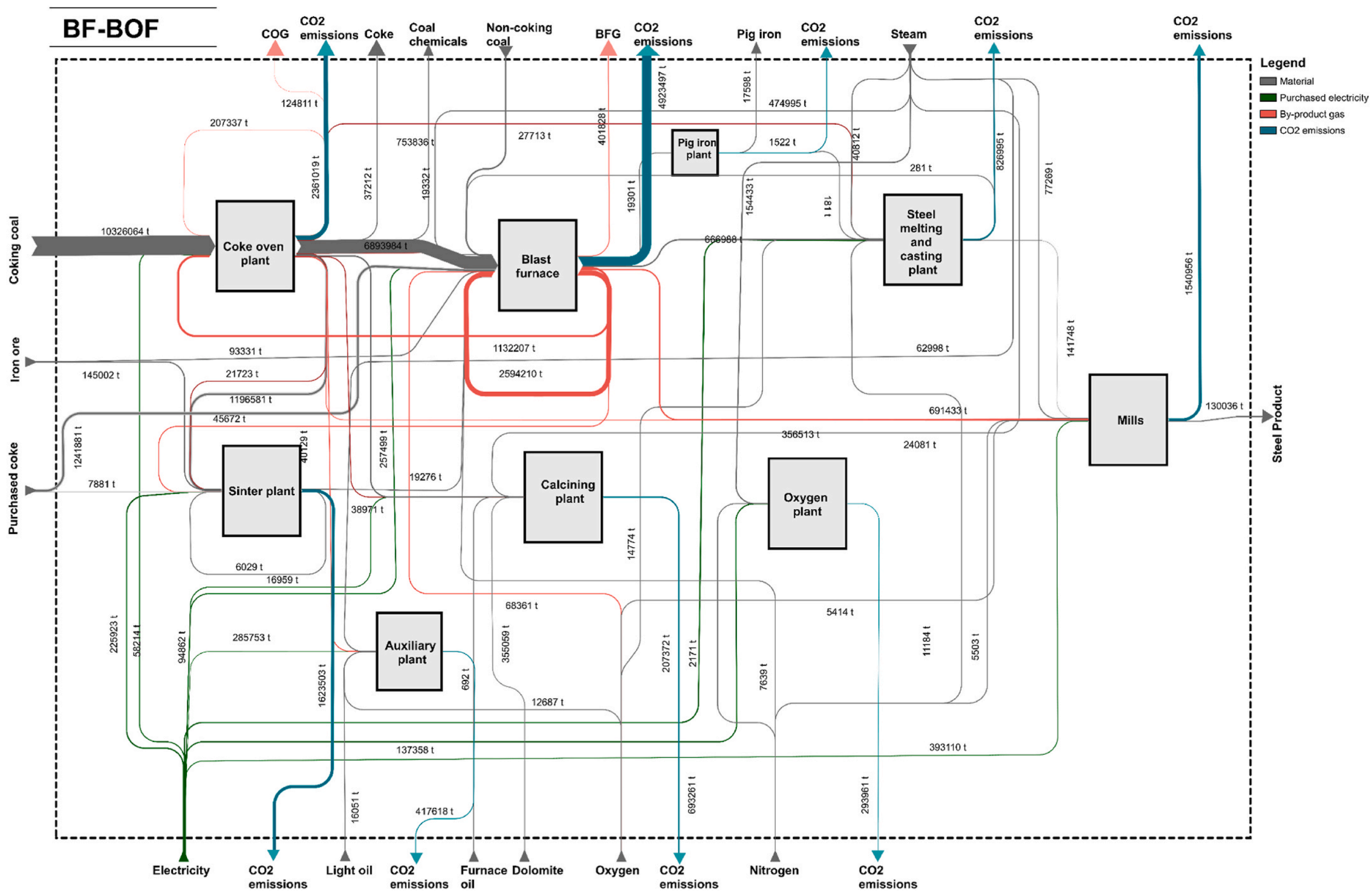

Fig. 4. Carbon-element flow diagram for ISI-A.

Table 3
Comparison with existing study for BF-BOF route.

References	Scope or Boundary	Location	Specific CO_2 emission
Zhang et al. (2018)	BF-BOF process, including coking, sintering, pelletizing, blast furnace ironmaking, basic oxygen furnace steelmaking, hot rolling, and cold rolling plant	China	2.497 tCO_2/tcs
Zhang et al. (2022)	BF-BOF process, including coking, sintering, pelletizing, blast furnace ironmaking, basic oxygen furnace steelmaking, hot rolling, and cold rolling plant	China	2.067 tCO_2/tcs
Song et al. (2023)	hybrid route composed of BF-BOF route and Scrap-EF route, including raw material acquisition, steel processing and production, transportation, and disposal stages	China	2.33 tCO_2/tsp
Na et al. (2024)	BF-BOF, including resource extraction stage, transportation stage, and manufacturing & processing stage of product.	China	2.59 tCO_2/tsp
Tian et al. (2022)	BF-BOF, including sintering, pelletizing, BF, BOF, rolling, lime, OPP, oxygen making and others	China	3.39 tCO_2/tcs
This study	BF-BOF process, including coking, sintering, blast furnace ironmaking, basic oxygen furnace steelmaking, pig iron plant, oxygen plant, calcining plant, auxiliary plant, slabbing mill, hot rolling, and cold rolling plant	India	**3.31 tCO_2/tcs**

material and energy flow is associated with the coke oven plant as evident from Fig. 3. Although ISI-A includes its oxygen plant, it also relies on imports for oxygen and nitrogen to fulfil its requirements. Steam generation occurs through waste heat recovery from calcining units and mills, with additional steam sourced externally. The annual consumption of coke amounts to 2.29 million tons, of which 85.15% is produced within the enterprise premises while the rest is imported externally. As far as fossil fuels are concerned, it uses coking coal (3.38 million tons) to produce coke in the coke oven plant while non-coking coal (0.26 million tons) is used in the blast furnace. Light oil (6171 kl) and furnace oil (238 kl) are also utilized within the enterprise, although in lesser quantities compared to coal. Apart from steel products, it also exports BFG (2,363,692 thousand cubic meters), COG (127,749 thousand cubic meters), some amount of pig iron (0.10 million tons), coke (10,690 tons), and coal chemicals (5716 tons) to other industries.

3.2. CO_2 emission of ISI-A

MEFA provides a clear picture of all material and energy inputs and outputs for each process, which was used to compute the CO_2 emissions of each process in ISI-A, as shown in Fig. 4. The total emissions from ISI-A amount to 12.68 million tons of CO_2 to produce 3.83 million tons of crude steel, which is equivalent to 3.31 tCO_2/tcs. Table 3 shows the comparison of CO_2 emissions per ton of crude steel production for the BF-BOF route during the current study (ISI-A) with other studies in the literature (Na et al., 2024; Song et al., 2023; Tian et al., 2022; Zhang et al., 2018a, 2022). This shows that ISI-A's emissions are relatively high compared to the average specific CO_2 emissions from previous studies, which is 2.57 tCO_2/tcs. Thereby, in order to understand the reasons for high carbon emissions for ISI-A, the assessment focused on process-wise

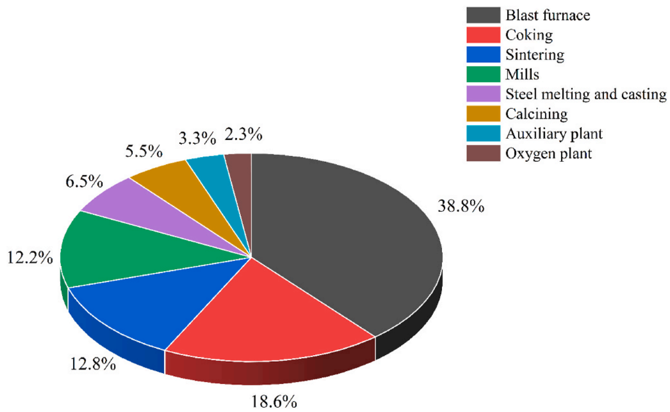

Fig. 5. Percentage of CO_2 emission of each process in ISI-A.

CO_2 emission.

3.2.1. Process-wise CO_2 emissions analysis

Examining the emissions from each process of the industry will help in better designing and developing the mitigation plan by identifying the priority areas for decarbonization for decarbonization. The blast furnace process appears as the biggest CO_2 emitter, as shown from the width of the CO_2 emission arrow in Fig. 4. Fig. 4 shows that coking coal and purchased coke are the primary sources of carbon input in the plant, contributing significantly to its carbon footprint. Blast furnace contributes to 38.3% of total CO_2 emissions while coking and sintering plants contribute 18.6% and 12.8% of total CO_2 emissions respectively. Fig. 5 shows the percentage of CO_2 emissions for each process within ISI-A, while the process-wise total CO_2 emissions are listed in Table S2. 76.74 % of total emission happens in system boundary 1 which includes coking, sintering, blast furnace operations, and steel melting and casting. It is also important to understand the process-wise emissions in terms of CO_2 per ton of crude steel (Fig. S1) and CO_2 emissions per ton of product (Fig. S2), which will provide us with the base of comparison with respect to other plants and industries based on BF-BOF. The processes and their respective emissions are mentioned in detail as follows.

3.2.2. Blast furnace process

In India, the blast furnace route accounts for a substantial portion of steel production, comprising approximately 68% of the total output (Ministry of Steel, 2023). Out of 3.31 tCO_2/tcs, the biggest share of specific CO_2 emissions comes from the blast furnace with 1.172 tCO_2/tcs (shown in Fig. S1), along with higher CO_2 intensity, equivalent to 1.158 tCO_2/t-product (shown in Fig. S2). It highlights the significant environmental impact of the blast furnace process, which is mainly attributed to the combustion of coal and coke in the presence of hot air to provide heat and generate carbon dioxide and hydrogen to reduce iron ore (Johnson et al., 2023). In Indian steel plants, consumption of coke is 30–35% higher, iron ore or sinter by 7–10%, and hot-metal and ferroalloys by 5–7%, compared to other developed countries, resulting in lower productivity of blast furnaces (Samajdar, 2012). In addition to that, Indian iron is characterized by having high iron content along with a high amount of alumina reaching as high as 10%–15% (Rachappa and Prakash, 2015). The high levels of alumina and silica present significant operational hurdles during both the sintering process and the subsequent smelting in blast furnaces. The higher alumina content in iron ore and sinter results in the formation of viscous slag during smelting, which in turn requires a higher coke consumption (Jha et al., 2020; Rachappa and Prakash, 2015). These operational hurdles due to the low quality of raw materials contribute to higher emissions by impacting the efficiency of the blast furnace, resulting in higher costs of steel production in India.

The blast furnace process also results in the generation of molten metal, slag, and flue gases. Flue gases contain coke, coal, iron ore, sinter, fluxes, unburnt carbon, high amount of iron oxide along with a mixture of other oxides, including silicon, calcium, magnesium, zinc, lead, and alkali metals (Birol, 2019; Sarkar and Mazumder, 2015), which are highly undesirable and results in environmental degradation. Since the potential of flue gas is not tapped in ISI-A, it is included in the CO_2 emission, contributing to increased CO_2 emissions. The material in the flue gas needs to be reused and recycled for further use to reduce the emissions. Indian coking coal fulfils only 24% of the coal demand for the blast furnace process as it possesses high ash content and requires extensive washing and crushing. Approximately, 76% of the coking coal is being imported from other countries (Ministry of Coal, 2024) such as Australia, Indonesia, Canada, US, which is being supplied at a very high cost, resulting in an increased financial burden on the Indian iron and steel sector. It forces Indian manufacturers to find better alternatives to the coking coal, which needs to be prioritized for the decarbonization of IISI. Alternative fuels such as natural gas, and hydrogen lead to lesser carbon emissions (Shanmugam et al., 2021), thereby efforts should be made to increase their usage in place of coking coal in blast furnaces.

3.2.3. Coke oven plant

With specific CO_2 emission of 0.537 tCO_2/tcs (shown in Fig. S1) and CO_2 intensity of 1.012 tCO_2/t-product (shown in Fig. S2), the coke oven plant is the second largest CO_2 emitting process in ISI-A. In this process, coking coal is converted into coke which is used in sintering and blast furnaces. With an input of 3.38 million tons of coking coal, it produces 2.33 million tons of coke. Apart from the main product, the by-products of this process include coke oven gas (COG) and coal chemicals which are either utilized in the plant or exported. In coke oven gas, coking coal is heated to around 1100 °C in the absence of air, which helps to remove the volatile components of the coal (IEA, 2020). The coke-to-coal ratio of ISI-A is approximately 68.93%, which is low compared to other industries in China Zhang et al. (2018), where the ratio is around 79.08%, and in Tian et al. (2022), where it is reported as 86.94%. A low coke-to-coal ratio leads to decreased efficiency of coke oven plants and increased environmental impact with higher CO_2 emissions.

Coking coal in India is being sourced from Gondwana belt regions which possess higher mercury and ash content (244.5 μg/kg and 17.2 %, respectively) (Das et al., 2023), leading to a reduction in the efficiency of coke oven gas. Rapid cooling of coke after it leaves the oven is essential to prevent burn-off and maintain high mechanical stability. Energy-saving efforts in coke production focus on reducing heat consumption, improving waste heat recycling, and minimizing electricity, steam, and water usage (He and Wang, 2017).

Due to the constraints posed by the quality of domestically available coal, the Indian steel industry relies heavily on imported coal to meet its requirements. Approximately 76% of the current demand for coking coal is fulfilled by imports from other countries such as Australia, Canada, US (Ministry of Steel, 2023). The significant role of coking coal is a major cost component in steel production, accounting for approximately 42% of the total expenses (Ministry of Steel, 2023). To address both cost and environmental concerns, the Ministry of Steel is implementing measures aimed at reducing reliance on imports and diversifying import sources for coking coal. It will help in the reduction of the expenses and the saved amount can be further allocated towards environmental initiatives and emission reduction strategies. Other details about how sintering, mills, steel melting and casting plants, calcining, and oxygen plants result in higher carbon emissions are mentioned under section 2 of SI.

3.2.4. Fugitive emissions

Fugitive emissions present a significant challenge for steel enterprises and can vary from one facility to another. Fugitive emissions typically result from various sources such as equipment leaks (Ellis, 2005), emissions from the bulk handling or processing of raw materials, and other specific processes (Amodio et al., 2013). In ISI-A, fugitive emissions contribute to a specific CO_2 emission of 0.339 tCO_2/tcs, highlighting the importance of addressing this issue. A significant proportion of BF-grade coke, approximately 14.68%, is lost between processes within the facility, highlighting opportunities for improving process efficiency and minimizing emissions.

Implementing leak detection and repair programs, optimizing processes, and conducting regular maintenance are essential strategies for mitigating fugitive emissions and reducing overall emissions from industrial operations (Amodio et al., 2013; Pilarczyk et al., 2013). Continuous monitoring using smart analytics shows promise in addressing the challenges of tracking fugitive emissions, thus curbing greenhouse gases(Liu et al., 2022). Real-time detection and quantification of fugitive emissions allow for prompt corrective actions to be taken to reduce emissions leaks and spills. Smart analytics can identify patterns and trends, enabling preventive measures to be implemented for future events. While, implementing continuous monitoring systems with intelligent analytics requires significant upfront investment in technology, infrastructure, and training. On the other hand, addressing fugitive emissions can yield long-term benefits, including cost savings, regulatory compliance, and improved efficiency.

3.3. Direct-indirect emissions analysis

Indirect emissions are mainly from the grid electricity used in the steel-making process, while direct emissions result from the utilization of coal and coke within the enterprise. Indirect emissions from electricity, steam, nitrogen, and oxygen are also considered. In simpler terms, it means that not only the direct carbon sources like coking coal and purchased coke are included, but also the emissions from generating the material and energy that are imported and used in the plant are taken into consideration.

Fig. 6 shows process-wise direct, and indirect emissions along with specific CO_2 emissions. To address the direct emissions, there is a need to transition of solid fuels to cleaner alternatives like biochar derived from agricultural waste (Durango Padilla et al., 2024). Substitution of solid fuel by liquid fuel and eventually by gaseous fuel is important to decarbonize the Indian steel industry (Liu et al., 2021; Marocco et al., 2023; Mousa et al., 2016). The electricity used within the premises can be procured from renewable sources to reduce the indirect emissions within the enterprise (Granobles and Saeys, 2020; Otto et al., 2017).

Decarbonization of iron and steel industry can happen via a) fuel substitution (use of biochar, hydrogen), b) CCUS (carbon capture storage and utilization, and c) better energy mix i.e., more use of renewable energy in the entire production process(Johnson et al., 2023; Li and Zhu, 2014). Of these, the first two strategies are still in the nascent stage, specifically in India. Therefore, to assess the impact on overall CO_2 emissions of ISI-A, a sensitivity analysis is carried out by considering changes in energy consumption patterns (applying different grid emission factors) of steel industry under various scenarios, while keeping all other parameters constant. The grid emission factors are taken for three scenarios- Constrained Renewable Energy Scenario (CRES), Unconstrained Renewable Energy Scenario (URES) and No-Fossil Fuel Scenario (NFS) as suggested by TERI (Rodrigues et al., 2023). In CRES, renewable energy capacity is limited to 748 GW of solar PV and 695 GW of wind potential as estimated by the National Institute of Solar Energy (NISE) and National Institute of Wind Energy (NIWE), respectively. The URES allows for greater renewable energy expansion to achieve the least-cost scenario. The NFS assumes no new coal or gas capacity will be added beyond 2025. The focus on grid emission factors is essential as ISI-A uses 103.34 GWh of electricity annually and the carbon intensity of electricity directly influences overall emissions. Fig. 7 shows the variation in specific CO_2 emissions (tCO_2/tcs) under these three scenarios from 2020 to 2050.

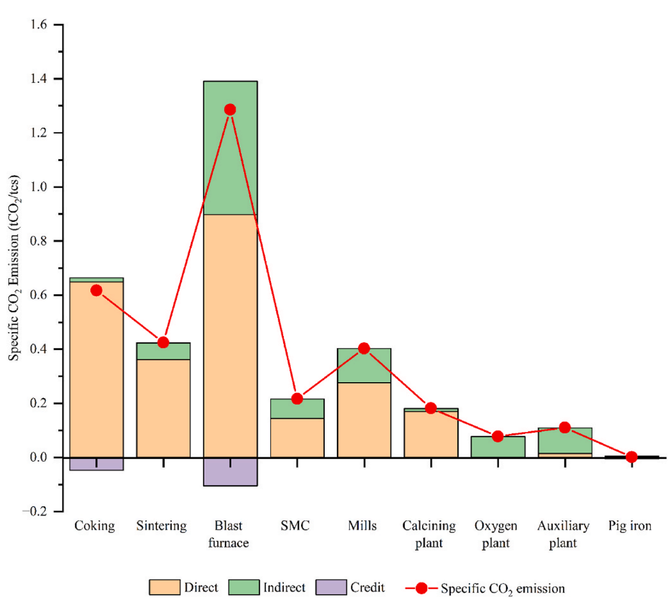

Fig. 6. Process-wise direct-indirect emissions for ISI-A.

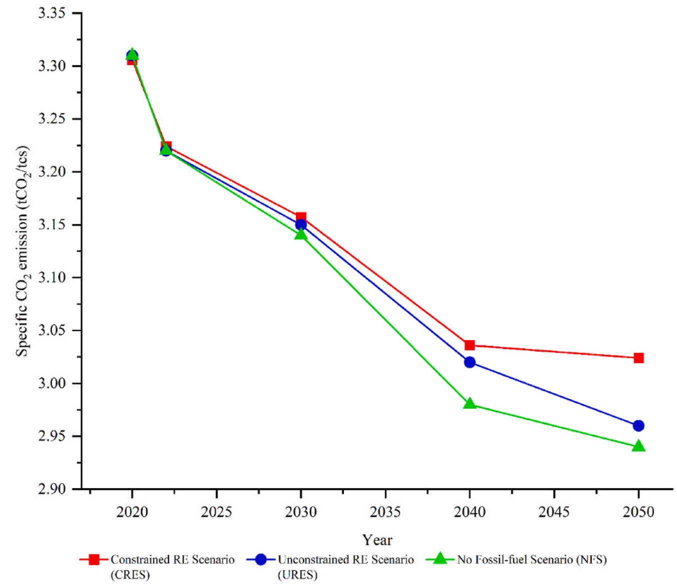

Fig. 7. Specific CO_2 emission variation under different scenarios.

As seen from Fig. 7, specific CO_2 emissions for ISI-A decrease across all scenarios over time, indicating improvement needed in power sector decarbonization. In the CRES scenario, where renewable energy penetration is limited, CO_2 emissions decline more gradually, from 3.31 tCO_2/tcs in 2020 to 3.02 tCO_2/tcs by 2050. The URES scenario, with fewer constraints on renewable energy, shows a slightly faster reduction, reaching 2.96 tCO_2/tcs by 2050. The most significant reduction is observed in the NFS scenario, where CO_2 emissions fall to 2.94 tCO_2/tcs by 2050 due to the complete phase-out of fossil fuels. It highlights the critical role of grid decarbonization in reducing the overall emissions from the steel industry. Transitioning towards a more renewable-based grid has the potential to significantly lower the carbon intensity of steel production, especially under scenarios that promote higher renewable energy adoption.

Efforts to improve energy efficiency Feng et al. (2018) and He and Wang (2017) and optimize process operations (Jiang et al., 2013) can also play an important role in reducing both direct and indirect emissions. Enhancing heat recovery systems and adopting best practices in energy management can help minimize energy consumption and reduce emissions intensity across the steelmaking process (Inayat, 2023; Zhang et al., 2013). IISI can take significant steps towards achieving its emission reduction targets by addressing direct and indirect emissions from

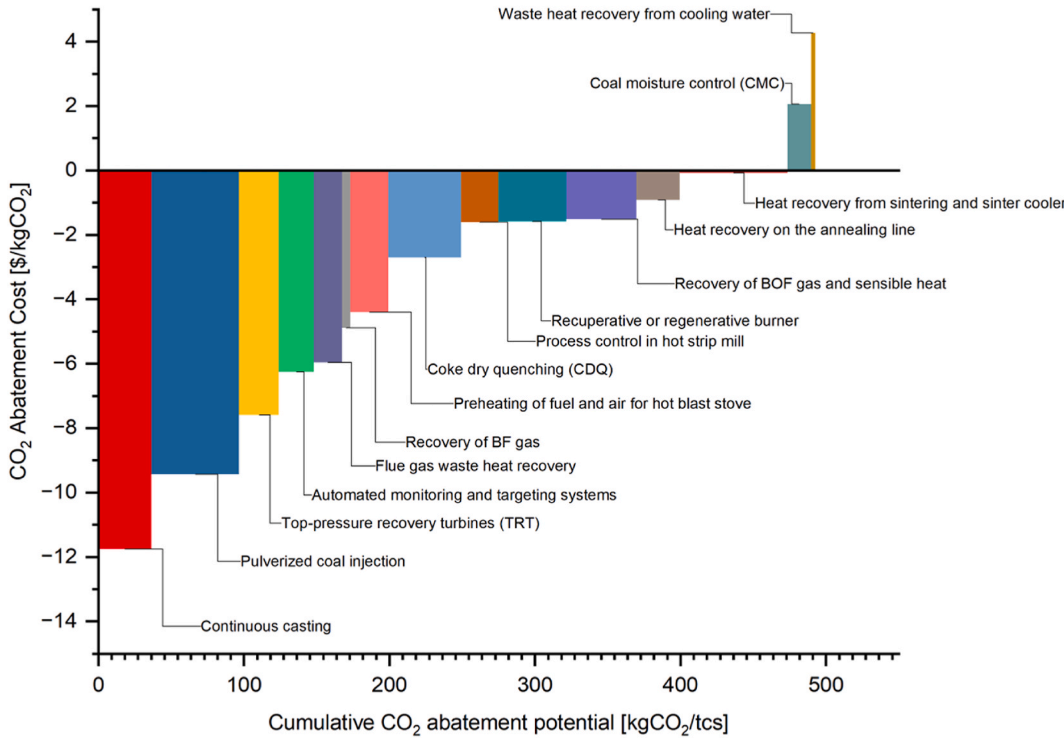

Fig. 8. Marginal abatement cost curve for best available technologies suitable for Indian BF-BOF steel route production.

the processes.

3.4. Marginal abatement cost curve (MACC) for emission reduction solutions

MACC encompasses two axes, with cost-effectiveness, measured in dollars per tonne of CO_2 ($/t$CO_2$) represented on the y-axis, and abatement potential, measured in metric tons of CO_2 per tonne of crude steel (tCO_2/tcs) represented on the x-axis (Fig. 8). The area of the bar on the MAC curve represents the total marginal investment cost required to achieve the CO_2 abatement potential associated with that particular mitigation measure. Negative abatement costs represent the opportunities to reduce carbon emissions with net economic gain. The lowest abatement cost corresponds to opportunities to avoid emissions at the least cost.

The analysis reveals significant variations in the cost-effectiveness of different technological solutions. With a discount rate of 10%, out of 15 mitigation measures, 13 mitigation measures had CO_2 abatement costs below zero (NPV and CO_2 abatement costs are tabulated in Table S5). While some technologies, such as continuous casting and pulverized coal injection, offer net savings benefits, others like coal moisture control and waste heat recovery from cooling water exhibit higher costs, indicating that the costs outweigh the benefits.

3.4.1. Technologies offering net savings benefits

Continuous casting which is used in steel melting casting plant has a negative CO_2 abatement cost of -$11.75/kg$CO_2$, representing net savings over its lifetime, as shown in Fig. 8. With significant energy savings and a CO_2 reduction of 36.5 kgCO_2/tcs, this technology should be encouraged for rapid equipment upgrades. It directly solidifies molten steel into semi-finished forms eliminating the need for reheating ingots, reducing heat loss, and minimizing scrap generation compared to traditional casting methods (Camisani et al., 2003). It allows for better control of the casting process, optimizing energy usage and improving overall efficiency(He and Wang, 2017). Continuous casting is widely adopted worldwide, accounting for 96.8% of crude steel output in 2022 (WSA, 2023).

With a CO_2 abatement potential of 60.41 kgCO_2/tcs and a CO_2 abatement cost of -$9.43/kg$CO_2$, pulverized coal injection (PCI) is the second favourable mitigation measure as shown in Fig, 8. Pulverized coal injection (PCI) allows for the injection of finely ground coal directly into the blast furnace, reducing the need for coke (Ren et al., 2013). Producing coke is an energy-intensive process that emits a significant amount of CO_2 (0.537 tCO_2/tcs). PCI can substitute for 40–50% of the coke needed in a blast furnace (Sahu et al., 2014). Over 60% of blast furnaces globally utilize PCI (Schott, 2016).

The top-pressure recovery turbines (TRT) utilize controlled expansion to convert the pressure energy of blast furnace top gas into low clean-gas pressure, allowing for the generation of electrical energy without extra input or CO_2 emissions (Johansson and Söderström, 2011). TRTs can generate around 40 to 60 kWh of electricity per tonne of crude steel (Charles and Cang, 2010). TRT, with a CO_2 abatement cost of -$7.59/kg$CO_2$ and an abatement potential of 27.3 kgCO_2/t, is widely adopted by the steel industry and installed in all blast furnaces in Japan and South Korea (Charles and Cang, 2010).

Automated monitoring and targeting systems are promising measures for enhancing energy efficiency due to their cost-effectiveness and non-intrusive nature (Tapoglou et al., 2015). It has a CO_2 abatement cost of -$6.26/kg$CO_2$. The Government of India initiated SAMARTH Udyog Bharat 4.0, an Industry 4.0 program aimed at enhancing competitiveness in the Indian capital goods sector (GOI, 2014). This initiative should be extended to the steel industry for CO_2 abatement, as automated monitoring and targeting systems have the potential to reduce CO_2 emissions by 24.04 kgCO_2/tcs which will encourage enterprises like ISI-A for data-driven energy management.

Flue gas waste heat recovery, along with the recovery of BOF gas and sensible heat together, provides a CO_2 abatement of 67.43 kgCO_2/tcs with a CO_2 abatement cost of -$7.49 per kg$CO_2$. Harnessing waste heat can enhance system efficiency, decrease fuel usage, and diminish CO_2 emissions (Inayat, 2023). Waste heat energy from the iron and steel industry can serve three primary functions: heating, cooling, and direct power generation(Inayat, 2023; Jouhara et al., 2017; Zhang et al., 2013).

The recovery of BF gas and the preheating of fuel and air for the hot blast stove are moderately adopted mitigation measures for the blast furnace process in the iron and steel industry. Together, they provide a CO_2 abatement of 31.87 $kgCO_2$/tcs with a CO_2 abatement cost of -$9.29 per $kgCO_2$. Raising the blast temperature by 100 °C can conserve 15–29 kg of cake per ton of crude iron(Zhang et al., 2012) and improve the efficiency of the entire blast furnace process(Zetterholm et al., 2017). Carbon monoxide recovered from BF gas via the vacuum pressure swing adsorption process can be utilized in the synthesis of value-added chemical products (Oh et al., 2022) which can provide additional revenue streams.

Utilizing techniques like recuperative or regenerative burners, implementing process control in hot strip mills, and maximizing heat recovery on the annealing line are among the strategies available for mitigating emissions in hot and cold rolling mills. Collectively, they deliver a significant reduction of 102.17 $kgCO_2$/tcs with a CO_2 abatement cost of -$4.92 per $kgCO_2$. When regenerative burners are paired with a recuperator system, they consume around 43% less energy compared to conventional recuperative systems (Manatura and Tangtrakul, 2010). While 19% of the heat required for heating steel coils can be reclaimed through heat recovery on the annealing line, the potential savings on fuel expenses may not sufficiently offset the substantial investment costs(Vander Heyde et al., 2020).

Coke dry quenching (CDQ) and coal moisture control (CMC) are two primary mitigation methods for the coking process. While CDQ displays a negative CO_2 abatement cost (-$2.7 per $kgCO_2$), CMC incurs a positive one ($2.05 per $kgCO_2$). This means CDQ saves money for each ton of CO_2 reduced, while CMC costs money for each ton of CO_2 reduced. CDQ technology prevails in the coke-making industry due to its energy-saving capabilities, pollution reduction, and improvement of coke quality whereas CMC reduces wastewater production and energy consumption, potentially saving 45–60 MJ per ton of blend coal and reducing wastewater by 30–40 kg per ton of coal with a 1% reduction in moisture content(Fang et al., 2019).

Prioritizing technologies with high CO_2 abatement potential heat recovery from sintering (73.83 $kgCO_2$/tcs) and CDQ (50.05 $kgCO_2$/tcs) is important for maximizing emissions reduction benefits and ensuring efficient resource allocation. The Ministry of Steel, along with the New Energy and Industrial Technology Development Organization (NEDO), initiated projects to install mitigation measures such as sinter cooler waste heat recovery, coke dry quenching, and sensible heat recovery from blast furnace hot stove waste gas at various steel sites in India, demonstrating 491.91 million tons of CO_2 reduction per year (NEDO, 2011). By adopting these proven technologies, ISI-A can significantly enhance its environmental performance, reduce operational costs through energy savings, and strengthen its competitive position in both domestic and global markets.

3.4.2. Sensitivity analysis with different discount rates

The discount rate affects the cost-effectiveness of the best available technologies for BF-BOF significantly. To understand how discount rates impact the economic viability of proposed mitigation technologies, different discount rates (5%, 8%, 10%, 15%, 20%, and 30%) were analysed.

As the discount rate increases, the economic benefits of the proposed mitigation technologies decrease notably as shown in Fig. 9. For example, for continuous casting, the net saving decreases from $15.59/$kgCO_2$ at a 5% discount rate to $5.43/$kgCO_2$ at a 30% discount rate. Similarly, pulverized coal injection (PCI) shows a decrease in net savings of $7.91/$kgCO_2$ when discount rate increases from 5% to 30%. Regardless of changes in discount rates, the overall emission reduction potential of mitigation measures remains unchanged.

Technologies with higher net savings tend to exhibit greater fluctuations in their values, such as continuous casting, PCI, and TRT. For example, TRT has net savings of $9.52/$kgCO_2$ at 5%, which decreases to $3.97/$kgCO_2$ at a 30% discount rate. This implies that the cost-effectiveness reduces significantly as the discount rate increases(Long et al., 2020; Wu et al., 2016). On the other hand, technologies with smaller abatement costs are less affected by changes in discount rates, such as heat recovery from sintering and the sinter cooler, where the net saving decreases slightly from $0.10/$kgCO_2$ at 5% to $0.04/$kgCO_2$ at 30% discount rate. Meanwhile, the abatement costs for CMC and waste heat recovery from cooling water also decrease but remain positive,

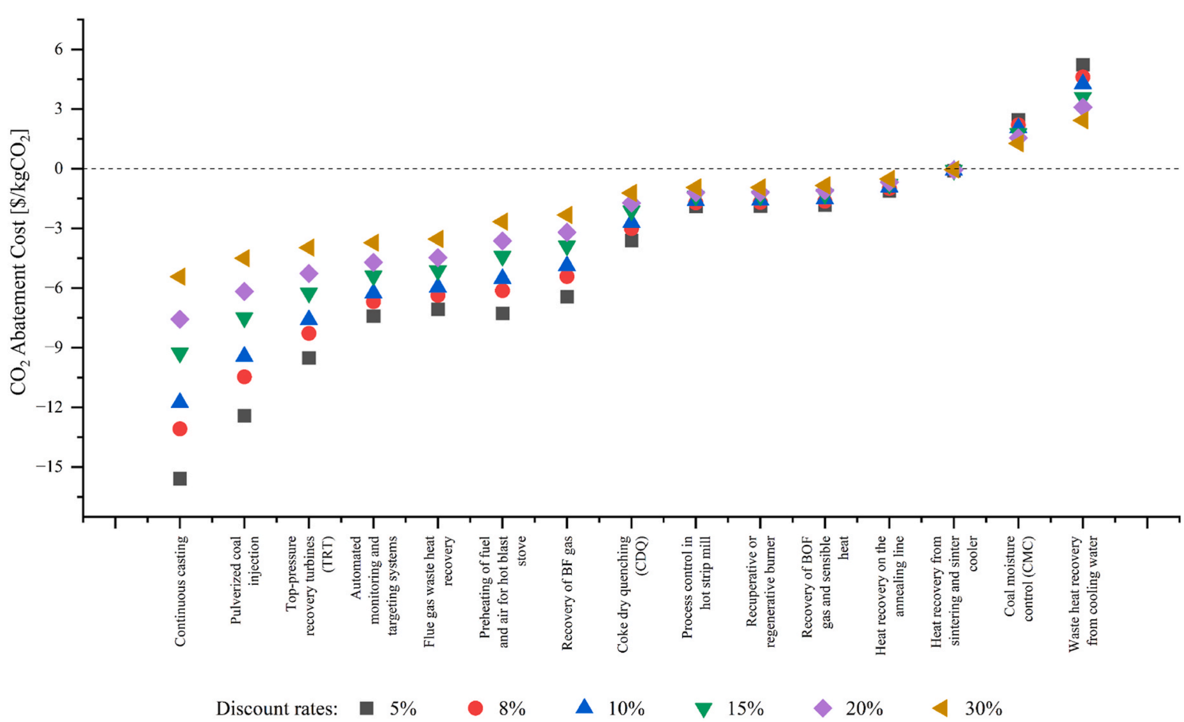

Fig. 9. CO_2 abatement cost at different discount rates.

meaning that implementing these technologies incurs a net cost rather than a net benefit. Even though the discount rates change from 5% to 30%, 13 out of 15 proposed technologies provide net savings over their lifetime, making them preferred decarbonization solutions that remain cost-effective across a range of discount rates. This analysis allows the industry as well as policymakers to make informed choices about which technologies to pursue, evaluating their potential return on investment under various discount rates.

3.4.3. Way forward for ISI-A

The financial viability of technological solutions remains a critical consideration for industry stakeholders. While some technologies offer significant emissions reduction potential, their high upfront costs may pose financial challenges.

Prioritize high-impact, cost-effective technologies: Technologies with the highest CO_2 abatement potential and the lowest CO_2 abatement cost, such as continuous casting, with net savings of $11.75 per kg$CO_2$ and pulverized coal injection with net savings of $9.43 per kg$CO_2$ should be prioritized by ISI-A. These technologies offer significant emissions reductions at a relatively lower cost, making them attractive options for incentivization and adoption. This will help ISI-A perform well under the PAT (Perform, Achieve and Trade) cycles introduced by Bureau of Energy Efficiency (BEE) in 2011 (BEE, 2011). If adopted, these technologies can save up to $997.12 per ton of crude steel over their lifetime, abating 96.76 kgCO_2/tcs emissions.

Invest in long-term sustainable solutions: While short-term solutions like automated monitoring and targeting systems provide moderate emissions reductions (24.04 kgCO_2/tcs), their limited lifetimes (10 years) suggest they are not the most cost-effective long-term investments. Instead, prioritize funding waste heat recovery (e.g., heat recovery from sintering and sinter cooler with CO_2 abatement of 73.83 kgCO_2/tcs) and advanced combustion technologies (e.g., coke dry quenching with CO_2 abatement of 50.05 kgCO_2/tcs), which provides higher CO_2 abatement and longer lifetimes.

Implement phased transition plans: Given the diverse range of technologies and their varying lifetimes and financial saving potential through energy-saving benefits, ISI-A should adopt a phased approach to implementation. Technologies with shorter lifetimes and higher energy-saving benefits such as flue gas waste heat recovery (CO_2 abatement of 19.24 kgCO_2/tcs) and process control in hot strip mill (CO_2 abatement of 25.61 kgCO_2/tcs) may serve as immediate targets for implementation, while gradually integrate long-term, high-impact solutions like coke dry quenching (CO_2 abatement of 50.05 kgCO_2/tcs) and recovery of BOF gas and sensible heat (CO_2 abatement of 48.19 kgCO_2/tcs), which offer higher energy saving benefits($208 per ton of crude steel over their lifetime) and longer lifetimes.

Optimize existing processes: ISI-A can improve its energy efficiency by integrating technologies like flue gas waste heat recovery and preheating of fuel and air for hot blast stoves which can offer emissions reductions of 45.27 kgCO_2/tcs. Along with that, regular energy audits and using automated monitoring systems can help ISI-A to detect fugitive emissions from the enterprise.

By implementing these mitigation measures, the ISI-A can potentially reduce CO_2 emissions by up to 0.49 tCO_2/tcs, with additional savings from mitigating fugitive losses amounting to almost 0.39 tCO_2/tcs. This would bring down carbon emissions to 2.43 tCO_2/tcs, aligning it with global counterparts such as Japan (2.21 tCO_2/tcs), Turkey (2.20 tCO_2/tcs), the US (2.09 tCO_2/tcs), the UK (2.08 tCO_2/tcs), Ukraine (2.49 tCO_2/tcs), and Brazil (2.21 tCO_2/tcs)(Koolen and Vidovic, 2022). These mitigating measures can offer cost savings over their lifetime through energy savings while also providing savings on carbon taxes in the global market. It is essential to invest in innovative technologies with continuous improvement to ensure long-term emission reductions.

The government can assist enterprises like ISI-A, by offering targeted financial incentives such as subsidies, tax breaks, and low-interest loans to support the adoption of high-impact technologies that have higher upfront costs. Setting up clear and achievable emissions reduction targets along with ensuring compliance and regulatory support can encourage enterprises like ISI-A to follow a structured path towards emissions reduction. Government can create platforms for collaboration to share best practices through workshops, technical seminars, and partnerships with international experts. This support would enable enterprises to not only meet their emissions targets but also contribute to the broader national goals of decarbonization.

4. Conclusion

This study provides a comprehensive analysis to evaluate the process-wise carbon emissions for the BF-BOF production route of the Indian iron and steel industry. By utilizing material and energy flow analysis and carbon balance approaches, the study shed light on emission hotspots and carbon-intensive processes. The blast furnace process is the largest contributor to CO_2 emissions, accounting for 38.3% of the total emissions, with specific CO_2 emissions of 1.172 tCO_2/tcs. It is followed by the coke oven plant, contributing 18.6% of total emissions with specific CO_2 emissions of 0.537 tCO_2/tcs. The sintering plant ranks third, contributing 12.8% of total emissions with specific CO_2 emissions of 0.317 tCO_2/tcs. The mills have specific CO_2 emissions of 0.402 tCO_2/tcs, further adding to the carbon footprint. For blast furnace operations, transitioning to alternative fuels such as biochar and hydrogen can reduce CO_2 emissions. Implementing waste heat recovery technologies and optimizing the use of by-products like BFG and COG can enhance efficiency. Replacing BFG with natural gas or utilizing pressure swing absorption (PSA) technology can significantly lower emissions. Enhancing the recycling of flue gas materials and utilizing BOF slag in the cement industry can further reduce the environmental impact. Addressing fugitive emissions, which contribute 0.339 tCO_2/tcs, is also crucial. Implementing leak detection and repair programs, optimizing processes, and regular maintenance can mitigate these emissions. Transitioning to renewable energy sources for electricity can reduce indirect emissions, further lowering the plant's carbon footprint.

The MACC reveals significant variability in the cost-effectiveness of different mitigation measures. Continuous casting and pulverized coal injection (PCI) emerge as highly beneficial, offering net economic gains and significant CO_2 reductions (36.5 kgCO_2/tcs and 60.41 kgCO_2/tcs respectively). Contrarily, technologies like coal moisture control (CMC) and waste heat recovery from cooling water incur higher costs, indicating less favourable cost-benefit ratios. For ISI-A, prioritizing high-impact, cost-effective technologies is crucial for achieving both emissions reduction and financial sustainability. A phased implementation approach focusing first on technologies that offer the greatest immediate benefits, like continuous casting, while gradually integrating more capital-intensive solutions such as coil moisture control and waste heat recovery. Supporting processes like calcination and oxygen production from system boundary 2 increase CO_2 intensity due to their segmented nature. Consolidating these processes into a separate unit will help in reducing the carbon emissions within ISI-A.

Technology integration strategies need to consider trade-offs for cost and emission reductions. Industries should prioritize solutions giving the most emissions reduction benefits at the lowest cost. By accelerating technological innovations and support from the government enterprises like ISI-A can make significant developments toward achieving its emission reduction targets while ensuring long-term sustainability and competitiveness in the global market.

This study has certain limitations like relying solely on emission factors from the World Steel Association (WSA) which may introduce inaccuracies, as they might not precisely match the specific characteristics of Indian resources and production methods. Further research is necessary to carry out the extensive measurements of emission factors across various regions of India, which will help in increasing the accuracy of the results.

CRediT authorship contribution statement

Biswajit Tikadar: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Deepika Swami:** Writing – review & editing, Supervision, Methodology. **Vaibhav Chowdhary:** Resources.

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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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123483.

Data availability

Data will be made available on request.

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