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STRATEGIC EVOLUTION AND PERFORMANCE IMPACT OF IRON AND STEEL INDUSTRY

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Abstract
This review paper aims to analyze the economic performance and future trends in the development of Indian iron and steel industry. Computational results depict a significant explicit growth in production and consumption of finished steel in India, reflecting compound annual growth rate (CAGR) of 2.7% and 4.39% respectively, from 2012 to 2022. This growth is in relation to the global demand of 1822 million tonnes in 2023. The minimum and maximum values in million tonnes of import-export of Indian finished steel are (4.46 in 2020, 11.71 in 2015) and (4.08 in 2015, 12.80 in 2021) respectively. Similarly, a substantial growth has been observed in production & capacity of the crude steel in India which reflects CAGR 4.36% & 4.92% respectively during 2012 to 2022. Further, steel demand in India reflects an expected robust growth of 8.6% in 2023, which is higher than 1.8% of global rise. CAGR for five years from 2018 to 2022 for {SAIL, RINL, TSL, Jindal Steel & Power Limited, JSW Steel Limited} is computed as {3.09 %, -3.14 %, 8.35 %, 12.46 %, 4.12 %} respectively. An analysis of iron ore production in India reveals a CAGR of 3.49% from 2010 to 2022, amounting to Rs. 964 billion and a production volume of 254 million metric tonnes (MMT). India holds the fourth position globally, producing 290 MMT and 180 MMT of usable iron ore and iron content respectively. In 2022, Australia claimed the top position in global production contributing 880 MMT and 540 MMT of usable iron and iron content. Therefore, CAGR of production, consumption and capacity presents a positive and impressive outlook for the industrial trend of development. Additionally, the adoption of hydrogen-based reduction, carbon capture techniques and solar plant installations has yielded fruitful results in achieving zero CO_2 emissions in the aforementioned industries.

Keywords: Steel, Iron, Production, Consumption, Carbon emission, CAGR

Introduction

Steel is a diverse family of iron alloys, which becomes readily malleable after melting process. It exerts a profound influence in our daily lives due to formability according to temperature, weldability, mechanical property, machinability and resisted according to corrosion & heat. Its presence is ubiquitous, found in electricity-power-line towers, natural-gas pipe-lines, machinery tools, military weaponry and an extensive list of applications. In our homes, steel serves as a protector of our families, enhancing convenience and safety. The undeniable benefits of steel make it an indispensable and versatile material, playing a central role in various facets of human development.

Steel is a crucial material that plays an essential role in providing a competitive edge to modern economy. It is widely used in industrial production and represents the backbone of manufacturing economy. Steel plays a pivotal role to make in India vision of government of India. The demand for steel in a country is primarily driven by sectors such as automobile, construction, infrastructure, power and machinery, accounting for more than 75% of the total steel consumed [7]. In 2022, China led the world in steel production, accounting for over half of the global production, while the European Union represented 7.2% of global crude steel production. In 2022, the estimated global demand for crude steel was over 1.8 billion tonnes, which reflects the expanding global economy. India holds the position of the 2nd largest producer of crude steel globally, commanding an approximate 6% share in the world market. Thus, India plays a significant role with the world's 2nd largest steel industry and ranking as the 3rd largest consumer of steel in this scenario [9]. Indian iron & steel industries are essential for supporting the national development and rapid economic growth. The steel industry constitutes

approximately 2% of Indian GDP [5] and provides employment to approximately 2.5 million individuals in both the steel sector and associated industries.

Worldwide, steel is manufactured through two primary processes: the blast furnace-basic oxygen furnace (BF-BOF) route and the induction furnace-electric arc furnace (IF-EAF) route. About 75% of the world's steel is produced using the BF-BOF route. The distribution of various process routes in the total production of crude steel in India over the last 11 years have been illustrated in the Table 1.

Table 1: Route -wise crude steel production in India

Route -wise crude steel production	Share (%)										
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
BOF	43	43	42	42	43	45	45	44	45	45	46
EAF	24	23	26	28	30	27	29	26	28	27	31
IF	33	34	32	30	27	28	26	30	27	28	23
Total	100	100	100	100	100	100	100	100	100	100	100

Route -wise global energy consumption for steel production

It is crucial to note that the steel industry is highly energy-consuming, ranking as the most energy-consuming manufacturing industry worldwide within the iron & steel sector. Fig. 1 & Fig. 2 represents the energy consumed by BF-BOF route and EAF route respectively [2]. In EAF route natural gas consumption increases up to 38% in comparison of 3% in BF-BOF route process which shows a better solution for green energy industrial development by EAF route. Since, EAF route process gives a better solution for decreasing the consumption of coal and increasing the consumption of natural gas.

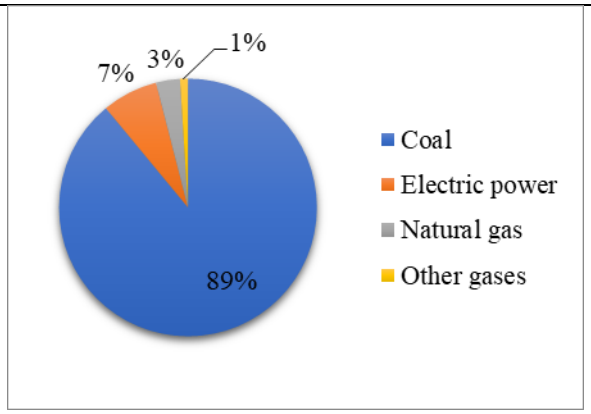

Fig. 1: Energy consumed (%) (BF-BOF) route

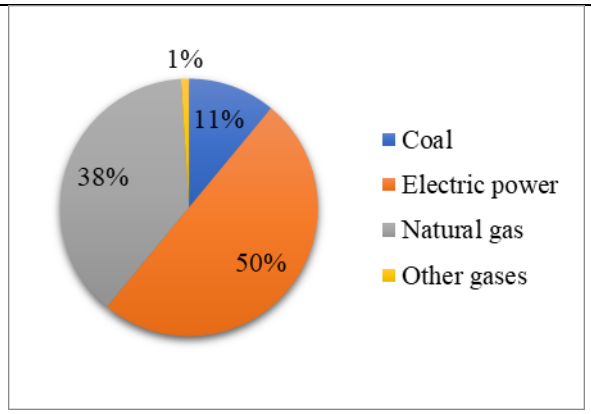

Fig. 2: Energy consumed (%) (EAF) route

Table 2: Scenario of homemade availability for pig iron (MT)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Production	6.87	7.95	10.228	10.24	10.342	5.728	6.249	5.983	4.548	5.855	6.283
Import	0.021	0.034	0.023	0.022	0.034	0.016	0.067	0.013	0.007	0.015	0.104
Export	0.414	0.943	0.54	0.297	0.387	0.518	0.335	0.421	0.823	1.407	0.675
Consumption	6.5	7.11	9.057	9.021	9.04	5.189	5.841	5.669	3.735	4.433	5.065

The production of steel typically involves iron ore, coal and limestone. **Pig iron** is a fundamental raw material in the production of steel. It's an intermediate product obtained from smelting iron ore in a blast furnace. This iron-rich material contains varying amounts of carbon, along with other elements

like silicon, manganese, sulphur and phosphorus. The production of pig iron in India is minimum 4.54 million tonnes (MT) in 2020 and maximum 10.34 MT in 2016 and similarly consumption of pig iron is minimum 3.73 MT in 2020 and maximum 9.05 MT in 2014. Current position of import-export are 0.104 MT and 0.675 MT respectively. Homemade availability of pig iron is detailed in the Table 2 given below, encompassing data from the last 11 years [4].

Sponge iron, with its distinctive honeycomb structure, is a vital raw material for steel production in India. As the largest global producer, India relies significantly on coal-based sponge iron plants, constituting 78% of the total production in 2021. This preference is attributed to the abundance of non-coking coal, lower investment requirements and limited access to natural gas, setting India apart from other developed nations. Since 2012, India has held the position of the world's foremost producer of sponge iron. The Table 3 represents the total production of sponge iron in India, delineating the distribution of production between coal and gas-based routes over the last 11 years [3].

Table 3: Homemade production of sponge iron in India

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Coal based	19.06	20.19	21.89	19.98	22.62	23.28	27.16	30.12	27.52	30.60	33.87
Gas based	3.94	2.68	2.35	2.44	4.35	6.22	7.05	6.69	6.07	8.40	8.12
Total	23.00	22.87	24.24	22.42	26.98	29.50	34.21	36.81	33.59	39.00	42.00

Reactions in coal-based & gas-based DRI process

Formulation for analysing the heat energy may be given as:

$$Q = m \times c \times \Delta T \quad (1)$$

where, Q=heat energy (Joules), m = mass of substance (kg), c = specific heat (j/ kg), Δt = change in temperature (K)

Following Nishant R. Dey (2015), The change in heat for each reaction on a molar basis may be represented as:

$$Fe_2O_3 + CO = 2FeO + CO_2 - 2.057\ GJ/kmol \quad (2)$$
$$FeO + CO = Fe + CO_2 - 0.257\ GJ/kmol \quad (3)$$
$$CO_2 + C = 2CO + 75\ GJ/kmol \quad (4)$$
$$2CO + O_2 = 2CO_2 - 135.71\ GJ/kmol \quad (5)$$
$$C + O_2 = CO_2 - 98\ GJ/kmol \quad (6)$$
$$2C + O_2 = 2CO - 3.44\ GJ/kmol \quad (7)$$
$$2H_2 + O_2 = 2H_2O - 29.83\ GJ/kmol \quad (8)$$

In this process equation (4) is endothermic and remaining equations are exothermic [8]. Indian industries of iron & steel contribute significantly to equitable economic growth, but they also account for substantial energy consumption estimated as 449.27 Mtoe [1]. This overview of India's energy consumption highlights the industrial sector's role, constituting about 30% of the country's total energy consumption. The total steel production capacity of India is 143.91 MT. The production increases to 11,900 thousand tonnes in August 2023 from 11,500 thousand tonnes in July 2023. Enhancing energy efficiency and fostering low-carbon growth are pivotal for reducing India's energy and emissions intensity [15].

India's annual production capacity reaches 47.85 MT with 285 direct reductions of iron (DRI) plants. The majority coal-based rotary kilns, ranging from 50 to 500 tonnes per day. Coal-based DRI plants contribute 36.74 MT, while gas-based counterparts, using methods like gasification and natural gas, account for 11.10 MT. While integral to meeting steel demand, especially in India, it's crucial to address environmental concerns.

Coal-based DRI production, known for **higher energy and carbon intensity**, involves controlled coal combustion over 8 to 10 hours to produce metallic iron. In contrast, gas-based methods utilize cleaner gases like H_2 and CO to reduce iron ore in a vertical shaft furnace, fuelled by natural gas from processes

like COREX. Addressing carbon emissions and improving energy efficiency remains essential for sustainable sponge iron production in India.

With India's steel industry projected to double carbon emissions by 2030 due to ambitious infrastructure goals, an urgent shift toward de-carbonization is imperative. The report advocates for adopting de-carbonization strategies, particularly replacing fossil fuels with hydrogen in the Direct Reduced Iron (DRI) process, potentially cutting emissions by up to 90%. India's National Green Hydrogen Mission aims to establish the country as a global green hydrogen production and usage hub. Anticipated growth in demand for green steel underscores the critical importance of prioritizing energy efficiency and de-carbonization in the global steel industry, including in India [10].

The analysis of production-consumption, imports-exports at domestic as well as international level are the key factors to be studied. The objective of analysis is to evaluate the position of Indian steel and iron industries in the world. This comprehensive examination aims to give information into the current state and potential future trajectory of the Indian steel and iron sector, considering its interactions with the global steel & iron market. An empirical approach relying on secondary data has been taken for above analysis. The data has been selected from various sources, including journals, articles, books, the World Steel Association (2012), annual reports of the Indian steel industry, the Joint Plan Committee (2012), and the Government of India (2015-2022). The study encompasses an 11-year period from 2012 to 2022, allowing for a comprehensive examination of trends and patterns within the specified timeframe.

Global ranking of crude steel production

Following world steel association, global crude steel production from 2012 to 2022 can be represented as shown in Table 4.

Table 4: World's crude steel production (MMT)

S. R.	Year	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	2012
1	China	1,018	1,032.8	1,064.8	995.4	920	831.7	786.9	803.8	822.7	779	724.7
2	India	124.72	118.2	100.3	111.4	109.3	101.5	95.5	89.6	87.3	81.2	77.3
3	Japan	89.2	96.3	83.2	99.3	104.3	104.7	104.8	105.2	110.7	110.6	107.2
4	United States	80.5	85.8	72.7	87.8	86.6	81.6	78.5	78.9	88.2	87	88.6
5	Russia	71.5	75.6	71.6	71.7	72	71.3	70.5	71.1	71.5	69.4	70.6
6	South Korea	65.9	70.4	67.1	71.4	72.5	71.1	68.6	69.7	71.5	66	69.3
7	Turkey	35.1	40.4	35.8	33.7	37.3	37.5	33.2	31.5	34	34.7	35.9
8	Germany	36.8	40.1	35.7	39.6	42.4	43.6	42.1	42.7	42.9	42.6	42.7
9	Brazil	34	36.2	31	32.6	35.4	34.4	30.2	33.3	33.9	34.2	34.7
10	Iran	30.6	28.5	29	25.6	24.5	21.8	17.9	16.1	16.3	15.4	14.5
11	Others	299	327.6	326.3	305.9	304.1	275.6	278.1	278.5	291.1	329.2	287.4
12	World	1,885.0	1,951.9	1,877.5	1,874.4	1,808.4	1,674.8	1,606.3	1,620.4	1,670.1	1,649.3	1,552.9

According to above Table, global crude steel production is about 1885 million metric tonnes (MMT) in 2022, marking a decrease of 3.43% as compared to 2021. Within this timeframe, China's crude steel

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production amounted to 1018 MMT, reflecting a decline of 1.43% as compared to 2021 as represented in table 4. Despite a decline, China retained its status as the leading global crude steel producer, accounting for 46% of total production in 2022. India emerged as the second-largest producer, registering a 5.52% increase compared to 2021. India's contribution to global crude steel production now stands at around 6.61%.

Global demand of finished steel production

Following source https:// www.statista.com, the demand of finished steel is steadily increasing from 2010 to 2014 with a slight dip in 2015 and again increases from 2016 to 2021 and global demand in 2023 was estimated to be 1822 MT as shown in Fig. 3.

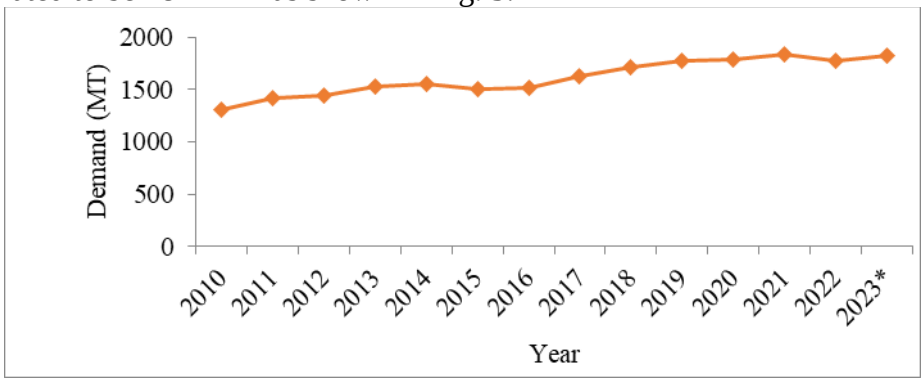

Fig. 3: Global demand of finished steel

Steel consumption in various sectors of India and world in 2022

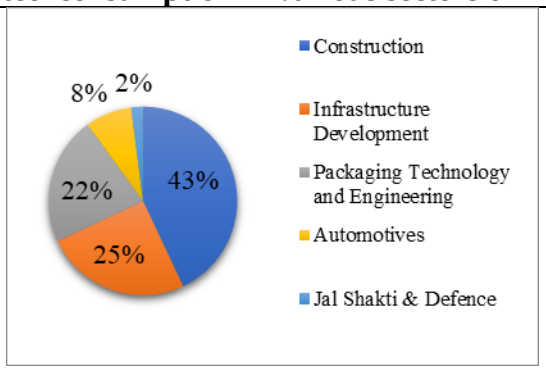

Fig. 4: Steel consuming in various sectors in India

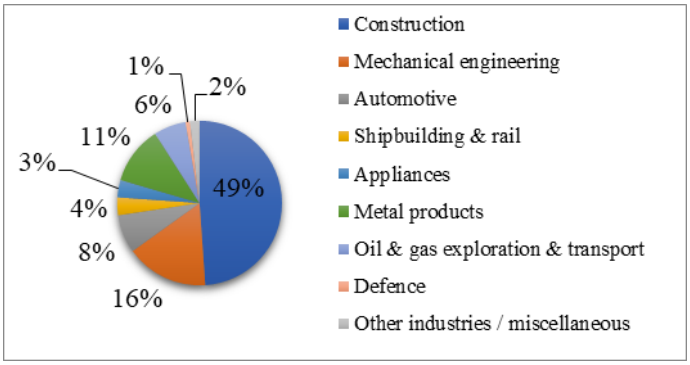

Fig. 5: Steel consuming in various sectors in World

Analysis of production, consumption and growth of steel in India

Following economic liberalization in India, we obtained a significant surge in production as well as consumption of finished steel approximately a new phase of growth for Indian steel industry commenced in 2005-06. This growth was propelled by the flourishing automobile sector, railways, real estate, construction and augmented government investments in infrastructure, as indicated in the annual reports spanning from 2015-16 to 2022-23. Fig. 6 illustrates the trends in the production, consumption and Fig. 7 represents the import and export of finished steel in the country over the past 11 years.

Industrial Engineering Journal
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Volume : 53, Issue 1, No. 1, January : 2024

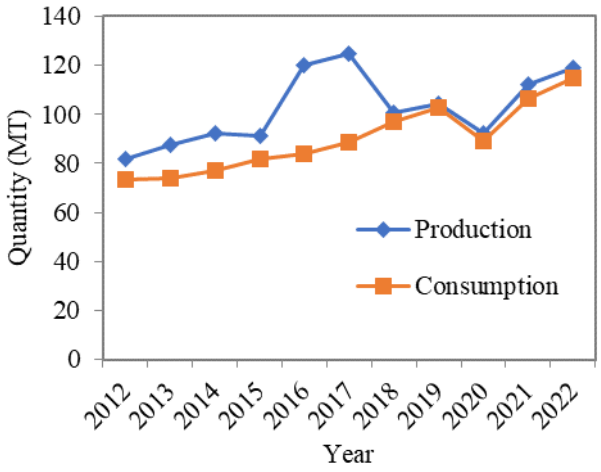

Fig. 6: Production-consumption of Indian finished steel

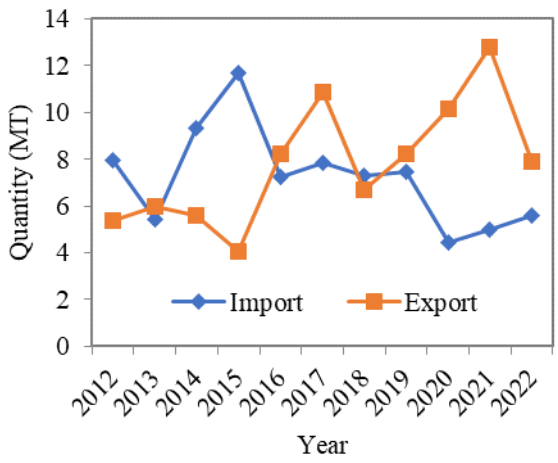

Fig. 7: Import-export of Indian finished steel

The production of finished steel in India has exhibited a fluctuating trend and grows gradually during the study period and produced finished steel of 118.71 MT in 2022 as compared to 81.68 MT in 2012 with CAGR of 2.71%. Similarly, the consumption of finished steel in India also increases gradually from 2012 to 2019, with a small decline in 2020 due to the impact of the COVID-19 pandemic. However, there was a subsequent rebound, with increased consumption in 2021 and 2022. Explicit consumption of finished steel in India [6] has increased from 73.48 MT in 2012 to 114.894 MT in 2022, reflecting a CAGR of 4.39%. Fig. 7 represents the fluctuation in the import-export quantity of Indian finished steel. The minimum and maximum values in MT of import-export of Indian finished steel are (4.46 in 2020, 11.71 in 2015) and (4.08 in 2015, 12.80 in 2021) respectively.

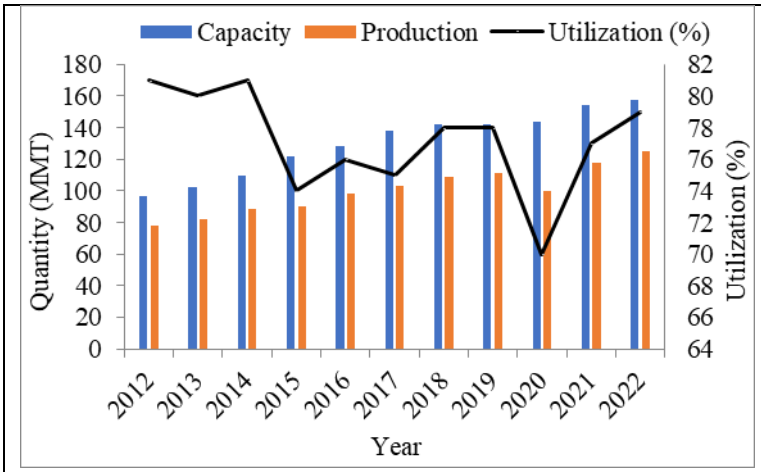

Fig. 8: Crude steel production, capacity & utilization of India

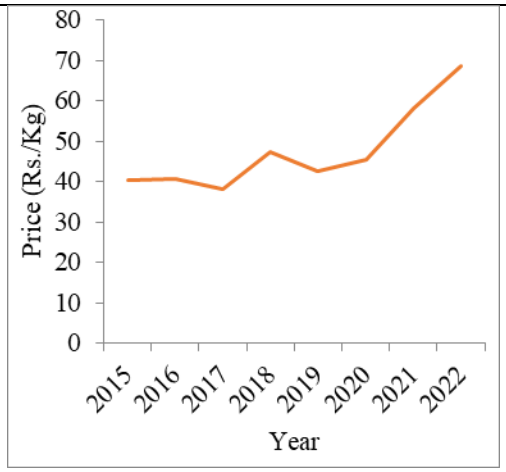

Fig. 9: Price of steel in India

In the same way, Fig. 8 represents the trend in capacity, production and utilization percentage of crude steel in the India over the past 11 years. The production of crude steel in India exhibited gradual growth rate of 4.36 % (except during covid period) from 2012 to 2022. The capacity of crude steel in India has consistently and gradually increased from 2012 to 2022. The apparent capacity of crude steel in India increases from 97.02 MT in 2012 to 157.59 MT in 2022, reflecting a CAGR of 4.92%.
Following source https://www.statista .com, the cost of a 16 mm steel bar in Delhi increases from Rs. 40 to 70 per kg during 2015 to 2022 as shown in Fig.9. This upward trend in steel prices has persisted over the past four years, driven by a sustained surge in steel demand.

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Trends in production in private/public sector

The private sector in the steel industry is presently a pivotal contributor to the production and growth of the steel sector in the country. Its significance extends beyond the production of both primary and secondary steel, encompassing substantial value addition in terms of quality, renovation, and cost-effectiveness. Table 5 represents the contribution of private and public sectors in crude steel production within the country over past 11 years.

Table 5: Trends in Production in Private/Public Sector in India

Sector	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Public Sector	16.48	16.77	17.21	17.92	18.46	19.75	21.19	21.01	18.94	22.9	22.1
Private Sector	61.94	64.92	71.77	71.87	79.48	83.38	89.43	90.33	81.3	95.29	102.61
Total Production	78.42	81.69	88.98	89.79	97.94	103.13	110.92	111.34	100.24	118.19	124.71
Share of Public Sector	21	21	19	20	19	19	19	19	19	20	18

The selected companies for evaluations are Steel Authority of India Limited (SAIL), Rashtriya Ispat Nigam Limited (RINL), Tata Steel Limited (TSL), Jindal Steel & Power Limited and JSW Steel Limited.

The Compound Annual Growth Rate (CAGR) for five years from 2018 to 2022 for {SAIL, RINL, TSL, Jindal Steel & Power Limited, JSW Steel Limited} is computed as {3.09 %, -3.14 %, 8.35 %, 12.46 %, 4.12 %} respectively.

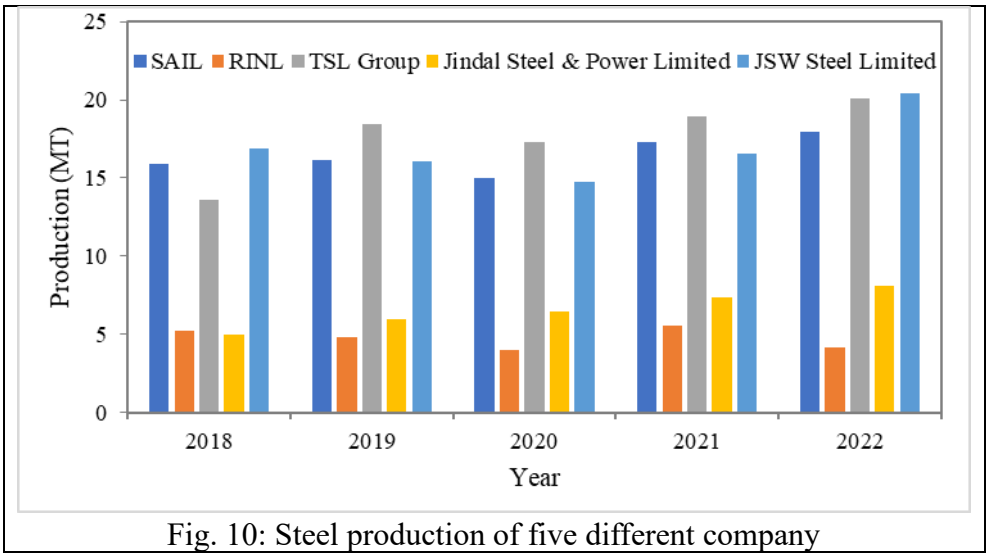

Fig. 10: Steel production of five different company

Production of Iron ore

Iron ore is a fundamental resource in the global industrial and infrastructural landscape which plays a crucial role in the production of steel. It is essential material that underlies modern constructions, manufacturing and transportation. The extraction and utilization of iron ore have far-reaching implications for the world economy, making it a subject of vital study and analysis. The production volume of iron ore in India reached approximately 254 MMT in 2022, as depicted in Fig. 11. The mined ore primarily comprised lumps, fines and concentrates of iron. In the year 2022, India's iron ore production value set a record of 964 billion Indian rupees, corresponding to a production volume of 254 MMT of iron ore as represented in Fig. 12. A substantial growth has been observed in production of iron ore (from 209 MMT in 2010 to 254 MMT in 2022), which reflects CAGR of 3.49%. Various chemical compounds are present in these ores, including hematite, magnetite, siderite and limonite.

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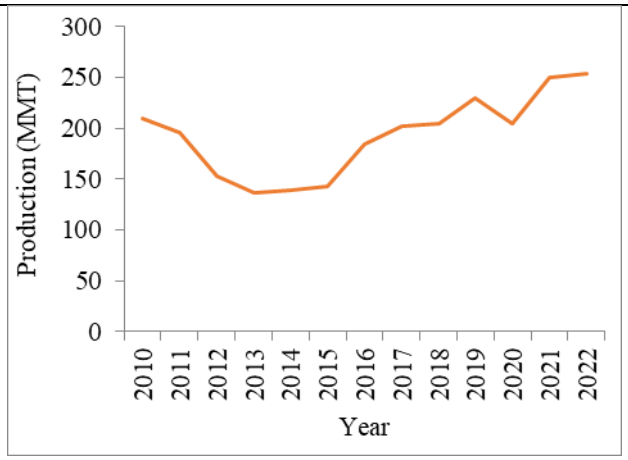

Fig. 11: Production volume of iron ore in India

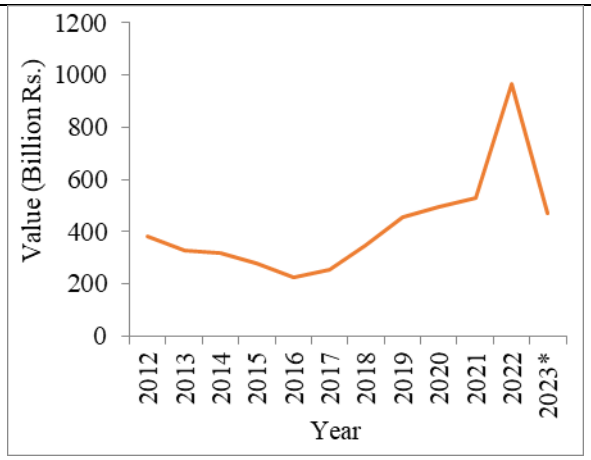

Fig. 12: Production value of iron ore in India

The average price of iron ore on the global market is a key metric that provides valuable insights into the dynamics of the iron. Following source: https://www.statista .com, the average annual prices for iron ore from 2014 through 2022, with forecasted figures for 2023 to 2024 are depicted in Fig. 13. In 2022, the average price for iron ore reached 121 nominal US$ per dry metric tonnes. Further global iron ore mining production has been depicted in Fig.14, which reflects Australia to be the leading country in 2022 and Brazil to be the second world's largest iron ore mine producer. Australia and Brazil are contributing 880 MMT and 410 MMT iron ore mining production respectively.

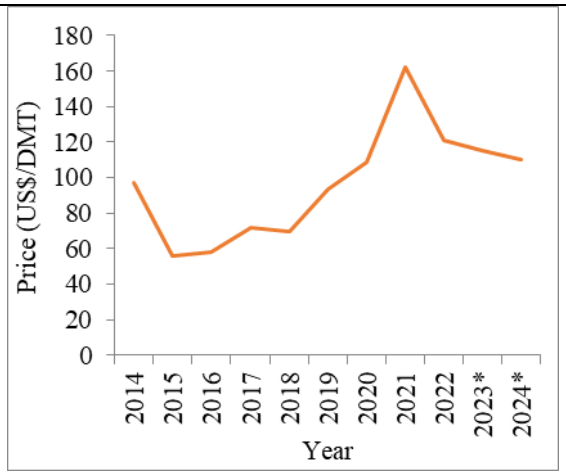

Fig. 13: Global average price of iron ore

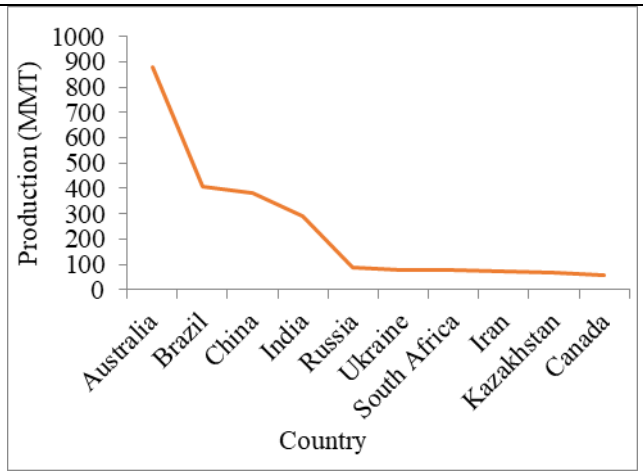

Fig. 14: Global iron ore mining production

Global export share of iron ore

Fig. 15, represents the global export share of iron ore by 11 countries of the world in 2022. Australia is the leading country in above exportation. Approximately 56% of the world's iron ore exports are originated from Australia.

In 2022, Australia exported $87.7 billion worth of iron ore, securing the top position. Brazil held the second position with an export value of $29 billion, while India's iron ore exports amounted to $1.57 billion, as represented in Fig. 16. This substantial export volume is attributed to Australia having the world's largest reserves of iron ore.

Industrial Engineering Journal
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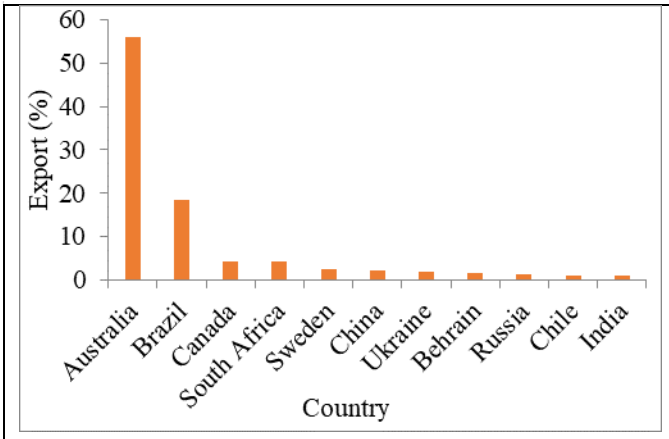

Fig. 15: Global export share of iron ore

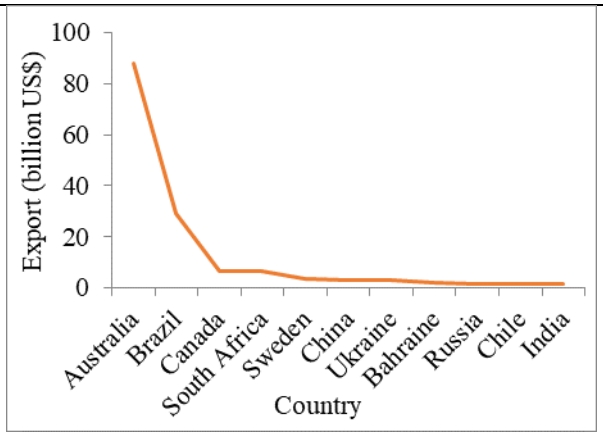

Fig. 16: Export price of iron ore exporting country

Global production of usable iron and iron content

Fig. 17 represents a comparative study of the production of usable iron and iron content among major iron-producing countries. In 2022, Australia secured the top position in global production of usable iron and iron content, contributing 880 MMT and 540 MMT respectively. China holds the second position, while India stood at the fourth position, producing 290 MMT and 180 MMT of usable iron ore and iron content respectively. The global production of usable iron ore can be represented as shown in Fig. 18. This production volume of usable iron has reached 2,600 MMT in 2022.

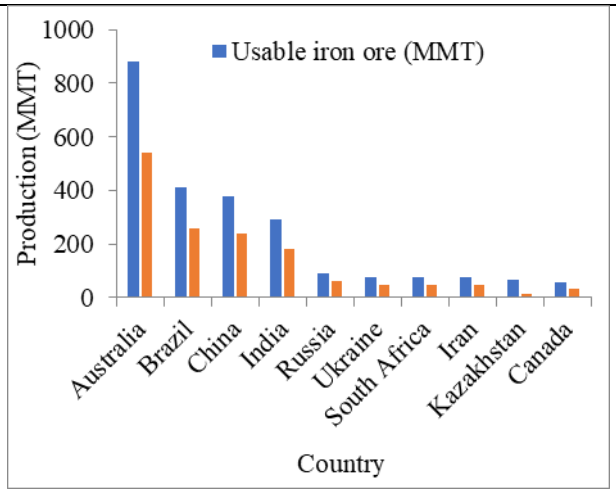

Fig. 17: Comparison of usable iron & iron content

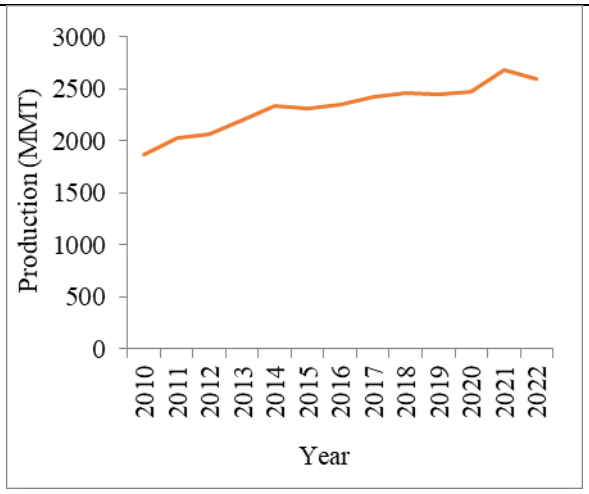

Fig. 18: Global production volume of usable iron ore

Presentation of Indian and global CO_2 emissions

The power industry is the largest contributor to global CO_2 emissions. In 2022, global power industry emissions increased by 1% from 2021 levels to reach a record high of 14.7 billion metric tonnes of CO_2. CO_2 emissions from power sector continuously increases from 2010-18 and small decline has been noticed in 2019 due to covid-19. Further, CO_2 emissions increase as shown in Fig. 19. Similarly, in transportation CO_2 emission continuously increases from 2010-19

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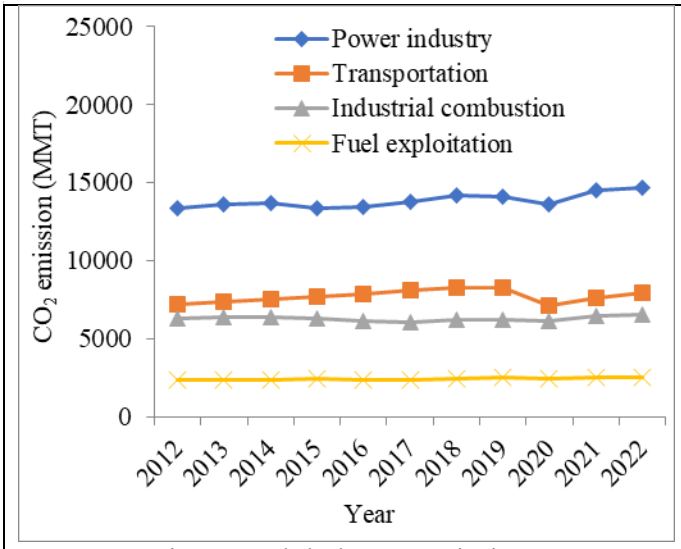

Fig. 19: Global CO_2 emissions

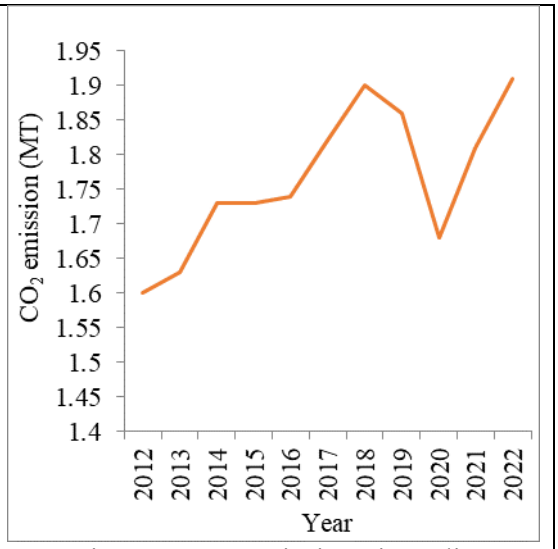

Fig. 20: CO_2 emissions in India

and small decrease in 2020 has been noticed due to increase in demand of EV vehicles. In industry the minimum CO_2 emission was seen in 2017 (6067 MMT) and maximum in 2022 (6538 MMT) due to the combustion of coal in steel & iron industry.

Future trends in iron and steel industry development for least CO_2 emissions

Iron and steel industry is the leading contributor of CO_2 emissions. This sector contributes 12% of India's total CO_2 emissions, emitting 2.55 tonnes of CO_2 per tonne of steel-surpassing the global average of 1.85 tonnes CO_2 per tonne of crude steel. Various operations in steel manufacturing process, such as sinter plants, calcining plants, coke ovens, blast furnace blowers, basic oxygen furnaces, oxygen plants, slab casters, and rolling mills, require electricity. Despite the diverse operations, the primary source of electricity in this industry remains coal. Many iron and steel companies in India have established captive electricity plants to meet their power demand, with coal, natural gas, and diesel accounting for 91%, 7% and 1% of captive generation, respectively. Consequently, the industry emits 2.6 gigatons of CO_2 per year, constituting 7% of global energy system emissions. The adoption of solar energy, being clean, cost-effective, noiseless, long-term investment**,** government incentives and tax benefits and locally available can assist steel companies in reducing electricity expenses and lowering carbon emissions. Further, Iron and steel industry are progressing towards lower CO_2 emissions by adopting low-carbon technologies like hydrogen-based reduction and carbon capture methods.

For sustainable development in iron and steel industry with least CO_2 emission, we have to improve the efficiency of its operations with renewable energy products. Nucor of North America is one of the most efficient and cleanest steel producers in the world by supporting the development with solar energy while Tata Steel's in Noamundi is the first solar powered iron ore mine in India to reduce the emissions associated with steelmaking. Integration of renewable energy sources and focus on recycling and circular economy models aid in reducing the carbon footprint. Ongoing research and development drive innovations in processes like plasma smelting, while government regulations and collaborations foster the industry's transition to cleaner production methods. Ultimately, a collective effort involving technological advancements, policy support and consumer demand for sustainable practices aims to significantly curb CO_2 emissions in iron and steel sectors as shown in Fig. 21.

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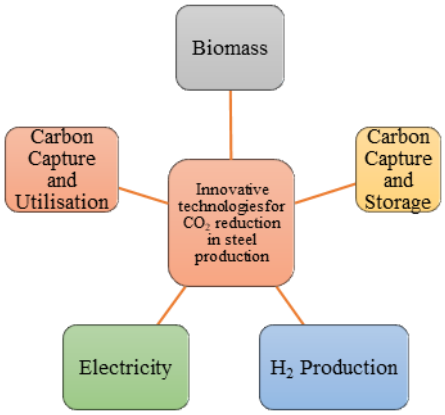

Fig. 21: Innovative technologies to reduce CO_2 emissions

The Indian steel industry is committed to significant emission reductions and achieving net-zero carbon emissions by 2070, aligning with COP26 climate goals. As a major carbon emitter, the industry is exploring Green Steel, a sustainable approach involving fossil fuel-free manufacturing using low-carbon energy sources like electricity, hydrogen, etc. This not only cuts greenhouse gas emissions but also improves cost-efficiency and steel quality. The National Hydrogen Energy Mission (NHM) emphasizes the role of low-carbon hydrogen and the Ministry of Steel is actively implementing policies to enable the de-carbonization of the sector. Indian progress in solar installation in steel and iron industry is represented by Table 6.

Table 6: Solar Installations for Steel Industry

Installation Location	Solar Plant Capacity	City
Krishna iron strips and tubes PVT LTD	512kW	Raipur
Vikas Stainless Pvt Ltd	319 kW	Hissar
Belmarks Metal (India) Private Limited	79 kW	Indore

Conclusion

The steel industry has experienced rapid growth in recent times, emerging as one of the fastest-growing sectors across the world. The findings reveal that India possesses the potential to become a leading steel producer in the near future. The consistent growth in production & consumption of steel and iron sector signals that India is on a trajectory for substantial expansion in future. The Compound Annual Growth Rate (CAGR) of production and consumption portrays a positive and impressive picture of the industry's development over the study period.

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