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REVIEW ARTICLE

Sustainable Production of Steel–Carbon Neutrality and Low Life Cycle Emission

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Abstract | Steel is most preferred and largest consumed engineering material. It is also the largest contributor to greenhouse gas emissions. Conventional steel production is highly carbon intensive and produces about 2.2 tCO_2 per tonne of steel produced. With predicted steel production growth of 25–30% by 2050, steel sector will be responsible for the largest generation of anthropogenic emissions among the process industries. Various steel-making process improvisations like Blast Furnace top gas recycling, usage of bio-mass, replacement of coke with hydrogen for reduction, fuel change over to natural gas can drastically bring down the emission levels of CO_2. Serious thought is given towards the reduction of CO_2 emissions through CCS (CO_2 Capture and Storage) and reutilization of caught carbon for chemical manufacturing. Means of carbonless steel production using hydrogen generated from renewable energy source are being considered to bring carbon neutrality to steel production by 2050. Steelmaking through the electrical arc furnace using electricity from renewable sources is gaining popularity considering the expected increase in scrap generation from 30 to 50% and nearly zero carbon footprint. The further reduction of CO_2 emission during the lifetime of use of steel is expected through the usage of lightweight materials in automobiles which lowers the fuel consumption and hence the lower CO_2 generation. Various routes being explored to bring CO_2 emissions to a lower level of 0.4–0.5t CO_2/t steel by enhancement of existing production facilities and by the deployment of innovative methods are reviewed.

1 Introduction

Metallurgical Industries are the second largest contributor to global CO_2 emission only next to the thermal power plants.[1] Among them, steel plants contribute to nearly half of the total emission of the metallurgical industries by virtue of the volume of production and the traditional red-ox route.[2] Production of steel involves higher energy consumption associated with a high level of CO_2 emissions. Blast furnace route for iron making is an energy-intensive route utilizing fossil fuels and contributes to about 7% of the anthropogenic CO_2 emissions.[3, 4] Researches on CO_2 emissions during steel production has revealed an average CO_2 release of 1.8t/ton of crude steel.[4–6] Steel will continue to be the choice of engineering material in the near future for various core sector applications such as infrastructure development, earth moving and heavy commercial vehicles, rail transport and automobiles for the techno-economic reasons. World steel demand is expected to grow at the rate of 4.3% year-on-year and Indian steel demand is poised to grow at the rate of 7.2%.[7] With increasing steel production, the CO_2 emission is only expected to increase and with most of the power

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production switching to renewable sources, steelmaking could be the largest contributor to greenhouse gas emission in the future.[7]

In the near future, it is essential to evolve the process of steel production to reduce CO_2 emissions and bring to a carbon neutrality level. The steel itself should be re-invented to produce ultra-high strength and lightweight steel which will contribute to the reduction of emissions during the life cycle of steel.[8] For steel to continue to be the material of choice in the future in a sustainable manner it is important to re-engineer both the production process and the product.

Conventional iron making through the blast furnace route provides very little scope to eliminate CO_2 emission completely from the steelmaking process. Production of iron from iron ore through the blast furnace route requires carbon in the form of coke both as a reductant and energy source. CO_2 emission can be reduced to some extent through the optimisation of the processes and effective utilisation of the energy by recovery.[9] To bring down the net CO_2 emission the most contemplated route at present is to capture CO_2 and to utilise it for the production of organic compounds or carbonated products. These methods may result in incremental improvements in the reduction of CO_2 emissions. However, for a sustainable future, major shift from carbon as a reductant and energy source is required.[10] Unless the energy required for the production of steel and during its life cycle is met by renewable sources, carbon neutrality may not be achieved. Various process options for the production of steel without using fossil fuel as a reductant or source of energy shall be discussed further.

2 Using of Alternate Reductant—Hydrogen

Carbon from coke is a major source of reducing agent of iron oxide from iron ore.[7]

$$\mathrm{Fe_2O_3} + \frac{3}{2}\mathrm{C} \rightarrow 2\mathrm{Fe} + \frac{3}{2}\mathrm{CO_2} \left\{ \Delta H^0 = +200\ \mathrm{kJ/mol} \right\}. \tag{1}$$

The kinetics of the reduction reaction are optimal at temperatures higher than 1000 °C. However, since the iron ore is associated with other gangue material, the temperature of the process is raised to more than 1300 °C to remove the impurities in the form of liquid slag. The liquid iron is saturated with about 4% carbon at high temperatures which is removed as CO_2 during the subsequent steel-making process.[11, 12] The energy required to raise the temperature of the reactants above the melting point of slag and the carbon saturated hot metal is achieved through partial oxidation of carbon from coke.[13]

$$\mathrm{C_s} + 1/2\,\mathrm{O_{2(g)}} \rightarrow \mathrm{CO_{(g)}} \left\{ \Delta \mathrm{H}^0 = -111\ \mathrm{kJ/mol} \right\} \tag{2}$$

$$\mathrm{C_s} + \mathrm{O_{2(g)}} \rightarrow \mathrm{CO_{2(g)}} \left\{ \Delta \mathrm{H}^0 = -393.78\ \mathrm{kJ/mol} \right\}. \tag{3}$$

In a blast furnace, the reduction of Fe_2O_3 by CO gas generated through partial oxidation of carbon from coal or coke is kinetically favoured over the reduction by carbon.

$$\mathrm{Fe_2O_3} + 3\mathrm{CO} \rightarrow 2\mathrm{Fe} + 3\mathrm{CO_2} \left\{ \Delta \mathrm{H}^0 = -35.2\ \mathrm{kJ/mol} \right\}. \tag{4}$$

The Blast Furnace Process is shown as schematic diagram in Fig. 1. In a blast furnace the raw materials—iron ore, flux and coke—are fed from the top. Pre-heated oxygen-enriched air blast is blown from the bottom through tuyeres. Pulverised coal is also injected through tuyeres. More often Nitrogen is used as a carrier gas for the pulverised coal injection. Typically, about 350 kg of coke and 200 kg of pulverised coal is used in the blast furnace for the production of one ton of hot metal.

By virtue of the red-ox reactions, steelmaking through blast furnace emits about 1.8 tons of carbon-dioxide per ton of liquid steel produced. In addition, the process also consumes electrical energy for various auxiliary units, nitrogen and oxygen generation.

Typically, a BF-BOF plant consumes about 130 kWh/ton of crude steel.[14] Assuming the entire electrical energy is generated from coal, the total CO_2 emission for the production of one ton of steel is about 1.92 tons.[4, 15, 16] The CO_2 intensity of electrical energy is dependent on the source.

Steel plants have taken various measures to reduce CO_2 emissions through minor process modifications such as hydrocarbon usage as reductant, injection of pulverised coal with high volatile matter or natural gas through tuyeres.[17] Table 1 summarises typical life cycle CO_2 intensity of electricity generated from various sources.

However, the reduction of emissions is very small through these processes. Substantial reduction in CO_2 emission intensity for the production of electricity could be achieved by changing the source from coal to renewable

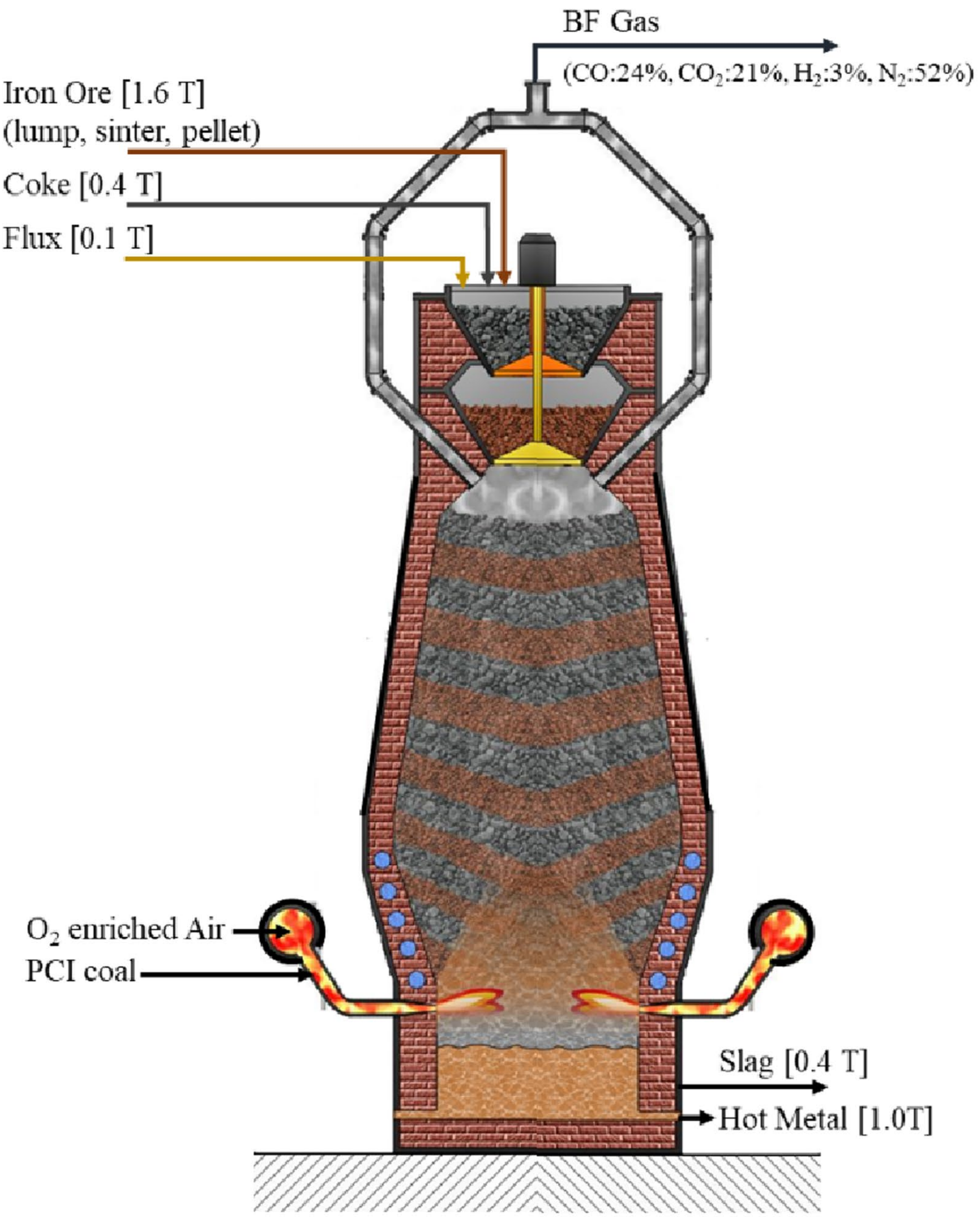

Figure 1: Process flow chart of blast furnace iron making.

energy source. However, in the blast furnace the proportion of CO_2 from electrical energy is very less compared to the CO_2 emission from the reduction reaction and smelting using coke. Apart from acting as a reductant, coke plays a major role as burden support in the blast furnace and has a very limited scope for replacement.

Major reduction in CO_2 emissions can be achieved altering the reduction process from carbon based to hydrogen based in DRI units.[18, 19]

Similar to reduction by carbon, iron oxide is reduced by hydrogen to yield metallic iron and water vapour.

$$\mathrm{Fe_2O_3} + 3\mathrm{H_2} \rightarrow 2\mathrm{Fe} + 3\mathrm{H_2O} \quad \left\{ \Delta \mathrm{H}^0 = +99.5\ \mathrm{kJ/mol} \right\}. \tag{5}$$

The reduction reaction by hydrogen is endothermic[20] compared to reduction by CO and requires an external energy input for the reduction reaction to progress. And since the

Table 1: CO_2 intensity of various modes of electricity generation.

Sl. No	Source	CO_2 intensity (g/kWh)
1	Coal	950
2	Natural Gas	475
3	Hydro-electric	24
4	Nuclear	12
5	Solar	48
6	Wind	12
7	Geothermal	38

reaction can take place in solid state, the temperature of the reduction process can much lower than the temperature encountered in the blast furnace process. Typically, in a DRI unit the reductant and heating agent is a mixture of CO and H_2 derived from cracking of natural gas or gasification of coal using steam. The proportion of CO and H_2 varies largely depending on the volatile matter composition of the coal in the coal gasification process.[21] Natural gas on the other hand has about 95% methane and rest higher level hydrocarbon. The reaction of cracking natural gas[13] with steam is

$$CH_{4(g)} + H_2O_{(l)} \rightarrow CO_{(g)} + H_{2(g)} \left\{ \Delta H^0 = 206.3 \text{ kJ/mol of } CH_4 \right\}. \tag{6}$$

As can be seen, the cracking reaction is endothermic and requires external energy for the reaction to proceed. In practice, part of the natural gas is burnt to provide the energy for raising the reaction temperatures to about 800 °C. Figure 2 shows a block diagram of DRI production process using natural gas. The natural gas in this case is reformed using steam.

The specific gas emission for iron produced from DRI unit is about 0.5 tons per ton of DRI. The emission further can be reduced by increasing the proportion of hydrogen through external injection of Hydrogen generated from the electrolysis of water.[22] DRI units can also be modified to use only hydrogen as a reductant and the external energy required for sustaining high temperature could be provided by electrical energy from a renewable source. This is a promising technology that can produce iron from iron ore with no CO_2 emissions. However, the challenge is to meet the entire energy requirement for electrolysis for the production of Hydrogen and reduction process from a renewable energy source.[20]

$$2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)} \left\{ \Delta H^0 = +242 \text{ kJ/mol of } H_2O \right\}. \tag{7}$$

Considering a process temperature of 1000 °C, the energy requirement will be about 4000 kWh per tonne of DRI. Figure 3 is a block diagram of iron production by direct reduction using hydrogen generated by electrolysis of water.

DRI is further to be melted to remove the gangue from the iron ore as slag and to convert molten iron to the steel of required composition with alloy additions. Considering an electric arc furnace for the melting and refining process, the energy required for the production of one ton of crude steel is about 560 kWh/tonne. Depending upon the route of DRI production the CO_2 emission intensity of DRI- EAF route of steel production could vary from 1.61 ton CO_2/ton of crude steel to 3.77 ton CO_2/ton of crude steel.

Table 2 gives the comparison of CO_2 emission intensity for various routes of steel production from iron ore, considering electrical energy production from coal. DRI production using hydrogen generated by electrolysis is higher than hydrogen produced by steam reforming of natural gas due to the fact that the electrical energy required for electrolysis is very high and electricity generation from coal has the highest CO_2 emission intensity at 0.95 kg CO_2/kWh.[18]

If the electrical energy required for electrolysis and EAF is produced from renewable energy such as wind power the CO_2 emission intensity can be as low as 0.508 tCO_2/tcs. Hypothetically if all the energy requirement is met by renewable power the CO_2 emission intensity will be about 0.056 tCO_2/tcs.

3 Steel Production from Scrap

Flat steel rolling mills, in general, are of larger capacities—in the range of 2 million tons per annum to 5 million tons per annum. To feed the mills balancing steel-making capacities of similar size is required. This would require multiple units of DRI and electric arc furnace combinations, which in turn is capital intensive.

However, rolling mills producing long products such as reinforcement bars, structural steel sections, plain carbon and alloy steel bars for engineering application, rails can be of varied capacities ranging from as low as 0.10 million tons per annum to 1.0 million tons per annum. A

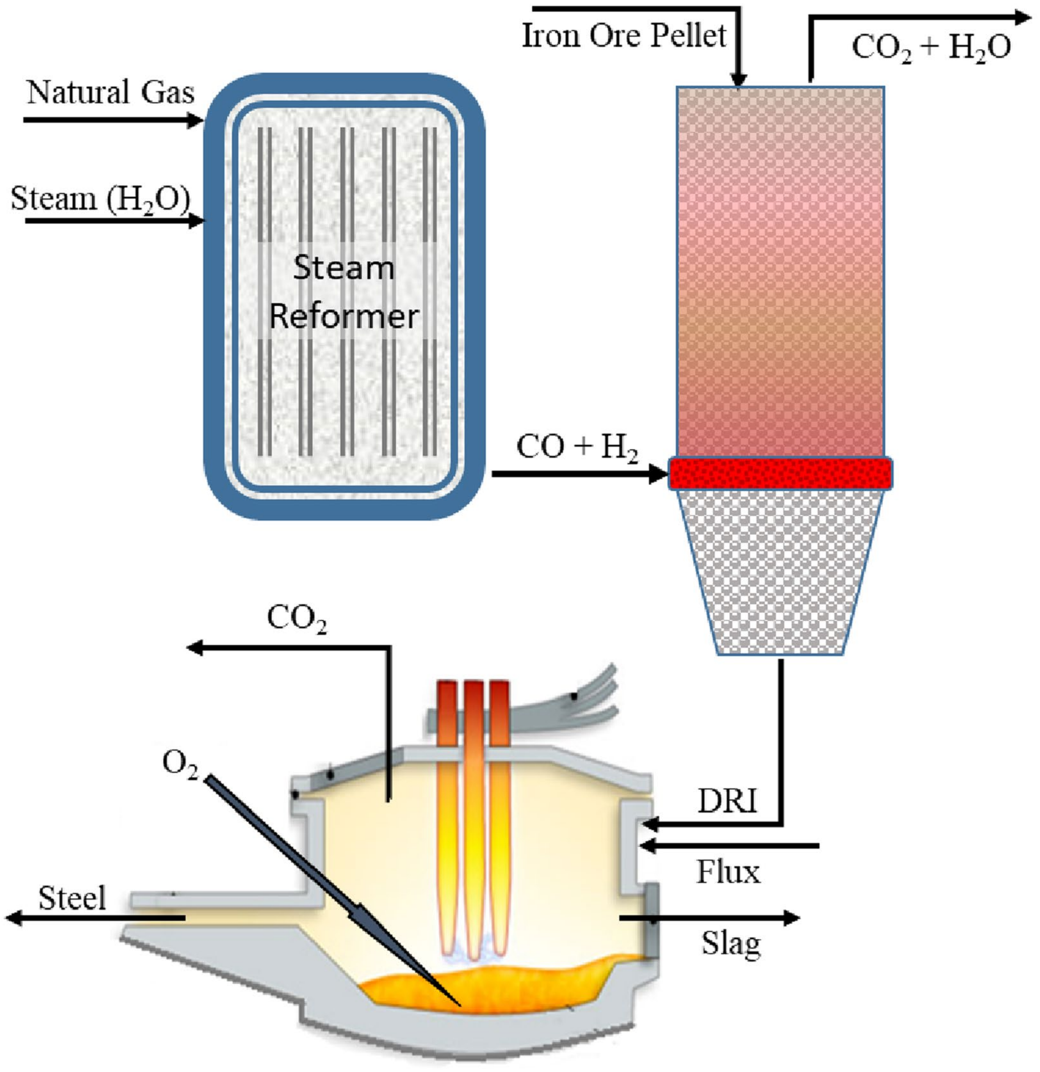

Figure 2: DRI Production using steam reformed Natural Gas.

micro or mini steel mill could be established near consumer point with a combination of DRI and/or scrap as input and electric arc furnace/induction furnace as a primary steel refining unit.[23] Micro units could utilise scrap which completely eliminates the requirement of iron ore and reductants and reduces the emissions to a greater extent.[24]

Melting of one ton of scrap requires about 930 kWh of energy which is equivalent to 0.88 tons CO_2 emissions considering coal as energy source or 0.44 tCO_2/tcs considering the natural gas source of electrical energy. Compared with 1.8 tons of CO_2 emission through BF-BOF route,[15, 16] CO_2 footprint of steel production from scrap is about 25% only. If the entire electrical energy requirement is met through a renewable energy source, the carbon footprint is close to zero[25–27] for steel production from scrap.

Table 3 lists the various combinations of steel production using DRI and scrap in electric furnaces. Both the routes of DRI production have been considered: from natural gas (Sl. No. 1 in Table 3) and with Hydrogen from electrolysis (Sl. No. 2 in Table 3) and natural gas is considered for heat input. As can be seen, if the electrical energy requirement is met through renewable energy sources, the carbon footprint of steel production can be as low as 0.508 tCO_2/tcs for iron input to EAF from DRI and 0.098t CO_2/tcs for producing from scrap.

The CO_2 emission of steel from scrap using EAF with renewable power source is negligible compared to 1.94 tCO_2/tcs resulting from BF-BOF route. The life cycle carbon footprint for

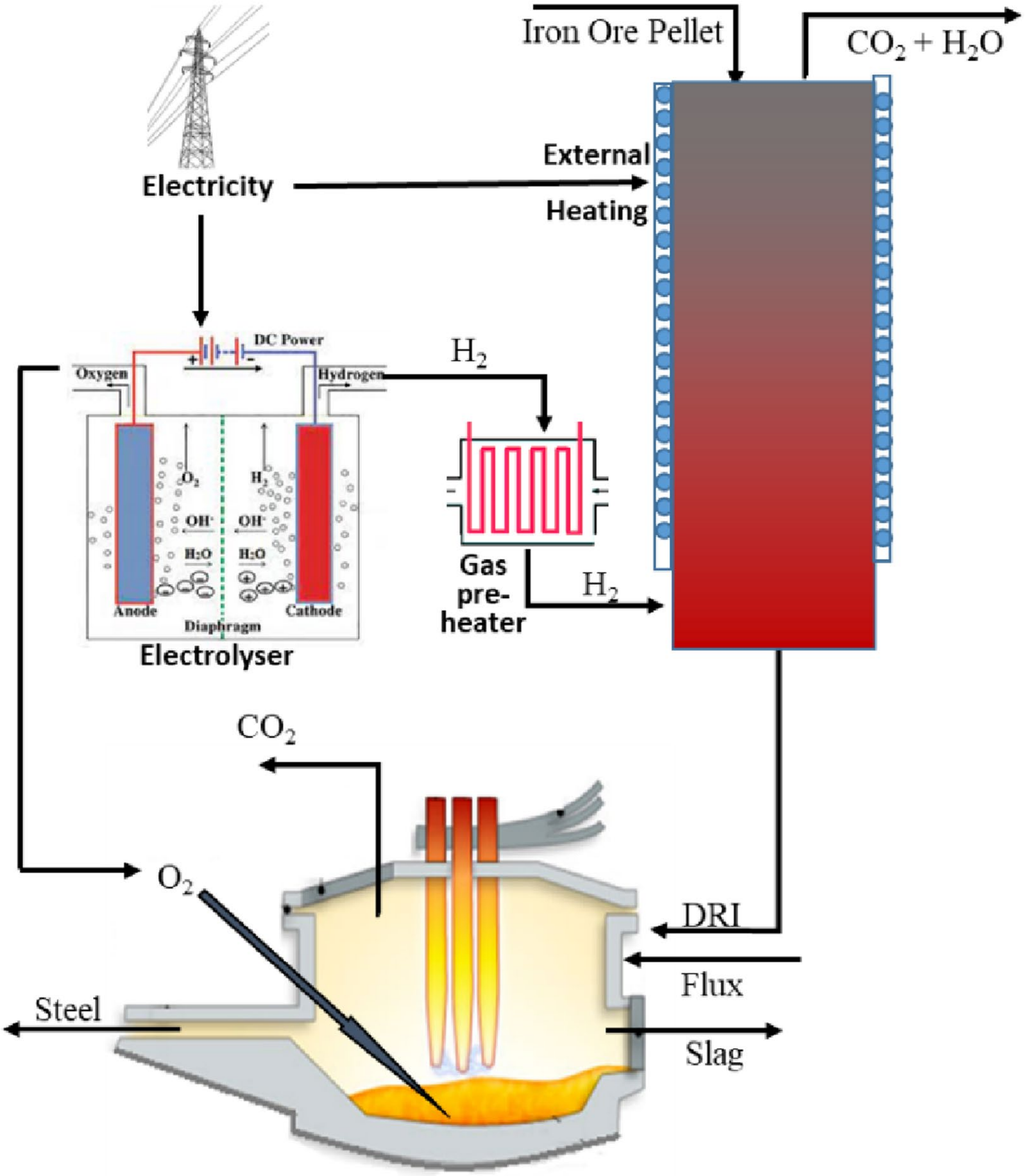

Figure 3: Process flow diagram for dri using hydrogen from electrolysis[20].

Table 2: Comparison of CO_2 emission intensity of primary steel production by various routes.

Sl. No	Route of steel production	CO_2 emission (t/tcs)
1	Blast furnace—basic oxygen furnace	1.94
2	DRI using natural gas—EAF	1.61
3	DRI using hydrogen from Electrolysis and thermal energy from Natural Gas – EAF	3.77

the scrap as input has been considered zero in this case, assuming the LCA footprint of the scrap has been accounted fully during it previous usage cycle.

4 Advanced High Strength Steel (AHSS) and Ultra High Strength Steel (UHSS)

4.1 Automobiles

Life Cycle Assessment (LCA) of CO_2 emission is a normalised method of evaluating the carbon footprint of any product from the production

Table 3: CO_2 emission intensity of EAF with various sources of iron and electricity.

Sl. No	Process route	Energy requirement GJ/tcs Thermal + Chemical	 Electrical	Total CO_2 emission intensity (tCO_2/tcs) Thermal energy + Electrical energy from coal	 Electrical energy from natural gas	 Electrical energy from wind
1	DRI + EAF	15.73	2.57	1.61	1.27	0.940
2	H_2-DRI + EAF	7.42	12.54	3.77	2.59	0.508
3	(50% H_2-DRI + 50% scrap)- EAF	4.32	7.32	2.21	1.24	0.302
4	100% scrap – EAF	1.23	2.11	0.648	0.369	0.098

till the end of life of application of the product.[28] In general, LCA is widely used in the automotive industry to assess the carbon footprint of the vehicle till its service life. Typically, for a mid-size passenger vehicle running on gasoline, the carbon footprint during manufacturing is about 25% and 75% is from the tail end emissions. The shift towards electric vehicles for passenger commute is gaining momentum leading to the elimination of tail-end emissions in the electric vehicle.[29] However, the source of electricity is the major deciding factor for the LCA carbon footprint. As mentioned in the previous section, if the electricity is produced from coal, the tail end emission is replaced by CO_2 emission from the power plant and the LCA carbon dioxide emission in fact increases. On the other hand, if the electricity is produced from renewable energy sources, the life-time CO_2 emissions are nearly zero. The CO_2 emission intensity of an electric vehicle is more than the conventional gasoline engine vehicle due to the addition of CO_2 emission during the production of the storage batteries.[30] To increase the range of electric vehicles, the weight of the vehicle itself is being reduced through the selection of material with a higher strength to weight ratio.

In a midsize vehicle of about 1500 kg,[31] proportion of steel is about 40%. Of these about 180–240 kg is the body-in-weight (BIW) and the rest of application is in chassis, suspension and safety parts and other components.[31] The weight of the steel used in the vehicle can be reduced using higher-strength steel. Currently, advance high strength steel (AHSS) with strength levels up to 980 MPa are used in the chassis and crash components. Small percentage of hot-formed steel with strength level up to 1500 MPa is used in some of the passenger vehicles. The steel weight can further be reduced by application of Advanced High Strength Steels with strength levels more than 1200 MPa and Ultra High Strength Steels (UHSS) with strength level in the range of 2000–2400 MPa. For instance, a typical suspension coil spring is made of steel with about 1800 MPa tensile strength and if steel with tensile strength more than 2200 MPa could be used the weight reduction is about 20%. Similarly, by using higher strength steels, the component weight can be reduced by 20–40%. According to World Auto Steel, weight reduction in a compact passenger car with an average kerb weight of 1249 kg can be as high as 80 kg per vehicle. This will amount to reduction of about 1500 kg CO_2eq during a service run of 250,000 km.[28] Reduction during production of the vehicle due to lesser material use will be about 260 kg. In effect the reduction in life cycle CO_2 emission by using AHSS and UHSS in future passenger cars is more than that achievable by using alternate material.[32] Electrical mobility coupled with AHSS usage will has greater potential for reducing the total CO_2 emission intensity. Again the extent of reduction will largely depend on the source of electricity and the grid mix.[33, 34]

4.2 Structural Applications

In the Indian context of steel consumption, only about 10% is used in automobiles whereas about 40% is used in building and construction. Of this 40%, substantial quantity is used as steel bars in RCC structures. Steel structural buildings and Pre-engineered buildings are gaining momentum in India. In structural buildings like industrial sheds and warehouses, steel forms more than 90% of construction materials used.[35] Typically for an industrial shed of 1000 sq. m. about 150 tons of steel in the form of columns, I-beams, angles and purlins. The yield strength of the steel varies from 250 to 350 MPa and the corresponding tensile strength from 410 to 520 MPa.[35]

The smaller sections are as rolled angles and beams and the columns generally are fabricated or hot rolled depending on the size. The carbon

Table 4: Comparison of Steel requirement for Conventional and High strength structural steels.

Detail	Conventional Steel	High Strength Structural Steel
Super Structure (kg /sq m)	60	30
Columns and Beams (kg/sq m)	90	54
Total weight of steel (kg/sq m)	150	84
Specific CO_2 emission (k CO_2/sq m)	286	161

footprint attributed to the use of steel in the construction of a warehouse or industrial shed is about 286 kg CO_2/sq.m of warehouse/shed. Of the 150 Tons of steel nearly 40 is the superstructures such as roof trusses and purlins. Similar to the use of AHSS in automobiles, if high strength roll-formed steel sections with YS > 600 MPa and UTS > 900 MPa is used in place of conventional hot rolled sections, the cross-section of the elements in the super structure can be reduced by nearly half and in turn about 50% in weight saving.

The weight of the superstructure can be reduced from 60 kg/sq.m to about 30 kg/sq. m of warehouse/shed. Similarly, using high-strength steel for the columns and beams, the weight reduction could be in the range of about 30%, keeping structural integrity in consideration. The total reduction in steel will be about 57 kg/sq. m of warehouse/shed. The reduction on the carbon footprint will be about 108 kg CO_2/sq.m of warehouse/shed. Further reduction in carbon footprint could be achieved by carrying out similar weight reduction exercise for the roofing material. Table 4 gives the comparison between the conventional rolled steel and high strength roll-formed steel.

5 Conclusions

1. Steel can be produced with zero CO_2 emission or minimum possible carbon footprint by re-engineering the process of reduction of iron using hydrogen.
2. Higher proportion of steel production from scrap using electricity from renewable energy sources can reduce the carbon footprint of steel products.
3. The extent of carbon neutrality achievable depends on the source of electrical energy.
4. Life Cycle CO_2 emissions can be reduced by replacing conventional steel with Advanced High Strength Steel and Ultra High Strength Steel in steel constructions and automobiles.
5. With a combination of low CO_2 steel production and the use of higher strength steel, steel will continue to be a choice of material for engineering application.

Publisher's Note

Declarations

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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