

Chapter 1 Introduction and literature review

Steel is the most important engineering and construction material used globally. Steel has the widest range of applications ranging from kitchenware to skyscrapers, advanced rockets and spacecrafts. With over 3500 different grades, steel is the most versatile material known to mankind. Use of steel in various sectors are shown in the Figure 1.1 [1]. World crude steel production for year 2021 reached 1950.5 million tonnes which has increased 10-fold in the past 100 years [2]. Steel production by top five countries is shown in Figure 1.2. China is the biggest crude steel producer, producing 53% (1032.8 MT) of the global crude steel. India produces 118 million tonnes of steel which is 6.1% of global production.

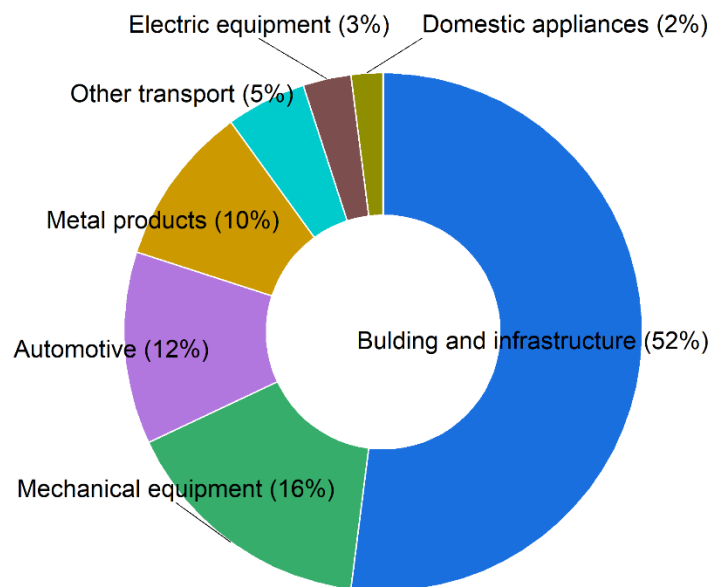


Figure 1.1 Sector wise steel consumption in 2019 [1].

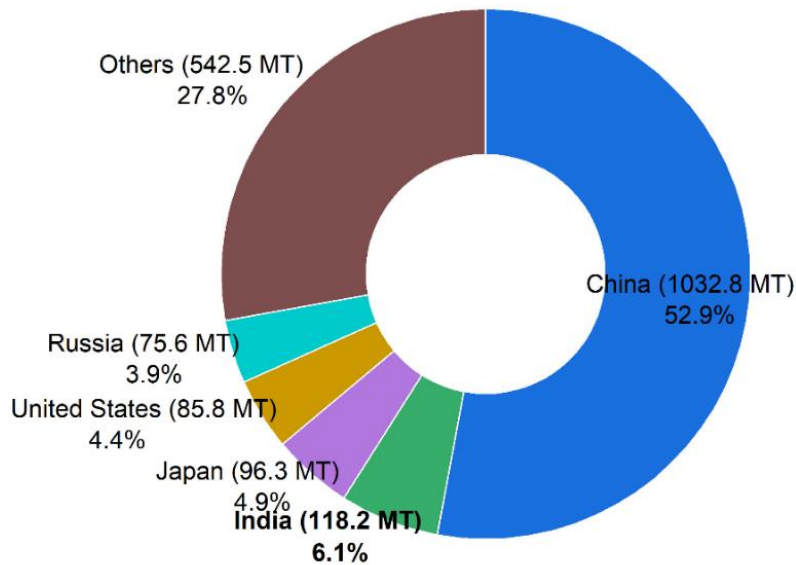


Figure 1.2 Crude steel production by top 5 countries [2].

1.1 Raw materials for steelmaking

There are three industrial routes for steelmaking practiced around the globe. The first and the most popular is the blast furnace-basic oxygen furnace (BF-BOF) route which constitutes almost 70% of total steel production. Second route is steel scrap melting in electric arc furnace or induction furnace (EAF/IF) and the third one is melting of directly reduced iron in electric arc furnace (DR-EAF). Production of steel requires iron ore/scrap steel, coal and limestone as raw materials. Typically, every tonne of crude steel produced via BF-BOF route consumes 1.4 tonnes of iron ore, 780 kg of metallurgical coal, 270 kg of limestone and 125 kg of steel scrap [3]. Typical iron rich hematite ores used in blast furnace contain 64-68% Fe. Metallurgical grade coal has fixed carbon (FC) content of 86-91%, volatile matter (VM) of 22-32%, moisture content up to 2% and calorific value of 8600-8800 kcal/kg. In general, CaCO_3 content in limestone should be greater than 95%, with SiO_2 content less than 5% and MgO & Al_2O_3 each below 3%[4].

Chemistry of the steel produced relies heavily on the quality of raw materials. Specially, in case of blast furnace ironmaking, metallurgical coke has to meet stringent quality requirements.

Coke produced from metallurgical grade coal after coking or coke making treatment is used in the blast furnace (BF). Coal does not have adequate strength and porosity to make it a suitable fuel for blast furnace application. Coke acts as a reductant, holds the overlying burden and provides thermal energy in the blast furnace. Metallurgical coke should have more than 85% FC, less than 10% ash and less than 2% VM [4]. Use of different raw materials in different routes of steelmaking, i.e., BF-BOF, Scrap-EAF and DRI-EAF are shown in Figure 1.3.

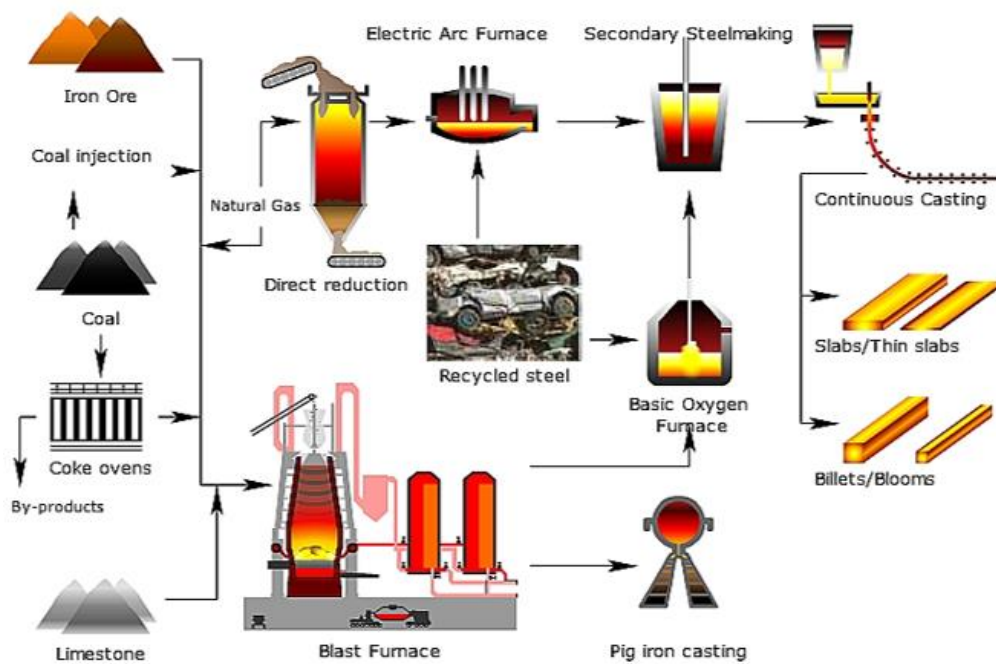


Figure 1.3 Raw materials, process flow and products in different steelmaking routes (EC Dragna et al., 2018 [5]).

1.2 Historical developments in steelmaking

Exact beginning of the ancient ironmaking process is not clear. However, as per archaeological reference, first ironmaking practice dates back to no earlier than 11th century BC [4]. The origin of ironmaking is generally credited to the eastern end of the Mediterranean. Evidences suggest that ancient ironmaking was performed in pit type furnaces in batch operations. In India, delicate surgical instruments evidently were in use before Christ. By 310 AD the knowledge of ironmaking was sufficient to produce non-corrosive iron pillars weighting 6-7 tonnes

standing tall presently at Delhi and Dhar [6]. The first blast furnace had appeared in 1340 in Belgium [7]. Wood charcoal was used as reductant and energy source in these blast furnaces and the practice continued till extensive deforestation was apparent in 1676 in United Kingdom. Dud Dudley in 1619 renewed John Robinson's patent in his own name for 21 years to smelt iron with mineral coal (known as pitcoal back then) [8]. However, due to various reasons pig ironmaking by pitcoal in the form of coke came into general use only after mid of 18th century. Abraham Darby was the first one to use coke successfully in the blast furnace in 1709 [9]. Finney and Mitchell suggested that the industrial revolution began with the transition of wood charcoal to coke as the primary fuel for ironmaking [10]. The blast furnace underwent several modifications and developments to become most efficient reactor for ironmaking. Coke as a fuel for blast furnace continued incessantly for over two centuries till middle of 20th century. During middle of 20th century researchers realised that reserves of prime coking coal suitable for coke making is limited in nature. Fossil fuels formed over a time span of more than 100 million years is being consumed with very high rate and as per a recent estimate will last for 100-150 years [11].

Thus, search for an alternate and carbon neutral fuel became essential. Many alternative processes devoid of blast furnace and coke have been developed in last 50-60 years as a result. These processes are broadly categorised as direct reduction (DR) and smelting reduction (SR) processes. Direct reduction process is the one where removal of oxygen from the iron ore takes place in solid state whereas smelting reduction is the one which yields liquid iron as a product (same as blast furnace). Direct reduction processes can be further classified in two groups based on the type of fuel used i.e., coal and gas based. SL/RN, Finex, Fastmet and Inmetco are some of the coal-based direct reduction processes. Hyl, Midrex and Finmet are some of the gas based processes [12]. COREX, FINEX, ITmk3 and Hismelt are some of the smelting reduction processes. Some of the plants based on these alternative processes are running successfully on commercial scale alongside blast furnace [13].

1.3 Fossil fuel consumption and CO₂ emission by steel industry

Use of fossil fuel (coke/coal/natural gas) for steelmaking generates CO₂ as one of the by-products. The generation of CO₂ is neither incidental nor accidental, as SO₂ and CO might be considered to be. It is basic and unavoidable during exploitation of fossil fuels. SO₂, NO_x, CO and most of the other industrial pollutants cause problems locally and precautions can be taken to avoid loss of life and property. CO₂ on the other hand cause no local problem and is not considered as a pollutant. However, this CO₂ being a green-house gas causes problems on global scale in the form of global warming by disturbing natural carbon cycle. Among greenhouse gases, CO₂ is more deleterious in the sense that it constitutes 70% of the total greenhouse gases and absorbs 15 μm wavelength photons in infrared region which otherwise could easily pass-through atmosphere [14]. As shown in Figure 1.4, CO₂ level in the atmosphere is rising rapidly due to heavy CO₂ discharge from anthropogenic activities.

The steel industry accounts for 20% (474 EJ) of industrial fossil fuel consumption [15]. It emits 2.6 Gt CO₂ which is 7% of global anthropogenic greenhouse gas emissions [16]. The recorded level of CO₂ in pre-industrial period was 285.2 ppm (in 1850 [17]) against a current level of 420.99 ppm (in June, 2022 [18]) in our atmosphere. In response to the rising CO₂ concentration in atmosphere, global average temperature has risen by 1.15 degrees and almost half of the polar ice has already melted [19]. Melting of polar ice has resulted in the rise in sea level in excess to 100 mm. The adverse outcomes of the climate change have not yet materialized completely. Events of submerging of coastal areas, change in wind & rain pattern, change in vegetation, drought, desertation will follow unless concerted corrective measures are taken globally.

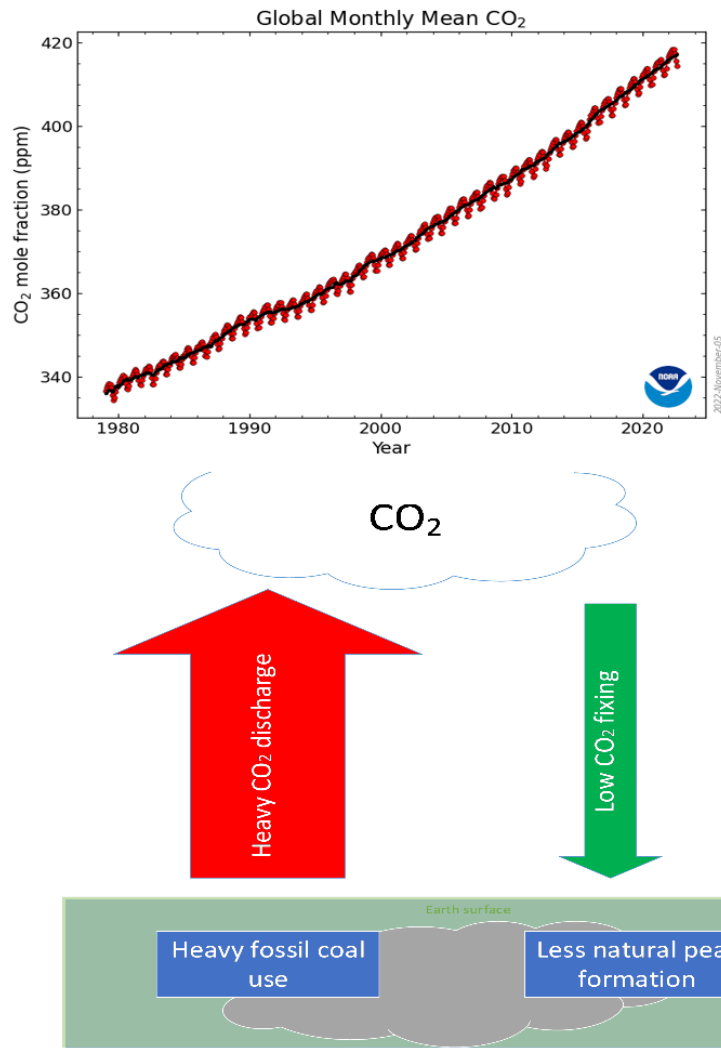


Figure 1.4 Rising level of CO₂ in atmosphere [14]

1.3.1 Global initiatives at controlling the environmental damage

Recognizing the severity of GHG emission problem, United Nations (UN) has forced nations to sign a treaty to reduce their green-house gas emissions. United nations framework convention on climate change (UNFCCC) was adopted on 9th May 1992. The goal of this body is to impede dangerous anthropogenic interference with climate on Earth. The Paris Agreement, which was enacted in 2015, aims to keep global warming considerably below 2 degrees, ideally to 1.5 degrees, in comparison to pre-industrial levels. The Paris Agreement is a legally binding international climate change accord. For the first time in Glasgow climate pact 2021, nations were urged to reduce their continued use of coal power and ineffective fossil fuel subsidies.

Governments may enforce rigorous emission standards for the iron and steel industry in the near future, compelling them to employ renewable and environment friendly energy sources. China, for example, already has a "Double Carbon" policy in place [20]. The Double Carbon policy aims to peak carbon emissions by 2030 and attain carbon neutrality by 2060. Governments and industries are actively working towards reducing the carbon and environmental footprint or greening of steelmaking processes [21]. Steel production without the use of fossil fuels is termed as green steel. To reduce 7% of the global CO₂ emission from steelmaking industry we have two alternative renewable non-fossil fuels for green steelmaking i) green hydrogen and ii) renewable biomass.

1.4 Use of hydrogen for green steelmaking

Hydrogen is an efficient and proven reductant for direct reduction of iron ore at lower temperatures [22-26]. For green hydrogen production water splitting is the only technology for large scale production. Other hydrogen production technologies, like steam-methane reforming, fermentation or photosynthesis are yet to develop for large-scale production [27]. Currently, water electrolysis consumes around 5 kWh of electricity to make one m³ of H₂ [28]. According to Kainersdorfer, it takes 810 Nm³ of H₂ to make one tonne of steel which requires 4.1 MWh of electricity.

Lab and pilot plant scale trials of iron ore reduction using hydrogen has begun in past few years [29-33]. Researchers at Max-Planck-Institut für Eisenforschung, Germany studied the fundamentals of hydrogen-based iron oxide reduction [34, 35]. They have also studied the iron ore reduction using hydrogen plasma [36]. Further, the process of direct reduction and plasma reduction were combined to maximize hydrogen utilization and improve process control [37]. The researchers also studied ammonia as a substitute to hydrogen for direct reduction of iron oxide [38]. Use of hydrogen plasma for smelting reduction in HPSR– The Sustainable Steel (SuSteel) project has been carried out successfully at a laboratory scale [29]. During smelting

reduction of hematite fine ore with hydrogen thermal plasma in lab settings, the degree of hydrogen utilization rose up to 60% [30]. Arcelor Mittal has successfully tested the partial replacement of natural gas with green hydrogen for the production of DRI at its steel plant in Contrecoeur, Quebec [32]. A joint venture of SSAB, LKAB and Vattenfall, sponsored by European union under the name HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is conducting pilot plant trials on direct reduction of iron ore pellets with hydrogen in Luleå, Sweden [33]. Apart from production difficulties of hydrogen, some problems related to easy transportation and storage have to be solved. We may have to wait for a period till generation of hydrogen without using fossil fuel (directly or indirectly) becomes commercially feasible.

1.5 Use of biomass for green steelmaking

As discussed earlier in §1.2, ironmaking process started off with the use of wood charcoal as a fuel and it soon became universal fuel for the smelting of iron ore. The same practice continued till about middle of the 18th century. The possibility of using wood charcoal for ironmaking could be re-examined specially, due to its renewability and non-polluting nature. Biomass can be made renewable by short rotation forestry or energy plantation. An energy plantation is one where some of the fast-growing trees are grown for their fuel value. It consists of raising larger than normal number of plants per unit area and harvesting them in shorter than normal (say 5 to 10 years) period of time [39]. In tropical countries like India with huge landmass and around 300 sunny days per year energy plantation becomes more favorable [40]. The biomass is renewable, carbon-neutral, highly reactive, material having low sulfur, low ash, high specific surface area and stable pore structure. A comparison of formation and consumption time cycles for coal and biomass are shown in Figure 1.5.

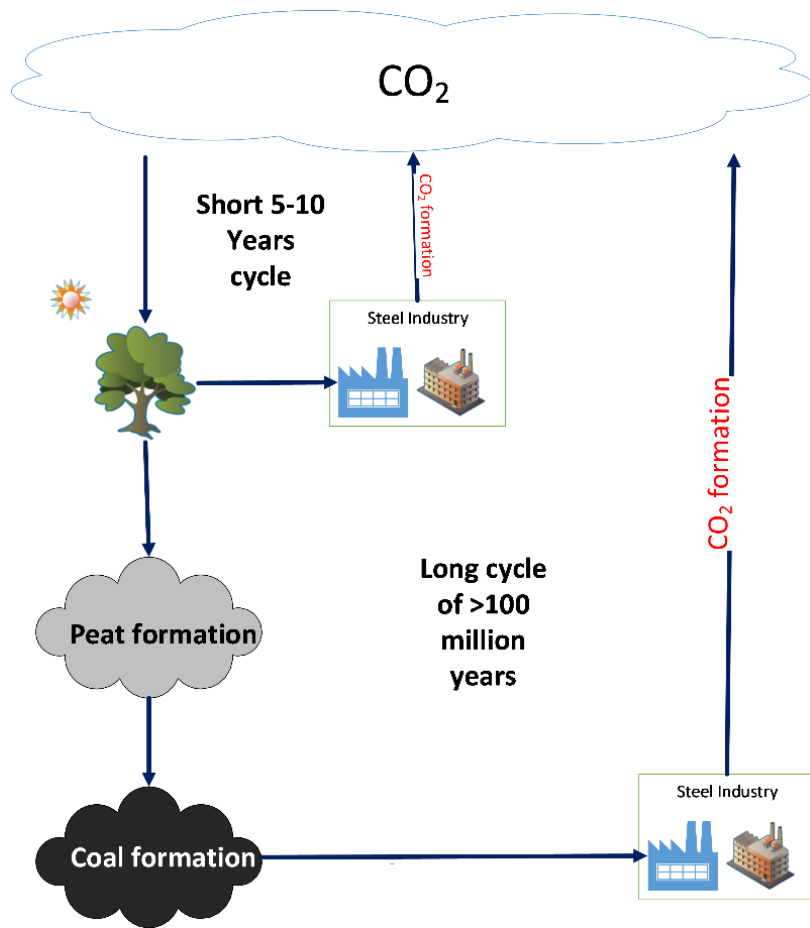


Figure 1.5 Formation and consumption time cycles for coal and biomass.

Firstly, biomass is carbon neutral in the sense that it releases the exact amount of CO_2 on pyrolysis which was utilized during photosynthesis in making the biomass. Whereas consumption of fossil fuels contributes to the atmospheric CO_2 . Secondly, being lower in sulfur content than fossil fuels, biomass is not likely to pollute the atmosphere with SO_2 . Also, steel made by using biomass will have lower sulfur level and might not need external desulphurization. Biomass cultivation and utilization would be a positive step in reducing atmospheric pollution and could substitute for fossil fuel used in ironmaking. The following section discusses recent research conducted across the globe on biomass application as a reductant and energy source in different ironmaking processes for possible replacement of fossil fuel and its potential in reducing the fossil CO_2 emission.

1.5.1 Blast furnace – Basic oxygen furnace (BF-BOF) route

Various researchers have tried replacing or partially substituting fossil fuel by biomass in blast furnace process. It was pointed out that important area of application for biomass in blast furnace are coke making, sinter making, pulverized injection through tuyeres and nut coke.

Table 1.1 lists typical biomass addition, possible substitution rate, amount of charcoal needed and net CO₂ emission reduction in the above-mentioned areas.

Table 1.1 Application of biomass derived charcoals for mitigation of CO₂ emission in different ironmaking processes (after Mathieson et al., 2011 [41])

Application and replaced carbon source	Typical addition, kg/THM	BM substitution rate, %	BM amount, kg/ THM	Net emission reduction t-CO₂/t-Crude steel	Net reduction in % of CO₂ Emissions
Sintering solid fuel	76.5–102	50–100	38.3–102	0.12–0.32	5–15
Coke making blend	480–560	2–10	9.6–56	0.02–0.11	1–5
BF Tuyere fuel injection (PC)	150–200	0–100	0–200	0.41–0.55	19–25
BF nut coke replacement	45	50–100	22.5–45	0.08–0.16	3–7
BF carbon/ore briquette	10–12	0–100	0–12	0.06–0.12	3–5
Steelmaking recarburiser	0.25	0-100	0-0.25	0.001	0.04
Total	761.75–919.25	0–100	70.4–415.25	0.69–1.25	31–57

Coke cannot be fully replaced due to its physical, chemical, and thermal roles in the process. Lab and pilot scale studies show that biomass can substitute 5-15% of coal in the coal blend used to make bio-coke [42-45]. Addition of biomass reduces coke strength and increases reactivity. However, biomass after pre-treatment like pyrolysis can be added in higher quantities without deteriorating the coke quality. Particle size, density and VM should be considered before adding to the coal blend.

Coke breeze is primary fuel used for sintering of iron ore fines. Due to low calorific value and high moisture content, substitution of coke breeze with biomass is not possible. However, pyrolyzed biomass i.e., charcoal can partially replace it and decrease SO_x and NO_x generation during sintering [46, 47]. Addition of charcoal has some limitations in terms of decreased sinter strength, yield and granulation [48]. Coke breeze up to 25 wt% can be replaced by charcoal and up to 40-60 wt% can be replaced by coke-charcoal composite [49, 50]. The amount of charcoal can be increased by increasing particle size, density and decreasing its reactivity [50].

Biomass with mill scale can be used as cold bonded briquettes for top charging in the blast furnace. Mechanical strength of these briquettes decreases with increase in the amount of biomass [51]. This issue has been tackled by increasing the binder (cement) content. Biomass along with iron ore in the form of composite pellet is also an alternative which can be used for top charging in the blast furnace. Reduction process is rapid due to close contact of carbon and iron oxide particles in these composites which acts as highly active microreactors [52]. The iron oxide was completely reduced above 1000 °C. Rate of the reduction increased with rise in reduction temperature due to improved decomposition of hydrocarbons into reducing gases in conjunction with more heat available for endothermic reduction reaction [53]. A complete reduction of iron ore to metallic iron required 30 wt% of sawdust [54]. Low crushing strength of these composite pellets limits its practical applications in the blast furnace. Top charging of these briquettes and composite pellets decreases CO₂ emission and energy consumption in the blast furnace.

The easiest option for biomass application in the blast furnace is injection of biomass through tuyeres as mechanical strength is not a requirement. Because of properties such as strong reactivity, low ash, low sulphur and high hydrogen content, biomass tuyere injection is advantageous in terms of low slag volume, high injection rates, improved process efficiency, and therefore higher production rate. Wood pellets can replace 20% while torrefied biomass

22.8% of pulverized coal [55, 56]. There are some limitations as well like low calorific value, grindability and cost [57]. Opportunities for using wood charcoal in steelmaking are shown in Figure 1.6.

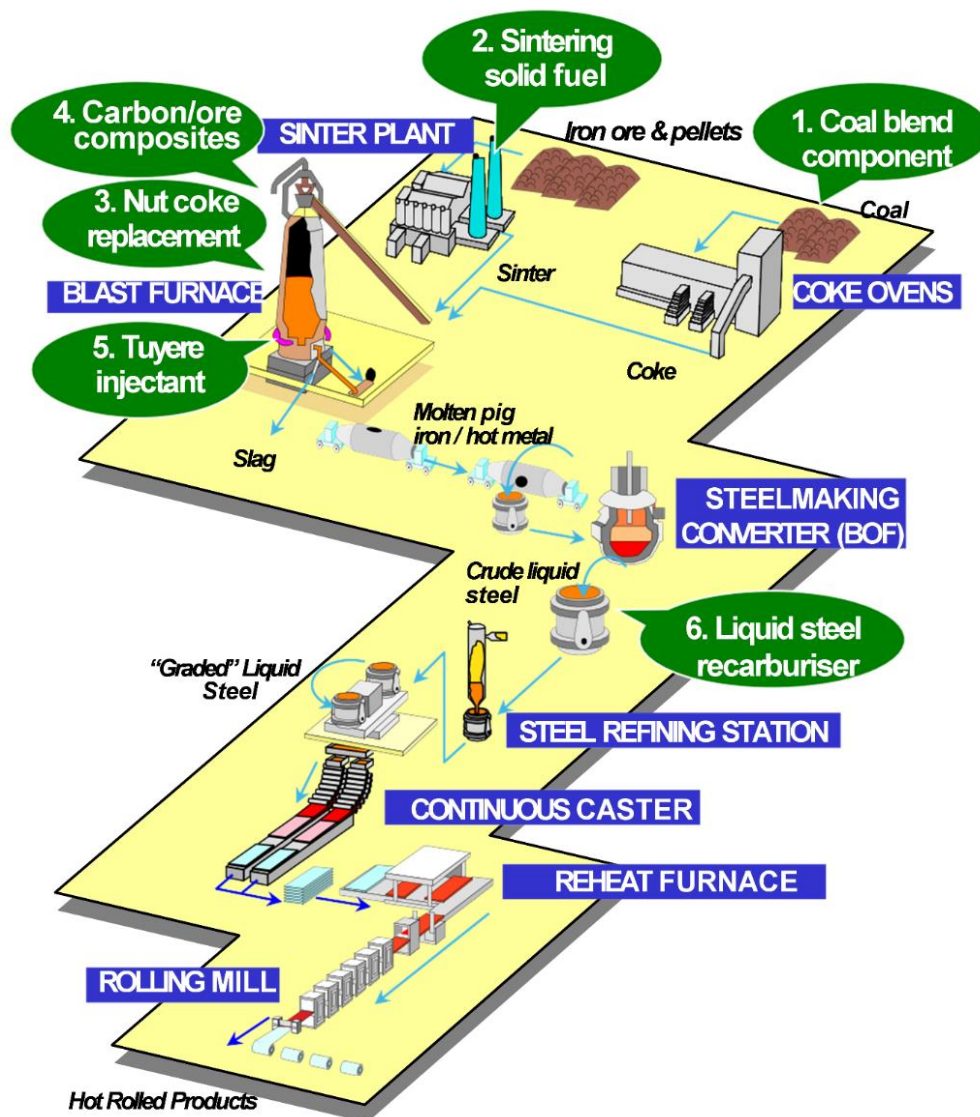


Figure 1.6 Prospects of using wood charcoal in steelmaking (Jahanshahi et al., 2013 [58]).

1.5.2 Alternative routes

Apart from the above-mentioned studies, work is also being carried out to evaluate charcoal as a reductant in alternative ironmaking processes. Owing to higher carbon content, lower phosphorous and sulphur, low ash and no constraint on mechanical strength enables charcoal

as a replacement of coal in alternative processes such as direct reduction. The European Union has developed ULCOS, or ultra-low CO₂ steelmaking [27]. The World Steel Association made considerable efforts through its CO₂ breakthrough initiative, including the Australian programme co-led by Bluescope Steel, OneSteel, and CSIRO. Iron ore-biomass composite might be used effectively in lower height blast furnaces as well in addition to reduction techniques like rotary hearth furnaces and rotary kiln furnaces [59-62]. Classification of direct reduction processes based on raw materials and energy sources are shown in Figure 1.7.

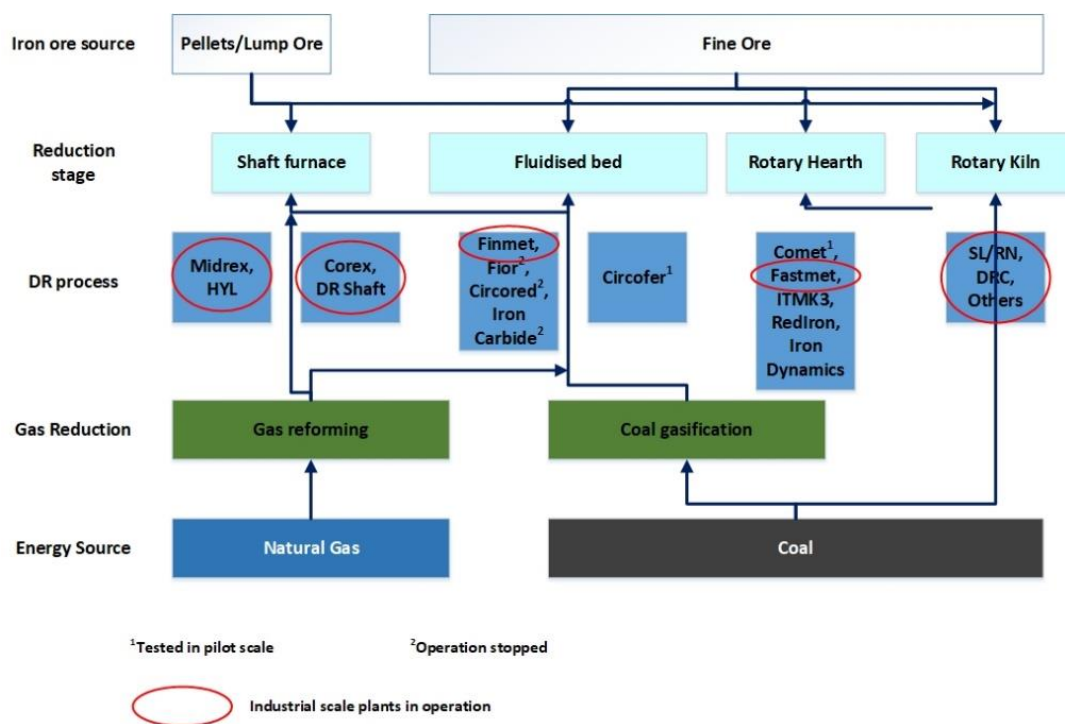


Figure 1.7 Classification of direct reduction processes (after Schenk, 2019 [63]).

Researchers have studied direct reduction of iron ore with hardwood biomass as sawdust and charcoal powder in composite pellets or packed bed type setup. Decomposition of biomass produces CO and H₂ along with CO₂, CH₄ and other lower hydrocarbons, which act as reducing agent to iron ore [64, 65]. Hardwood biomass sawdust mixed with iron ore starts reduction reaction at 670 °C and completes at 1200 °C [54, 66]. Additionally, carbon deposition on iron ore can induce reduction to occur at temperatures above 500 °C [67]. Generation of the CO and

H₂ gases increases with rise in reduction temperature [53]. Increasing the heating rate promotes reduction rate efficiently up to 20 °C/min [68]. Reduction of iron ore by biomass is two stage process: reduction by product of volatile cracking followed by reduction by non-volatile carbon. Diffusion of reducing gas controls the first stage and the Boudouard reaction or carbon gasification controls the second stage according to Wei et al. [69]. Other authors reported that diffusion controls the reduction reaction at lower temperature i.e., 800-1000 °C, chemical reaction controlling the reduction at higher temperatures [70, 71]. The activation energy for the reduction is reported to be in the range of 84 to 185 kJ/mol [69, 71].

Biomass derived charcoals have higher reactivity towards CO₂ than fossil coal enabling over 100 °C lower reduction start temperature (about 800 °C) [72, 73]. Higher reactivity is due to amorphous nature of wood charcoal [74]. The maximum reaction rate in case of charcoal is approximately 1.5 times the rate obtained with coal and concomitant with much higher reduction extent [72, 73]. Iron oxide (mill scale) reduced with charcoal achieved a total iron content of 98.56%, with the metallization ratio of 99.25% [75]. A reduction temperature of 1200 °C and reduction duration of 20 mins is sufficient for complete reduction of composite pellets [76]. Iron ore composite pellets reduced at 1000 °C with charcoal derived from hardwood gives reduction over 90% [77].

Increasing the amount of charcoal in composite pellets increases the rate and extent of reduction [73]. Increasing the heating rate promotes reduction rate efficiently up to 20 °C/min [78]. Reduction sequence is the same as in reduction of iron ore and coal composite pellet i.e., Fe₂O₃ → Fe₃O₄ → FeO → Fe [78-81]. Iron ore and charcoal composite pellets first expand and then shrink same as coal [82]. Preheating at lower temperature before actual reduction process increases extent of reduction of iron ore composite pellets by creating pores and increasing the contact area between iron oxide and reducing gas for the subsequent reduction process [83].

Increasing the composite pellet size from 8 to 16 mm resulted in decrease of reduction rate [74, 83].

It is agreed that initially solid carbon reacts with hematite and forms magnetite and CO gas (Equation 1). CO gas then reacts with magnetite and forms wustite and CO₂ (Equation 2). CO₂ generated from gas-solid reaction reacts with solid carbon to produce CO which is known as Boudouard or carbon gasification reaction (Equation 3). Gasification and iron oxide reactions take place simultaneously. CO generated from gasification reaction reduces wustite to iron metal as shown in Equation 4 [84, 85]. Researchers reported that the reduction reaction is controlled by the Boudouard reaction or carbon gasification [84] with its highly endothermic nature [86]. The activation energy for the charcoal reduction reported in literature is in the range of 59 to 160 kJ/mol [65, 87, 88].

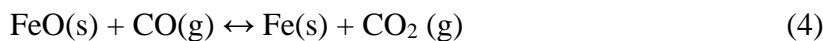
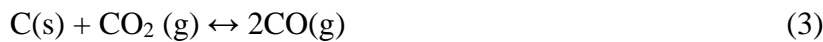
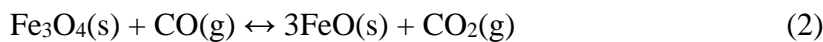
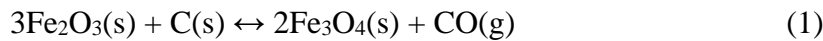


Table 1.2 lists the prior studies carried out in last 30 years on the application of different hardwood biomasses in alternative route of ironmaking. The table shows that different biomasses such as *Acacia*, *Eucalyptus*, *Sprue*, *Pine*, *Cypress*, *Birch*, *Oak*, *Bamboo* and wood sawdust were studied for their use in ironmaking across different countries.

Table 1.2 Prior studies performed on various hardwood biomasses in view of their potential use in direct reduction of iron ore.

Year	Author/s	Country	Biomass Species	Biomass Characterization					Carbonization			Charcoal Characterization						Reduction			
				Proximate	Ultimate	TGA	Strength	SEM	Temperature	Time	Heating rate	Proximate	Ultimate	Strength	SEM	FT-IR	Raman	CO ₂ Reactivity	C/O ratio	Charcoal type	Temp & time
1989	Kumar & Gupta [89]	India	Acacia and Eucalyptus														*				
1992	-do- [90]	-do-	-do-						*	*	*										
1992	M Kumar et al. [91]	-do-	-do-	*	*		*														
1992	M Kumar et al. [92]	-do-	-do-									*	*								
1994	-do- [93]	-do-	-do-														*				
1994	Kumar & Gupta [94]	-do-	-do-														*				
1995	-do- [95]	-do-	-do-													*					
1998	M Kumar et al. [96]	-do-	-do-										*	*							
2005	Paris et al. [97]	Germany	Spruce and Pine						*					*		*					
2006	V Strezov [54]	Australia	Sawdust	*	*													*		*	*

2007	Strezov et al. [98]	Australia	Sawdust	*	*	*			*		*			*							
2010	Konishi et al. [77]	Japan	Cypress									*	*						*	*	
2011	Luo et al. [99]	China	Sawdust															*		*	
2012	Park et al. [100]	Korea	Pitch pine			*			*			*	*								
2013	Zuo et al. [73]	China	Sawdust	*	*							*	*					*		*	
2014	Noumi et al. [101]	Brazil	Eucalyptus						*		*						*				
2014	S Agrawal [102]	India	Eucalyptus						*	*	*						*				
2016	Guo et al. [103]	China	Sawdust	*	*															*	*
2016	Wilk et al. [104]	Poland	Pine, Birch & Oak		*				*	*											
2017	Guo et al. [105]	China	Sawdust		*															*	*
2017	Liu et al. [106]	China	Pine	*	*	*														*	*
2017	Yuan et al. [85]	China	Bamboo	*		*												*	*	*	
2018	Usui et al. [74]	Japan	Cedar & Cypress						*	*	*	*	*		*				*	*	*
2019	Surup et al. [107]	Norway	Norway Spruce & Oak	*	*	*						*	*		*		*	*			
2020	Phounglamcheik et al. [108]	Sweden	Spruce & Birch			*			*		*		*			*	*				
2021	Murakami et al. [109]	Japan	Cypress	*	*													*		*	
2022	Yi et al. [110]	China	Sawdust	*	*	*									*			*		*	

Present work	India	Acacia, Albizia & Leucaena	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
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Notations: * means study carried out and empty box means not studied; Proximate- Proximate analysis, Ultimate- Ultimate analysis, TGA- Thermo-gravimetric analysis, Strength- compressive strength, SEM- Scanning electron microscopy, FTIR- Fourier transform infrared spectroscopy, Raman- Raman spectroscopy, CO₂ Reactivity- Reactivity of charcoals against CO₂ gas, C/O ratio- Molar ratio of carbon in charcoal to oxygen in iron ore, Charcoal type- Charcoals produced from different wood species or at different carbonization parameter, Kinetics- Reaction kinetics of iron ore reduction.

Researchers have characterized the wood, studied the effect carbonization parameters. Researchers have further characterized the produced charcoals and have used it for direct reduction of iron ores. It is noticeable that Kumar and Gupta from 1989 to 1999 [39, 90, 91, 93, 94, 96] have systematically studied *Acacia nilotica* and *Eucalyptus* for use in ironmaking. They have characterized the biomass, studied the carbonization process of the biomasses and characterized the product charcoals. However, they did not perform the reduction of iron ore using the produced charcoals. Other researchers have limited their studies to some part and some parameters of the process such as carbonization or reduction studies by using different biomass species.

1.6 Objective of the present work

Biomass is a renewable energy source and reductant with potential to decarbonize ironmaking industry. There are two possible applications for biomass: i) in blast furnace and ii) in alternative routes of ironmaking. Scope of this study is limited to use of biomasses in alternative route of ironmaking i.e., direct reduction of iron ore. Researchers have worked on various biomasses including agricultural, industrial and domestic wastes for reduction of iron ore. Still, it is not fully known as to which biomass will be better for ironmaking or what are the criteria of selection. Any biomass species out of forest or locally sourced waste cannot sustain huge scale of ironmaking. The practice will lead to deforestation as was the case in the past. If biomass is to be used for sustainable ironmaking, it needs to come from short rotation forestry or man-made forests. As evident from the Table 1.2, there is a huge scope for systematic study to utilize hardwood biomass in alternative route of ironmaking. After extensive literature review, objective of the present study was set to substitute the fossil coal by wood charcoal in direct reduction route of ironmaking. The objective was met by carrying out the research work in the following 4 major steps:

- i. Selection and characterization of biomass species suitable for ironmaking and short rotation forestry. (Chapter 2)
- ii. Characterization of charcoals produced from selected wood. (Chapter 3)
- iii. DRI preparation from iron ore-charcoal composite pellets. (Chapter 4)
- iv. Exploration for use of DRI in steelmaking. (Chapter 5)