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Decarbonisation Options for Rotary Kiln-Induction Furnace Process of Crude Steel Production

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The iron and steel industry is one of the significant contributors to global greenhouse gas emissions, and iron-making is the most energy- and emission-intensive step. India is the world's second-largest steel producer and the largest producer of sponge iron. The Indian sponge iron industry is primarily rotary kiln based and integrated with a captive power plant and a steel-making unit. This study investigates various decarbonisation options and their impact on the rotary kiln process for sponge iron production. The current process uses two different streams of coal, which can be replaced with bio-char and natural gas, whereas the low-grade dolomite can be replaced with a better grade one. The rotary cooler and magnetic separator in a conventional sponge iron plant can be replaced with a gravimetric separator enabling hot charging of sponge iron to the steel-making furnace. The savings in energy and carbon dioxide (CO_2) emissions are estimated based on the changes in electricity production/demand and the reduction in CO_2 emissions due to the elimination of coal. The options considered can reduce the emission intensity of crude steel production by 2,579 kg CO_2/t crude steel.

1. Introduction

The iron and steel industry is one of the world's largest carbon dioxide (CO_2) producing sectors due to its high production volume, with 1,816.6 Mt of crude steel produced in 2018. The direct emission from this sector is 2.6 Gt CO_2 which is 7 % of the global CO_2 emissions from energy systems (International Energy Agency, 2020). The average emission and energy intensities of this industry of crude steel (tcs) are 1.81 t CO_2/t and 19.51 GJ/t (World Steel Association, 2023).
Many studies on the decarbonisation of the iron and steel sector were reported in the literature. Hasanbeigi et al. (2013) discussed a model to estimate the energy efficiency improvement and CO_2 emission reduction possibilities for the Chinese iron and steel industry. Li and Zhu (2014) discussed the impact of various technology options on energy and emission savings and the associated cost for the Chinese iron and steel industry. Dey et al. (2015) analysed the energy aspects of the rotary kiln process for sponge iron production and discussed the possibilities of energy conservation through heat integration. Toktarova et al. (2020) proposed various future scenarios for steel-making based on different decarbonisation measures and compared them based on the cost and CO_2 intensity of steel. Nwachukwu et al. (2021) investigated the role of forest biomass in decarbonising the iron and steel industry. Fan and Friedman (2021) discussed the technology options and their economic assessment for the global iron and steel industry, considering all major processes. Nduagu et al. (2022) performed the life cycle assessment of greenhouse gas emissions for the Indian sponge iron industry considering rotary kiln and shaft furnace-based processes.
Most studies on the decarbonisation of the iron and steel industry analysed the blast furnace–basic oxygen furnace and electric arc furnace routes. Only a few research works focused on the rotary kiln–induction furnace process in detail, including technological and economic analysis. This paper analyses a 350 t/day (tpd) sponge iron plant integrated with an induction furnace and a captive power plant. Several decarbonisation options, such as the use of a gravimetric separator, better grade dolomite, use of biochar, and natural gas injection, are identified. The impact of these decarbonisation options on direct CO_2 abatement, power loss/power savings, and additional power generation is discussed in this work, along with their economic evaluation.

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2. Indian iron and steel sector

India is the second largest iron and steel producer, with 111 Mt of crude steel production in 2018-19 (Ministry of Steel, 2020), and contributes to 6.0 % of the global crude steel output. Indian iron and steel sector is one of the most diversified iron and steel sectors in the world, with an estimated 44.5 % of production from the Blast Furnace – Basic Oxygen Furnace process, 19.6 % from the Rotary Kiln-Induction Furnace process, and 5.1 % from the Shaft Furnace- Electric Arc Furnace process (Ministry of steel, 2020). The remaining production is from blast furnaces combined with electric arc furnaces, scrap processing in electric furnaces, and other processes like Corex. With a specific energy consumption of 25.1-27.2 GJ/t (Ministry of Steel, 2021) and a CO_2 emission intensity of 2.3 t CO_2/t (International Energy Agency, 2020), the Indian iron and steel sector is both energy-and emission-intensive.
India is the world's largest producer of sponge iron, contributing to nearly one-third of the global sponge iron output. Global sponge iron production in 2018 was 104 Mt. Contrary to other geographies of the world where sponge iron is produced in shaft furnaces using natural gas, 80.1 % of the sponge iron produced in India is from the coal-based process (Ministry of Steel, 2020). The rotary kiln process uses iron ore (hematite), non-coking coal, and dolomite as feed material. Most of these sponge iron plants are integrated with a captive power plant for waste heat recovery and induction furnaces to convert sponge iron into crude steel. Indian sponge iron industry uses locally available high-grade iron ore (>60 %). However, using low-grade non-coking coal makes the Indian sponge iron industry more energy-and emission-intensive.

2.1 Process description

In the rotary kiln process, feed (iron ore, coal, and dolomite) and slinger coal (also called injection coal) enter the kiln through the feed and discharge end. Air is injected into the kiln through the discharge end and portholes along the length of the kiln. A schematic diagram of a typical rotary kiln-based sponge iron plant is shown in Figure 1.

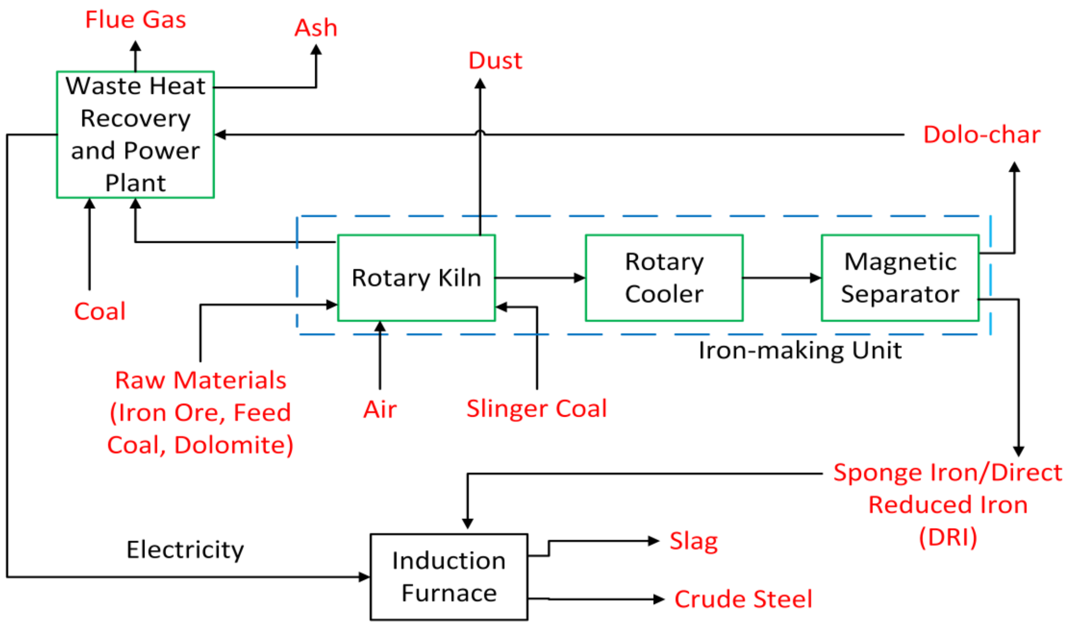

Figure 1: Schematic diagram of a rotary kiln-based sponge iron plant integrated with a captive power plant and induction furnace for crude steel production

Coal is a source of reductant and thermal energy and dolomite acts as a sulfur absorber. The iron ore (Fe_2O_3) is reduced to metallic iron in the kiln. Due to counter-current motion, waste gas leaves through the feed end, and sponge iron, calcined dolomite, and coal char leave as a solid mixture through the discharge end. This solid mixture is indirectly cooled in a rotary cooler to 110 °C (Dey et al., 2015), and the sponge iron is separated from the solid mixture using a magnetic separator. The sponge iron is finally melted in an induction furnace to make crude steel. Kiln off-gas with unburnt hydrocarbons is combusted, and the heat is recovered in a waste heat recovery boiler (WHRB). Dolo-char from the magnetic separator unit is mixed with coal and used as fuel in the captive power plant. The overall energy balance for the rotary kiln process is given in Eq(1).

$$Q = \Sigma m_2 h_2 - \Sigma m_1 h_1 + \Delta H_{reduction} + \Delta H_{calcination} + \Delta H_{loss} \quad (1)$$

Where Q is the energy required; m_2 and m_1 are the mass of products and reactants; h_2 and h_1 are the specific enthalpies of products and reactants; $\Delta H_{reduction}$ and $\Delta H_{calcination}$ are the energy required for the reduction of iron ore (Fe_2O_3) to iron (Fe), and calcination of dolomite; and ΔH_{loss} represents the kiln energy losses. The mass and energy balances considering 1 t of crude steel as the basis are shown in Figures 2 and 3. The calculated CO_2 emissions in the various steps of the rotary-kiln process are mentioned in Table 1. The power plant produces nearly 29 % of the emissions with an emission intensity of 1.21 kg CO_2/kWh. Surplus power generated is supplied to the grid. The plant can be given power generation credit in terms of CO_2, which is equal to the power supplied to the grid multiplied by the captive power plant emission intensity. Various decarbonisation options, their methodology of calculation, and their impact is discussed in section 3.

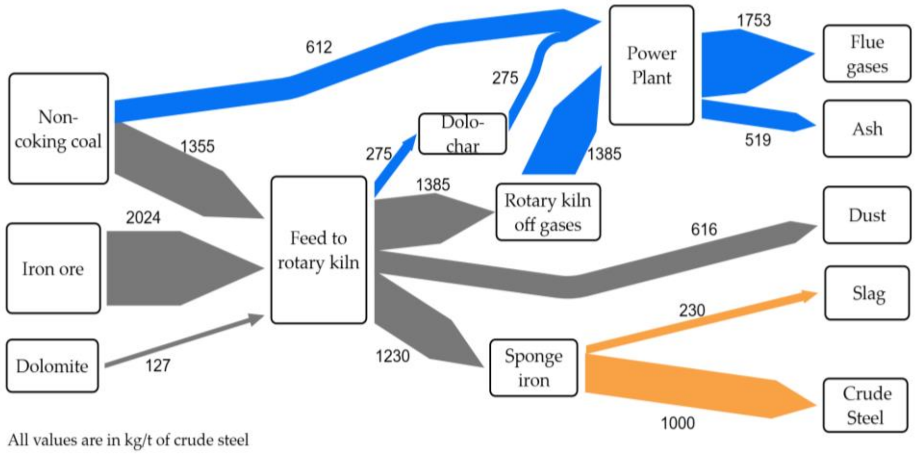

Figure 2: Mass balance for rotary kiln – induction furnace process for crude steel production (basis: 1 t of crude steel)

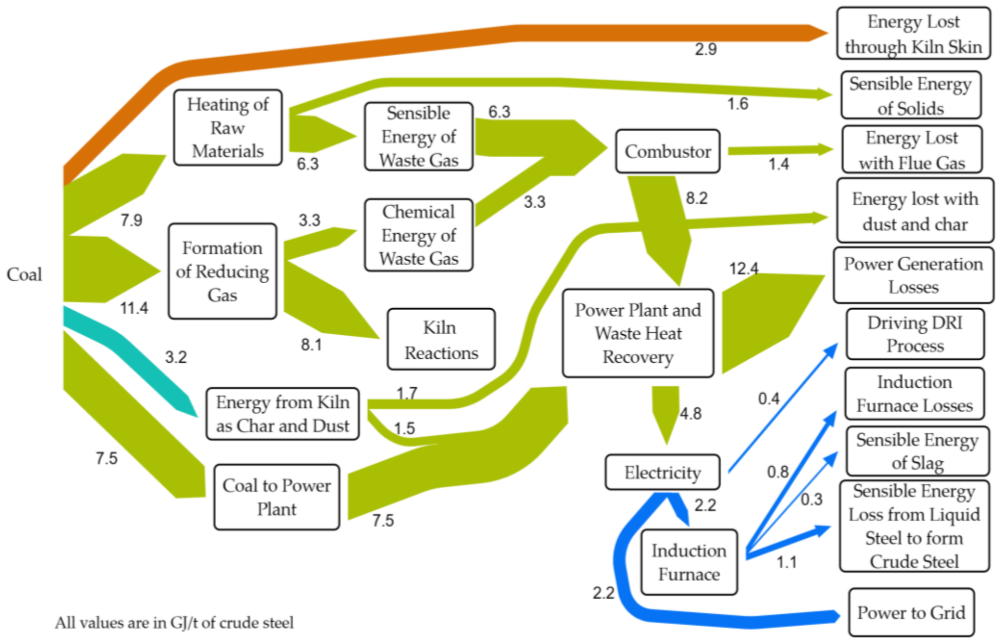

Figure 3: Energy balance for rotary kiln – induction furnace process for crude steel production (basis: 1 t of crude steel)

Table 1: CO_2 emissions in various process heads in the rotary kiln-induction furnace process of crude steel production (Surplus power generated is supplied to the grid. Power generation credit equals the power supplied to the grid multiplied by the captive powerplant emission intensity.)

Process heads	CO_2 emissions (kg CO_2 / tcs)
Coal combustion (rotary kiln)	2114
Dolomite calcination	56
Char combustion (power plant)	165
Coal combustion (power plant)	711
Total CO_2 emissions	3046
Power generation (credit)	-750
Net CO_2 emissions	2296

3. Decarbonisation measures

Decarbonisation of the rotary kiln–induction furnace process is necessary to improve the emission intensity of the Indian iron and steel sector. Four emission reduction measures – one each encompassing energy efficiency, material efficiency, fuel change, and use of renewable energy – are considered in this study. Their impacts and the corresponding carbon abatement costs are mentioned in Table 2. The total cost of an option is calculated by adding the fixed cost, maintenance cost, and operation cost. Annual maintenance cost is assumed to be 10 % of the fixed cost. The annualised fixed cost is the fixed cost times the capital recovery factor.

Table 2: CO_2 abatement potential and associated costs for various decarbonisation options

Sl. No.	Decarbonisation options	Type of options	Direct CO_2 abatement (kg/tcs)	Loss in power generation (kWh/tcs)	Net CO_2 abatement (kg/tcs)	Carbon abatement cost (US$/t CO_2)
1	Gravimetric separator	Energy efficiency	0.0	-175.9	213.7	-39.5
2	Bio-char replaces feed coal	Use of renewable energy	1,241.5	-378.7	1701.6	45.4
3	Better grade dolomite	Material efficiency	56.6	0.0	56.6	45.8
4	Natural gas injection	Fuel change	607.1	180.8	607.1	66.0

3.1 Use of gravimetric separator

In the conventional process, the sponge iron leaving the rotary kiln at 1,020 °C (Dey et al., 2015) is cooled to 110 °C for two reasons: (i) to prevent re-oxidation of the sponge iron when exposed to air, and (ii) ease of magnetic separation owing to the strong magnetic properties of iron at a lower temperature. In the proposed alternative, a gravimetric separator can separate calcined dolomite, char, and sponge iron based on the differences in their densities. In plants with appropriate induction furnace capacity, a gravimetric separator can replace the rotary cooler and magnetic separator (see Figure 4). The hot sponge iron from the gravimetric separator can be directly fed to the induction furnace. The total electricity conserved in the induction furnace, rotary cooler, and magnetic separator is subtracted from the energy consumed by the gravimetric separator resulting in a net electricity savings of 175.9 kWh/tcs. The operating cost is calculated as the cost of power saved, which is negative due to electricity savings.

3.2 Bio-char replaces feed coal

Due to the high temperature inside the rotary kiln at the feed end, part of the feed coal is converted to char. This coal char helps form carbon monoxide (CO), which reduces the iron ore to sponge iron. The feed coal can be replaced with biochar. Biochar is substituted on an energy-equivalent basis. This helps to decrease the amount of fossil carbon consumed in processing sponge iron and crude steel. The amount of CO_2 savings is estimated by adding the emissions from feed coal and the emissions for the same amount of power generated from biomass pyrolysis by-products and subtracting the emissions due to power loss in waste heat recovery due to char substitution. Operating cost is estimated by subtracting the cost of coal and extra power generated from the cost of woody biomass required for biochar production.

3.3 Use of better-grade dolomite

Dolomite is added in the rotary kiln to absorb the sulfur present in coal, which is otherwise absorbed by sponge iron and reduces its quality. Calcination of dolomite releases CO_2 into the atmosphere. The amount of lime in dolomite that absorbs sulfur varies from 20 % to 60 %, depending upon the mines from which it is sourced (Yrjas et al., 1995). The use of better-grade dolomite helps decrease emissions from the calcination step. The net CO_2 abatement is calculated by adding the direct emissions from calcination and the emissions due to the coal (energy) used for it. This option doesn't have a fixed cost. Operating cost is calculated by subtracting the cost of energy (coal) from the extra cost incurred due to the use of better-grade dolomite.

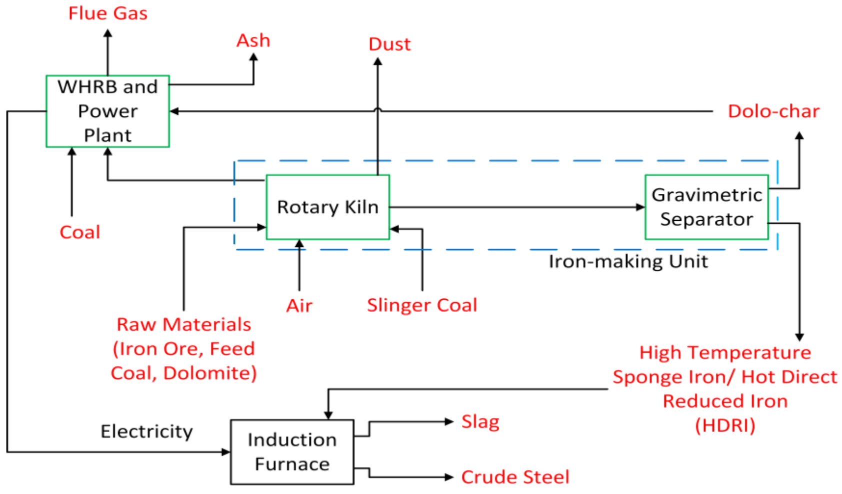

Figure 4: Schematic diagram of rotary kiln – induction furnace process for crude steel production retrofitted with gravimetric separator

3.4 Natural gas injection

Coal is a solid fuel and is more carbon-intensive than a gaseous fuel like methane. Natural gas can replace slinger coal for a less carbon-intensive and energy-efficient process. In the kiln, slinger coal has a combustion efficiency of 71 %, while that of natural gas is 95 %. The fuel substitution is done on an energy-equivalent basis. The CO_2 saving is estimated by subtracting emissions due to natural gas injection from emissions due to slinger coal and adding the emissions due to power loss because of natural gas injection. Operating cost is calculated by adding the cost of natural gas and the cost of power lost due to natural gas usage and subtracting the cost of slinger coal.

4. Discussion

A gravimetric separator option has a net negative cost of CO_2 abatement, implying CO_2 abatement is economically rewarding, and the rest of the decarbonisation options require a net positive cost (see Table 2). The negative cost of CO_2 abatement is due to the electricity conserved. Despite better-grade dolomite usage being a material efficiency option, there is a net CO_2 abatement cost due to the higher price for a better-grade material. The use of biochar is a decarbonisation option due to the use of renewable woody biomass. The marginal abatement cost curve for the decarbonisation options considered is presented in Figure 5. Together, all these options can help abate nearly 56 Mt of CO_2 annually in the Indian iron and steel sector.

5. Conclusions

Among the options considered, the use of biochar to replace feed coal has the highest CO_2 abatement potential because of the carbon-neutral nature of biomass. The overall CO_2 abatement by all four options is higher than the current emission intensity of 2,296 kg CO_2/tcs because of the surplus power generation from biomass pyrolysis gas generated during the production of biochar. However, there is actual emission of 448.7 kg CO_2/tcs from natural gas combustion and calcination. These decarbonisation options are difficult to implement from a commercial perspective because of the high associated costs, as nearly 90 % of the emission abatement cost is in the range of 40-70 US$/t CO_2 abated. By implementing the gravimetric separator option completely and the bio-char option partially, 399.7 kg CO_2/t of crude steel can be abated without a net cost. This shows that the rotary kiln-based process route can be completely decarbonised conceptually, provided there are suitable incentives for the industry and consumers. Future work is directed towards the inclusion of other decarbonisation options like painting the rotary kiln with low emissivity paint, use of variable frequency drives, replacement of slinger coal with bio-syngas, etc., for the cost-effective decarbonisation of the sponge iron sector.

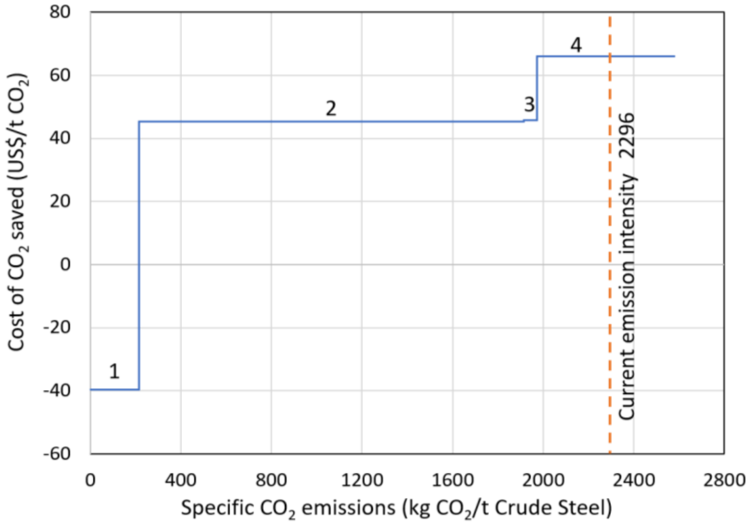

Figure 5: Marginal abatement cost curve for various technology options for decarbonisation of the rotary kiln-induction furnace process of crude steel production (Considering all four decarbonisation options, more CO_2 seems to be abated than actually emitted because of the power credit from biomass pyrolysis gas generated during biochar production.)

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