Sustainability Enhancement of the Coal Based Direct Reduction of Iron Premised on a Rotary Kiln

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Abstract. Sustainability of steel manufacturing industries in most under developing economies around the globe has become an issue of concern bothering around both environmental and systemic sustainability. The principles of circular economy (CE) in systems thinking (ST) have been proposed in this paper as a measure towards augmenting the sustainability of coal based Direct Reduction of Iron (DRI) process. The DRI approach for steel production is preferred for economic reasons in most low-income countries, even though it is an inevitably dirty process, emitting gaseous and solid wastes in large quantities. The pollution level of the DRI process violates the United Nations sustainable development goal no. 13 which focuses on climate action. The concept of CE in ST has been presented as a comprehensive measure that is capable of reducing and aiding with the recovery of wastes in the DRI process through effective tracing, tracking and control within an integrated network.

Keywords: Direct Reduction of Iron · Sponge Iron · Wastes · Sustainability · Circular Economy · Systems Thinking

1 Introduction

Sustainability has become increasingly important amongst industries worldwide over the past decade. Organizations are directing their resources towards the minimization of environmental impact of their products and operations [1]. Coal based Direct Reduction (DRI) of Iron is one sector that needs attention on environmental sustainability as it has greatly expanded over the past decade [2]. Sponge Iron has gained more use in the steel making industries in the (EAF) Electric Arc furnace due to its high iron content, less availability of high-quality scrap and the increasing cost of scrap metals [3, 4]. Coal is an abundantly available resource in many developing countries and is used to power energy intensive industrial processes [5]. The use of electricity and natural gas is limited in powering these processes because of the cost associated with it. Globally, India has been the largest producer of sponge iron up to 2018, and 80% of DRI plants in India are coal powered [6].

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1.1 The DRI Process

Sponge Iron or Direct Reduction Iron (DRI) refers to a porous metallic substance that is produced by the direct reduction of iron ore, where oxygen is removed from the iron oxide using coal or natural gas as reductants and dolomite as a desulphurizing agent [7]. Raw materials are fed into the rotary Kiln by a conveyor to generate fugitive dust and particulate matter. The kiln has 2 zones, the preheating zone is responsible for moisture removal from the raw materials at temperatures ranging 900 °C-1000 °C and thermal decomposition of coal takes place releasing hydrocarbons and hydrogen. The metallization zone is where the final reduction to metallic iron takes place with most CO2 reduced to CO. A lot of emissions are generated during this stage from combustion reactions in the kiln [2]. After the reduction process, a mixture of sponge iron and char is discharged from the kiln into the cooler where cooling takes. Water is sprayed at the cooler shell to indirectly cool the material from about 1000 °C to 120 °C. Coal based DRI units are critically air polluting in nature emitting high concentration of particulate matter from point sources [2, 4]. Figure 1 shows a schematic diagram of the DRI process including the various waste outlets.

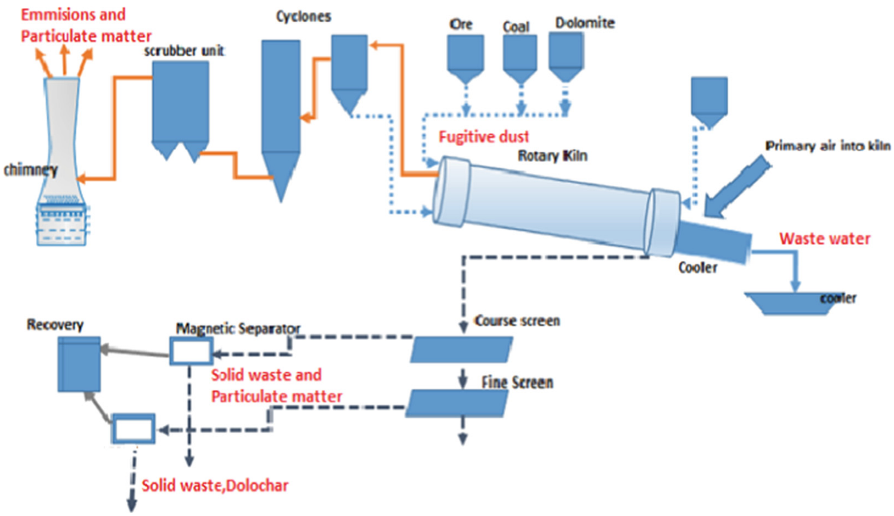

Fig. 1. Schematic process flow diagram of DRI, showing sources and exit points for wastes

Raw material utilization and waste generation for the DRI suggest that 1.6 tonnes of ore,1.2 tonnes of non-coking coal and 0.05 tonnes of dolomite are needed to produce 1 tonne of sponge iron and 0.2 tonnes of solid wastes [2, 5]. This implies that for every 10 tonnes of sponge iron produced, almost 2 tonnes of solid wastes are produced in the form of semi-processed iron and coal char. Most DRI plants are medium scale producers, with a capacity of 100tonnes per day (100TPD). Such plants have the potential of disposing up to 20 tonnes of solid waste into the environment, thus causing environmental degradation. CE principle helps to recover waste by recycling and giving it a second life as a new product.

2 Circular Economy in Systems Thinking for Sustainability of the DRI Process

The concept of Circular Economy (CE) depicts the life cycle of a system from conception to completion and utmost disposal or recycling. Systems Thinking (ST) is a holistic approach to understanding a systemic problem and the interrelationship that exists amongst the members of a system. The European Commission [8] stated that CE is a concept premised on five monitorable processes [9] namely: i) system input, ii) design & development, iii) production and deployment, iv) operations and/or consumption, and v) discard or recycle. CE in ST allows for a much broader utilisation of a ST network diagram to not only understand the problem comprehensively, but to proffer an integrated solution comprising all stakeholder in the DRI production process. The sustainability of any system such as the DRI, is premised on the proffering of a holistic solution to identified problems. Several system networking and mapping tools can be utilised for a comprehensive integration and exploration of a system's elements. In this paper, the VENSIM software was deployed for the ST network of elements. This was used to demonstrate how the elements of the DRI process interact to enable circularity of the system. From Fig. 2, both negative and positive interactions can be identified and mitigated as deemed necessary for sustainability of the DRI system. The output of one systemic element serves as an input to another element in a looped network depicting circularity from raw material acquisition through the processing phases and stages to disposal. Stakeholders responsible for the facilitation of the different activities in the network are known prior. Negative activities within the network can be easily traced and tracked. Also, effective control measures can be easily disseminated amongst the stakeholders in the circular system for sustainability.

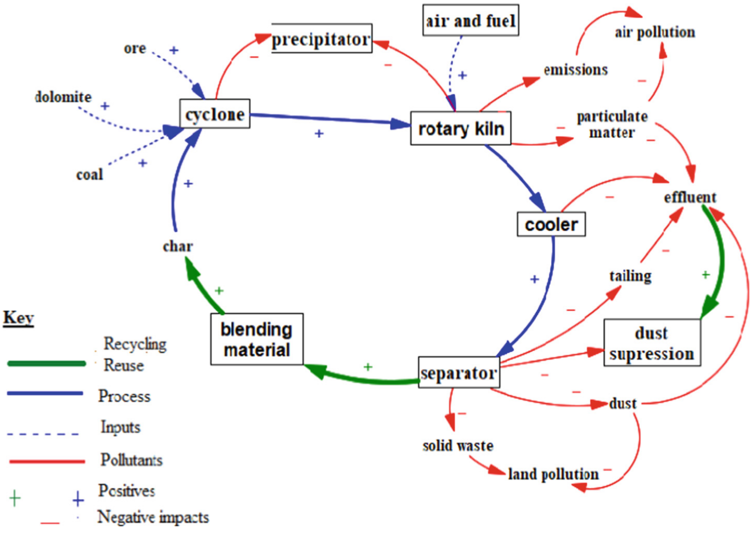

Fig. 2. Systems map for the DRI process

The developed map enables visualization of the impacts of the DRI process and how they contribute to pollution and land degradation. The concept of CE in ST aids decision makers and stakeholders to have a much clearer perspective of the sustainability measure of the DRI system throughout its life cycle. The ST map can also be used to generate a causative tree diagram for the problematic processes with a view towards optimizing the process through visualization of the displayed quantities of the causative factors. Circularity of the DRI process can be achieved by reusing and recycling waste products back into the process. From the systems map, it is seen that waste dolochar can be blended with other materials in the cyclones and used as feed in the rotary kiln. Up to 20 tonnes of dolochar can be recycled back into the system for a 100TPD capacity plant, and this cuts on the cost of raw materials utilised. Wastewater from the cooler can be used for dust suppression, though some academics argue that mineral elements can be leached into the soil from this process.

3 Wastes from Coal Based DRI Process

The Sponge Iron production is critically air polluting in nature emitting high concentration of particulate matter from point sources and from several secondary sources. The three main types of wastes generated are solid wastes, liquid wastes, and gaseous emissions.

3.1 Wastewater

Wastewater is generated from scrubbers, After Burning Chamber (ABC) and coolers, it is processed in the classifier which is used for the removal of course, heavy, and suspended particles [10]. Total wastewater per tonne of sponge iron is 2.88 m^3, this comes from the ABC, clarifier, wet scrubber, and the dust suppression system. Overflow of the clarifier goes to the cooling tower while underflow of the clarifier goes to the sludge pond. Water is continuously sprinkled over the rotary cooler shell and is allowed to fall on a setting tank located below the rotary cooler. The water requirement varies from 5-6 kl/h 100 TPD DRI [11]. Wastewater can be treated and recycled in the system for dust suppression.

3.2 Dust and Particulate Matter

Major sources of fugitive dust generation in coal based DRI plants are the raw material handling yard (unloading, stacking, reclaiming operations), product discharge system (cooler discharge conveyors, transfer points), junction house, screens, magnetic separators, storage silos. The summation of these waste adds to 0.13 tonnes/tonne of DRI produced [11] The main raw materials, coal and iron need to be crushed to a size between 0–20 mm, sizing of raw mate-rials involve the crushing, screening, and conveying operation. During these processes, fines are generated, and micron size dust is dispersed in the air. Particulate matter (PM) consists of particles that, based on their size are classified in coarse (diameter < 10 μm; PM10), fine (diameter < 2.5 μm; PM2.5) and ultrafine ($0.1 <$ μm; PM0.1) [12].

3.3 Gaseous Emissions

Emissions or pollutants into the air results in undesirable changes to the climate and this degrades the environment. A lot of emissions are produced during the DRI process because of the various reactions of carbon from coal thus producing a lot of carbon derived emissions. Principal air emissions include particulate matter (PM, or dust), Sulphur dioxide (SO2), nitrogen oxides (NOx), carbon dioxide (CO2), carbon monoxide (CO), lead and ozone [12]. The process of employing coal as a reducing agent produces a lot of CO2 and CO from the reactions between the carbon and iron oxide inside the kiln. [13].

3.4 Solid Waste, Coal Char and Dolochar

Studies on characterization of dolochar suggests that the dolochar samples from various dump sites consist of quartz (free as well as locked), free lime, aluminum silicate, Fe particles, and Ca or Mg and or Ca + Mg + Fe oxide phases [14]. Proximate analysis indicates that the dolochar fine samples contain more fixed carbon than the dolochar lump samples [5]. The concentration of heavy metals is also more in case of fine samples than the lump samples. The (Fe) content is invariably the same in both lump and fine dolochar samples. Dolochar or solid waste contributes to the highest volume oof waste generated, the quantity ranges from 0.2–0.3 tonnes/tonne of DRI produced.

3.5 Impact of Waste from Sponge Iron Production

Wastes generated from the DRI process have adverse effect on the environment and human life. Wastewater from this process contains metals, suspended solids, benzene, and fluorides. These degrades the soil and water bodies as the sludge is disposed in the environment [14]. Effluent discharge also alters water quality and PH, thus resulting in hard water formation. Emissions such as (SO2), NOX, CO2, CO, cause a number of diseases such as increased pulse rate, cardiovascular disease, throat irritation, bronchitis, eye irritation, chest pain, drowsiness, headache, nausea, stupor, coma, disorientation [15]. GHGs contributes to global warming and acid rain while dust and particulate matters cause stunted plant growth and soil contamination from dissolved metals leached from deposited dust. In humans, pulmonary health problems such as black lung disease and bronchitis are associated with inhaling particulate matters [16].

4 Pollution Drivers in Sponge Iron Production

In a bid to manage and enhance sustainability of the DRI process, the following pollution drivers as listed in Table 1 would need to be kept at the barest minimum. Different researchers have in the past deployed diverse but specific strategies per pollutant type as presented in Table 1 towards their minimization. These specific strategies can be assessed and deployed within the ST and CE integrated approach.

Table 1. Pollutants and specific control strategies

Pollutant	Strategy
CO2	Use of wood char as a reductant instead of coal, to reduce the amount of CO_2 produced [17] Optimisation of the DRI process through multiscale process modelling to reduce CO_2 emissions [6, 18]
Particulate matter	Application of EPA air pollution dispersion model ISCST-3 to predict the impact of the sponge iron industry emissions on ambient air quality [19]
Dust and Particulate matter	Gas Cleaning Plant (GCP) based on Venturi Scrubbers for the treatment of DRI gases [11]
Dolochar	Recycling of solid wastes e.g., dolochar can be used as a low cost and highly efficient adsorbent for phosphate removal from aqueous solution [20]
Char	Recycling, char mixed with coal fines can be used as fuel in Fluidized Bed Combustion Boilers (FBC) [2] Reuse of char as an element for denitrification in wetlands [21]

5 Conclusion

The Integration of Circular Economy and Systems thinking has a great potential in the enhancement of sustainability of different processes as this enables holistic understanding of the problem domain coupled with the proffering of an integrated solution. The Coal based DRI processes can be sustained over time if proper holistic strategies are deployed to monitor and control the network of activities. This would minimize the overall cost of the production process and negative impact on the environment. The 3Rs (Reduce, Reuse and Recycle) for sustainability would certainly be achievable if an integrated approach such as CE in ST is adopted.

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