Materials Processing Institute

CIRCULAR ELECTRIC STEELMAKING FOR 2050

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CIRCULAR ELECTRIC STEELMAKING FOR 2050

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Abstract

A circular economy requires resources to be exploited for as long as possible by i) extracting their maximum value whilst in use, ii) material recovery and iii) the subsequent generation of new products. Steel lends itself well to this system thanks to its inherent recyclability; it is almost 100% recyclable, a characteristic that the industry already exploits through electric steelmaking and is being further developed through advanced and optimised re-processing techniques.

Industrial symbiosis is a significant feature of sustainable development and aids the development of a circular economy by expanding material lifespans and identifying transformative business models. Industrial symbiosis has been found to lead to both economic and environmental savings within the iron and steel industry and is practiced through a range of resource and waste management methodologies. Despite this, industry-wide challenges remain, and the impending decarbonisation of the sector will lead to new obstacles that must be overcome through collaborative research and development.

This paper outlines the current circular economy and industrial symbiosis methodologies utilised in electric steelmaking, the gaps, and the remaining challenges. This includes the management of scrap and other raw material inputs, and the management of co-products and waste from the production process. The potential knock-on effects of decarbonisation are outlined, and a 2050 circular economy / industrial symbiosis roadmap is provided.

The aim of this summary is to provide details, to the iron and steel sector and the wider supply chain, of the remaining and future potential for circular economy and industrial symbiosis in electric steelmaking. Thereby enhancing awareness and stimulating discussion around research and development opportunities.

Introduction

A circular economy (CE) requires a shift from the linear "take-make-dispose" business model, where raw materials are extracted from the Earth's reserves, transformed into a useful product, put into service, and then retired as waste, usually to landfill and certainly not recycled, to a circular model which aims to exploit resources for as long as possible [1]. Implementing a CE leads to economic growth, reduced environmental impacts, job creation, and added value, and therefore directly impacts on the three pillars of sustainability, the economy, the environment, and society [2]. Steel lends itself well to a circular economy as steel scrap is 100% recyclable and is recycled into new steel through the Electric Arc Furnace (EAF) process [1].

Similarly, to the CE model, the related concept of Industrial Symbiosis (IS) leads to environmental and economic improvements, and the development of green skills [3], [4]. In simple terms, the aim of IS is for the by-products of one company or industry to become the raw materials of another, thereby enabling these materials to be utilized sustainably, creating a CE. In a broader sense, there are also opportunities surrounding the sharing of other resources such as energy, capacity, and expertise [5]. In the electric steel industry IS is demonstrated through activities such as the reuse of EAF slag as an additive for cement, concrete, and aggregate [6].

This manuscript outlines some of the current CE and IS strategies employed in electric steelmaking, describes the gaps in these strategies, and potential future challenges. Finally, a 'Circular Economy and Industrial Symbiosis Roadmap' is presented to support the UK Electric Steelmaking sector, and the Iron and Steelmaking sector as a whole, in the transition to a sustainable, circular economy.

Circular Economy in Electric Steelmaking

Steel is 100% recyclable. Scrap steel is utilised in both the EAF process for secondary steelmaking and as an additional source of iron in the primary steelmaking route through the Basic Oxygen Furnace which relies predominantly on iron ore as a feedstock [1]. Despite this inherent characteristic, it has been predicted that steelmaking will depend on the consumption of iron ore until 2100 [7].

In 2020 the UK produced 7 million tonnes of steel: 5.7 million tonnes from the integrated steelmaking route and 1.3 million tonnes from the EAF route [8]. The value of steel scrap exported from the UK in 2020 fell by 18%, approximately 6.5 million tonnes [9]. The ongoing transportation of materials from country-to-country results in often unnecessary additional carbon emissions, furthermore, reprocessing often takes place in countries with poorer environmental standards than in the UK, such as China [10].

The presence of residual elements in steel scrap leads to a reduction in its value and inhibits its recycling into new steel due to metallurgical quality requirements in the melt. Copper presents as the most prevalent residual element in steel scrap due to its use in electronics throughout a range of steel products. If end-of-life products are shredded prior to the recovery of the copper, there are currently no industrial processes available to remove the residual material from the scrap or the melt [11].

Daehn et al. [11] use the automotive supply chain to exemplify how copper can be reduced in scrap steel. This includes redesign, either by using less copper, aluminum wiring, or design for disassembly, improved separation techniques, and incentives to reduce contamination [11].

In the absence of a reduction in residual elements prior to the melt, down-cycling of the scrap to a lower value steel is currently the most viable option. This scrap management methodology will cease to be feasible as the market for low grade steel diminishes and primary steel production reduces. Consequently, the supply chain must consider appropriate strategies to address this issue whilst also considering the associated energy requirements for new separation techniques [11].

To achieve a fully, circular economy, the steel industry must consider moving up the waste hierarchy, away from recycling and towards reuse and remanufacturing. Remanufacturing requires manufacturers to take back components at end-of-life and to recondition those components to a like, or as-new state for reuse. This strategy increases the life cycle of the products and reduces the environmental impact associated with recycling e.g. raw material use, energy use, and emissions. Currently, remanufacturing is not widely adopted as few components are designed for such an end-of-life strategy [12].

Industrial Symbiosis Strategies for Electric Steelmaking

3.1. Slags

The characteristics of steel slags are dependent on the process through which they are produced and as such, tend to be classified according to that process. For electric steelmaking, slags are produced by the EAF and the ladle furnace. Crude EAF slags are crystalline, dense, with high skid resistance and tend to be utilised as concrete and road aggregate. Comparatively, stainless steel EAF slags are less dense and are used for cement and concrete. Ladle furnace slags have an even lower density and are used as a pH stabilizer and for roads and cement [6].

Despite these well-established routes to market, research is underway at the Institute, in partnership with other key players in the Foundation Industries, to develop new processes and materials. The aim of this research is to increase the value of the steelmaking by-products and to consider ways in which to reduce the environmental impacts related to not only their own processing and use phases, but also how they may reduce the environmental impacts of other key materials.

3.2. Zinc-rich by-products

Electric steelmaking results in the production of zinc-rich dusts containing 10 – 25% zinc, depending on the amount of scrap charged and its quality. 10 – 25 kg of dust are produced for every tonne of liquid steel manufactured, in which zinc is present as zinc ferrite ($ZnFe2O4$) and zincite (ZnO). This by-product is valuable due to its high proportion of zinc which can be recovered through a Waelz kiln. The Waelz kiln is a mature process and can recover over 90% of zinc from EAF arising dusts. The zinc is recovered as zinc oxide and sold on to zinc smelters to produce high-grade zinc or high-grade zinc oxide [13].

Alternative, less advanced, methodologies for zinc recovery from zinc-rich dusts include hydrometallurgical techniques such as acid, alkali, or ammonia leaching. Research has shown that aqueous ammonium salt–ammonia mixtures leached more zinc than aqueous ammonia and aqueous ammonium salt solutions alone. Ammonia-ammonium carbonate was found to give the best compromise between zinc selectivity (over iron) and zinc leaching efficiency [14].

Oxidative Ionothermal Synthesis (OIS) has been found to be a potential technique for the direct oxidation of metallic zinc from zinc oxide [15]. OIS uses ionic liquids with varying water content, temperature, and exposure time to different species, to produce nano and micro materials. In this case OIS could be utilized to recover high value materials from EAF dusts. Due to their low melting point and very low volatility, ionic liquids have been identified as an environmentally friendly substitute for industrial organic solvents [15].

Other thermal treatment options such as via Rotary Hearth Furnaces, Sinter Plants, and even the EAF itself also offer potential recovery routes for zinc-rich dusts. While these processes are relatively well developed in comparison to those outlined above, they present with the added burden of carbon emissions which must be accounted for and ultimately diminished in line with the UK's ambition to achieve net zero by 2050.

3.3. Waste heat

Heat is essential to electric steelmaking, though sources of waste heat are characterized as low- to medium- grade heat and therefore are difficult to convert into other usable forms of energy. Despite this, waste heat recovery and reuse is able to increase the energy efficiency of manufacturing processes and also has an economic benefit [16]. Although uptake is limited, processes are available to recover heat for recirculation, pre-heating, steam generation, and even district heating [17][16].

Successfully implemented heat recovery technologies include the organic Rankine cycle (ORC), Goswami cycle, supercritical carbon dioxide cycle, and the Kalina cycle. With respect to electric steelmaking, the ORC is a viable option. This heat recovery system generates steam and is then stored prior to being converted to electric power through an ORC turbine and then to thermal power which produces heat.

Circular Economy and Industrial Symbiosis Roadmap

The Materials Processing Institute was recently awarded £22m by the Department for Business, Energy, and Industrial Strategy to support the UK steel and metals sectors across the circular economy, digitalisation, decarbonisation, and advanced materials. The Institute has developed a Core PRISM Project to address the circular economy and industrial symbiosis through the installation of the Circular Economy Technology Centre on the Institute's campus in Middlesbrough.

Figure 1 outlines how the Circular Economy Technology Centre will tackle the three main circular economy and industrial symbiosis challenges outlined above through a range of projects, the funding mechanisms that will be sought to support those projects, and the processes that will be installed to facilitate the research. This is the current list of projects that the Institute are pursuing with respect to electric steelmaking, a wider list relating to the iron and steel making industry, and UKPLC as a whole, can be obtained on request from the authors. Please note, additional research is underway to address waste heat utilization, though this will not be addressed by the Circular Economy Technology Centre and therefore is not included in Figure 1. For further information on this subject, please contact the authors.

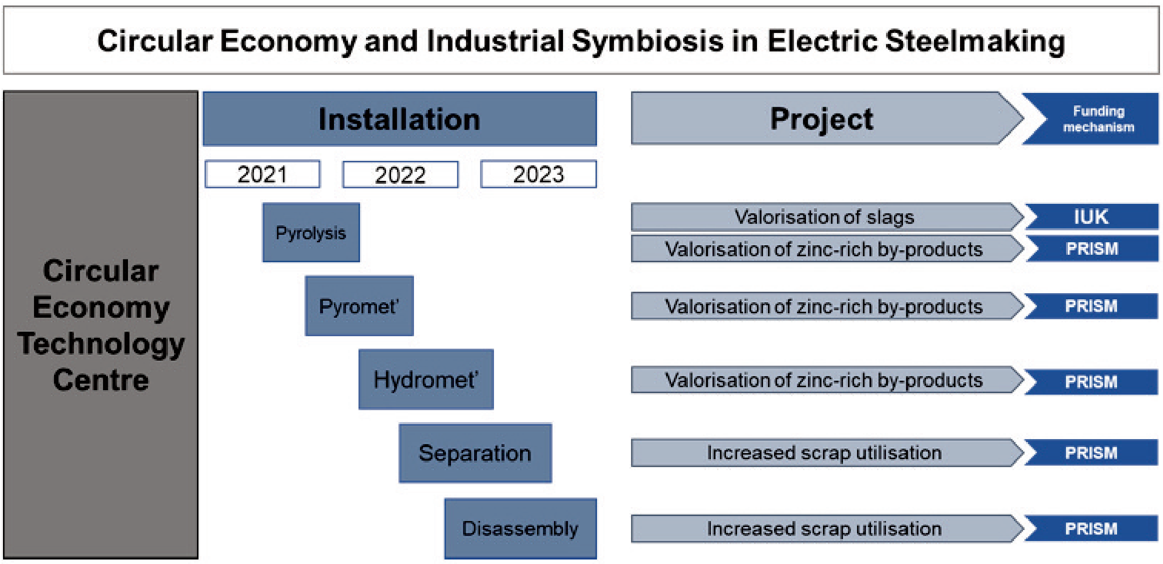

Figure 1.

Conclusion

To achieve a sustainable, circular economy, UK electric steelmaking must continue to increase its utilisation of high-quality scrap and reduce the volume leaving the country. Furthermore, the sharing of by-products and other resources across the Foundation Industries and wider supply chains will reduce the environmental impact relating to landfilling and virgin raw material extraction, whilst having a positive economic impact.

The research underway at the Materials Processing Institute is supporting the Electric steel industry and the wider supply chains to develop robust solutions to global challenges.

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