Towards a Closed-loop System for the Steel Industry[1]

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The Fourth Industrial Revolution and the circular economy

Ever since the First Industrial Revolution, industry has largely adhered to a linear approach: we take resources from nature, make them into products, and then dispose of what we created as waste. This linear economic model is reaching its limits in many regards, notably through the resource scarcity and environmental issues that it has caused.

We currently find ourselves entering the age of the Fourth Industrial Revolution, a shift driven by digitalization and the vast volumes of data it generates. This revolution is expected to trigger fundamental changes in the way we produce and consume goods and resources. Whereas the First Industrial Revolution accelerated waste, the fourth has the potential to eliminate it altogether. In other words, we are moving towards a more sustainable economy, a so-called 'circular economy.' As we approach this era of the full incorporation of digital data technology, a systemic shift towards a circular economy should begin in the foreseeable future.

A circular economy is based on 'closing the loop', or making the concept of waste obsolete. It can be delivered through the application of the 6Rs (reduce, repair, refurbish, reuse, remanufacture, and recycle) to products and materials in value chains that are linked to circular opportunities or business models. The 6Rs is an approach that expands upon the conventional 3Rs (reduce, reuse and recycle) or 4Rs (reduce, reuse, remanufacture, recycle). Recently, in addition to recycling, there has been a strong focus on additional activities for intensifying resource use and extending life-spans, such as repair, refurbishment, reuse, and remanufacturing. Under the 6Rs approach, materials are continuously cycled back through the value chain, resulting in the minimization of energy and resource consumption. In essence, the circular economy seeks to replace today's linear 'take-make-dispose' approach and to eliminate any loss or waste in the market.

1 This article is an adaptation of a presentation at the worldsteel Conference on the Impact of the Circular Economy on the Steel Industry held on September 10, 2018 in Brussels, Belgium.

Figure 1. Circular Ecoonomy Technologies

Source: Compiled by POSCO Research Institute based on Accenture's ten technologies for disruption

This cannot be achieved without the advancements in supporting technologies and data platforms offered by the Fourth Industrial Revolution. Just like any other economic paradigm shift, the most important enabler of the transition to a circular economy is the advance of technology.

Accenture (2016) identifies ten disruptive technologies in this regard[2]. The technological needs for the circular economy can be categorized into four types: 1) advanced collection, sorting and recycling technologies; 2) efficient material processing technologies; 3) production technologies that support designing for circularity; and 4) interactive platforms for enhanced connectivity. These technologies are maturing rapidly and will offer concrete benefits that support circular economy businesses.

The steel industry from a circular perspective

In order to manage the shift to a circular economy, a good starting point would be understanding the current status of circular aspects of the steel industry—its advantages and disadvantages, limitations, and challenges.

Steel's circular advantages

Steel has many circular advantages, such as infinite recycling without loss of key properties, permanent materials, and easy separation and recovery.

Heavy investment in the development of grades of advanced ultra-light high-strength steel has led steel weight

2
Digital, engineering and hybrid technologies such as mobile, M2M(Machine-to-Machine), cloud, social, big data analytics, trace and return systems, 3D printing, modular design technology, advanced recycling technology, and life and material sciences

Table 1. Overview of Eight Key Materials and Their Environmental Impacts (Relative)

Material	Production Volumes (tonnes)	Greenhouse gas emissions	Water consumption	Land use
Steel	9%	23%	2%	0%
Aluminium	0%	1%	0%	0%
Plastic	2%	3%	1%	0%
Cement	21%	30%	0%	0%
Glass	1%	2%	0%	0%
Wood	14%	1%	0%	52%
Primary Crops	47%	14%	96%	22%
Cattle	6%	26%	2%	27%

Source: 'Circular Economy and Environmental Priorities for Business', Ecofys and WBCSD, May 2017

to be reduced in many manufacturing applications, such as the weight of auto sheets being reduced by up to 40%.[3] This has contributed not only to reducing vehicle weight, but to improving fuel economy with lower CO_2 and NOx emissions. In the consumption phase, steel also makes up a large portion of buildings and infrastructure which have an extensive service life of up to 100 years. Steel provides an extended lifespan compared to other materials such as aluminum. Above all, recycling provides the core advantage of steel, given its superiority in terms of quantity and quality of recycling. Steel has an remarkable recycling rate ranging from 70 to 90%,[4] the advantage of theoretically infinite recyclability without loss of key properties, and easy separation and recovery.

Environmental impact

However, steel has a relatively high environmental impact in the production phase compared to other key materials.

Table 1 shows figures estimated by Ecofys and WBCSD (2017) for material volumes and related carbon emissions, as well as the water and land footprints of eight key materials in a circular economy. While steel accounts for 9% of total production volume, it is responsible for 23% of global greenhouse gas emissions and 2% of water consumption. Compared to aluminum, plastic, cement, and glass, steel has a very high carbon intensity. Therefore, from an environmental point of view, carbon is the focus area for steel if it is to contribute to a circular economy.

Material flows

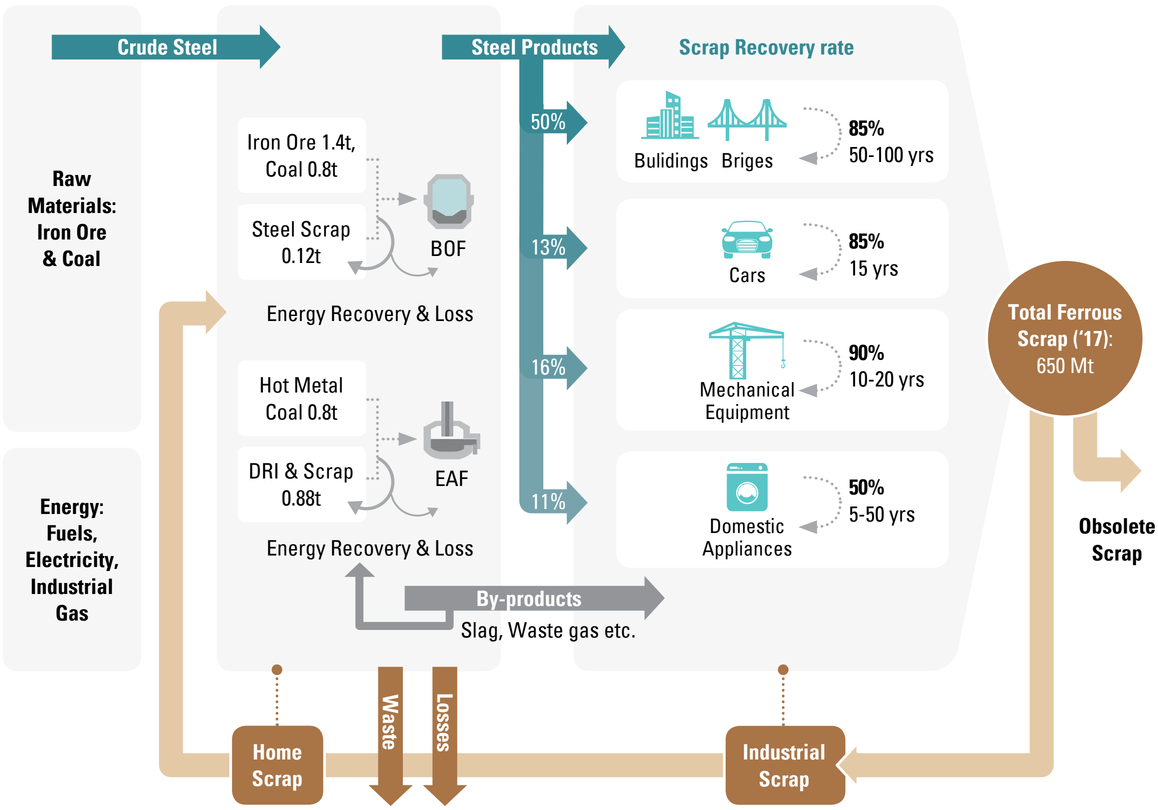
In terms of material flows, around 650 Mt of steel scrap are recycled every year (saving 945 Mt of CO_2) according to worldsteel. Today, 30% of all new steel products are made from recycled steel.

However, considering the overall lifecycle, including steel-consuming industries, the scrap recovery rate remains far below 100%. The scrap recovery rate varies from 50-90%. There are considerable losses of material and energy within steelmaking boundaries and with each use cycle

3 'Steel – A Permanent Material in the Circular Economy', World Steel Association, 2016

4 'Recycling Rates of Metals, a Status Report', UNEP, 2011

Figure 2. Material Flows of Steel



Source: Compiled by POSCO Research Institute based on 'worldsteel Factsheet: Steel and Raw Materials', 'worldsteel Short-range Outlook (2017-2018)', and 'World Steel Recycling in Figures (2013-2017)' by the Bureau of International Recycling

as well. A number of studies, including Hatayama et al. (2014), suggest that it is inevitable for more than half of the scrap generated annually to be down-cycled (down-graded) unless there are improvements in logistical and technological progress in steel recycling and recovery. The steel industry needs to address recycling challenges at every stage of its value chain in partnership with steel-consuming industries.

It should be pointed out that there is still a paucity of data with the needed complexity for describing steel's material flows in society. There is a need to fill the data gap and understand the broader picture of the steel material flow. This should provide the fundamental base for progressing to a closed-loop recycling system.

Causes of circular leakages in the steel industry

This brings us to the question of what precisely causes circular leakages in the steel industry. Losses and waste stem from material complexity, geographic dispersion, a lack of incentives, and insufficient infrastructure. The first is material complexity. Steel use in products is diverse, with a high level of material variation and complexity. It is growing increasingly difficult to identify, separate, and recycle materials.

Geographic dispersion is a further challenge. The recovery and recycling system is mostly localized and fragmented and there is an issue with

Figure 3. Barriers Facing a Closed-loop System in the Steel Industry

Material complexity	• Mixed streams of products from different industries • High level of material variation and complexity • Difficulty in identifying, separating, and recycling materials
Geographic dispersion	• Recovery/recycling system mostly localized and fragmented-scrap collection rate, recovering/recycling technologies and costs • Disjointed supply chains
Lack of Incentives	• Low intrinsic value of products/material per unit • Lack of markets at scale and 'right' policies
Lack of infrastructure	• Lack of data and infrastructure to support closed-loop system, global material flows, lifecycle environmental impacts • Need for greater digitalization of the recycling chain

Source: Compiled by POSCO Research Institute

disjointed supply chains. Third, there is a lack of incentives. Despite the potentially large volumes of products, recycled products have a lower intrinsic value. Moreover, the lack of markets at scale and of necessary policies and standards to promote the circular economy aggravates recycling. Finally, there is a need for big data and infrastructure to support a closed-loop system: The recycling chain and its data platform must be further digitalized.

Towards a closed-loop system for the steel industry

The circular economy and the steel industry value chain

The circular economy will affect not only steelmaking processes, but the entire value chain of the steel industry.

For R&D, it is essential to focus on product development and design based on lifecycle analysis and to pursue process innovation toward carbon-free and zero-waste targets. There is a need to enhance the recycling of raw materials and gradually adopt more substitutable renewable energy and eco-friendly raw materials.

Manufacturing processes must target minimizing loss and waste. Environmental damage should be reduced using smart tech-based management of resources and waste streams.

Products should be made from ultra-light, high-strength, and high-performance steel with a longer service-life and greater recyclability. By-products need to be processed as an additional revenue stream.

In terms of logistics and services, reverse lo-

Figure 4. The Circular Economy and the Steel Industry Value Chain

Circular Economy	R&D	Raw Materials	Manufacturing/ Process	Product	Logistics & Services
Changes	• Product development & design based on lifecycle analysis • Carbon free and zero waste process innovation	• Enhanced recycling of resources • Substitutable renewables, eco-friendly raw materials	• Minimize losses and reduce environmental impacts • Smart tech-based management of resources and waste streams	• Ultra light, high strength & high performance • Longer service-life, recyclable steel • By-products as a revenue stream	• Reverse logistics for a wider range of product categories • Circular economy data platform and e-marketplace

Source: Compiled by POSCO Research Institute

gistics for the wider range of product categories should be emphasized, as well as circular economy data platforms and e-marketplaces.

Cases

Here are some cases that illustrate how steel companies embrace the circular economy concept and implement business practices in their value chains.

Nucor Nucor is responding to global challenges by producing high-quality steel, reducing CO_2 emissions, and establishing a more innovative and sustainable business model, both in terms of environmental impact and financial return. Nucor is one of the leading companies that recognize how process innovation is the key to unlocking untapped potential.

The introduction of mini mills resulted in faster manufacturing and reduced energy-consumption. The micro mill developed by Nucor enables an increase in the efficiency and productivity of producing ultra-thin cast strips with considerably less energy consumption and CO_2 emissions. Furthermore, it is more adaptable and suitable for installation nearby scrap production sites or customers, a form of so-called decentralized recycling that is highly relevant in a circular economy.

POSCO POSCO is a positive example of pursuing product innovation from a circular lifecycle perspective. Its high-performance and eco-friendly GiGA steel has multiple circular advantages, including high durability, a longer lifecycle, and less lifecycle impact. In particular it contributes to a reduction in CO_2 emissions of roughly 10% in automotive use.

PosMent, developed cooperatively in 2012 between RIST, POSCO E&C and POSCO, is an eco-friendly cement with a higher slag content. PosMent replaces cement clinker, which in turn contributes to the reduction of CO_2 emissions and improves physical properties such as pres-

> A growing number of steel companies are already implementing circular economy models to an extent and exploring future opportunities.

sure resistance and strength. It is one of the best examples of waste product being recycled and applied as a raw material in a different value chain in another industry, in this case the construction industry.

Furthermore, in order to accelerate product innovation and provide transparent information, POSCO established the Lifecycle Inventory (LCI) database for POSCO's World's Premium (WP) products and promoted Environmental Product Declaration (EPD) certifications.

Tata Steel Companies can create value by providing platforms that improve efficient material flows and asset utilization. Tata Steel's Mjunction represents a highly relevant illustration.

Mjunction is a joint venture established between Tata and SAIL in 2001. It provides a digital platform that connects buyers and sellers of scrap, waste, and idle assets. Mjunction has increased its business volumes from $13.8M in 2002 to $9.45B in 2016. It is now the world's largest e-marketplace for steel. For the steel industry, the most important value of Mjunction is that it helps to build data-driven recycling markets and improve transparency across the entire value chain.

Mjunction by Tata Steel is a good example of how platforms enabled by digital technologies can help facilitate efficient material flows.

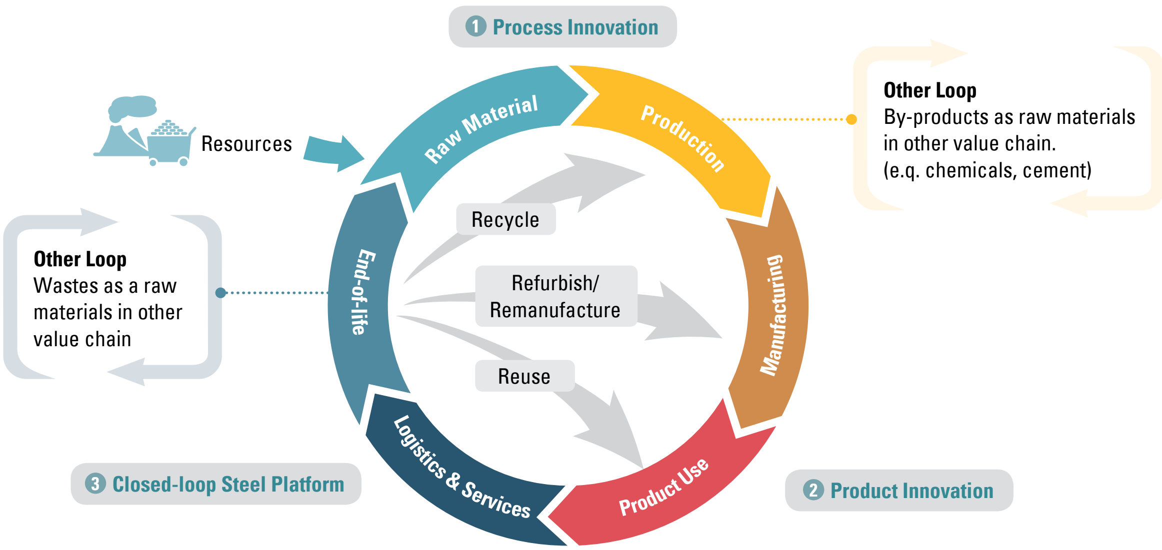
ThyssenKrupp ThyssenKrupp's Carbon2Chem project is an interesting case of adding value to waste. It offers an illustration of cross-industry utilization of CO_2 as a valuable raw material.

The Carbon2Chem project aims to use gases from steel production as a raw material to produce chemical products. This is a cross-sectoral collaboration which promotes cost-effectiveness through value creation in a circular economy, fossil-fuel savings through the replacement of conventional feedstock, and significant CO_2 savings. If fully implemented, Carbon2Chem can help the German steel industry reduce 20 Mt of CO_2 emissions annually. This project can also contribute to recovering the hydrogen included in emission gases and apply it as a source of renewable energy.

A circular economy model for the steel industry

As shown in these cases, a growing number of steel companies are already implementing circular economy models to an extent and exploring future opportunities. In this regard, we suggest three main innovations for the steel industry as it responds to the challenges and opportunities provided by the circular economy—process innovation, product innovation, and closed-loop steel platform development.

Figure 5. A Circular Economy Model for the Steel Industry



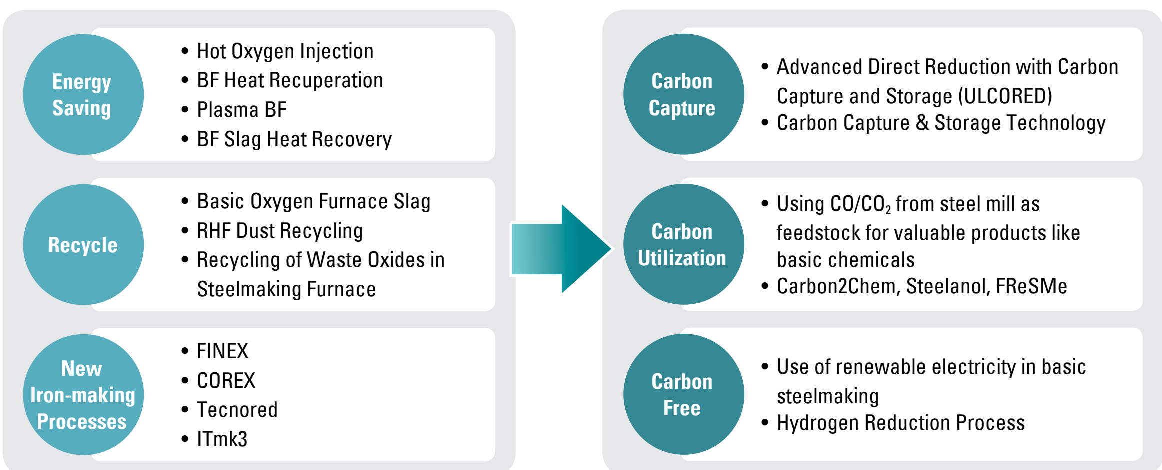
Source: Compiled by POSCO Research Institute

1 Process innovation

In the Fourth Industrial Revolution, the drive toward a circular economy and global climate action are guiding the industry toward eco-friendly steel making processes.

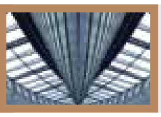
The steel industry has been working to develop energy-saving technology, recycling technology, and eventually new steelmaking processes which are able to replace conventional blast furnaces. Such efforts will continue in the future. On top of this, the steel industry will further upgrade carbon capture and utilization technologies and conduct research on the hydrogen-reduction steelmaking process. All this will eventually re-

Figure 6. Diagram of Process Innovation



Source: Compiled by POSCO Research Institute

Figure 7. Product Innovation

Design for closed-loop product		• Products are designed to minimize the resource and energy intensity across the lifecycle • Design for long service life, efficient reuse and remanufacture, e.g. modular steel buildings
Explore lifecycle implication		• Assess the product's lifecycle impact or environmental footprint to identify strengths and weaknesses • Review current and emerging customer requirements and understand their lifecycle implications
Create value from by-products		• Further improve by-product recovery rates and expand their use by improving the quality of the materials recovered • Channelize by-products for commercial applications like slag being used in concrete and road construction

Source: Compiled by POSCO Research Institute

duce CO_2 emissions to zero.

❷ Product innovation

Product innovation focuses on maximizing a product's circularity and minimizing its lifecycle impact.

Design is critical for conserving resources and enhancing product reuse across the entire lifecycle. Improved designs can help make steel products longer-lived and easier to repair, refurbish or upgrade. It can assist recycling businesses to reclaim valuable materials and components when they dismantle products. Modular steel buildings can be a good example.

Including in the design stage, one of the key considerations for companies seeking to recycle products is the product's entire life. It is important to assess the impact of a product's lifecycle and environmental footprint to identify strengths and weaknesses. Reviewing current and emerging customer requirements and understanding their lifecycle implications is another important area.

Lastly, there are significant circular opportunities to add value to by-products such as slag. There is a need to further improve by-product recovery rates and expand their use by improving the quality of the materials recovered. It is also necessary to channelize by-products for commercial applications like slag being used in concrete and road construction.

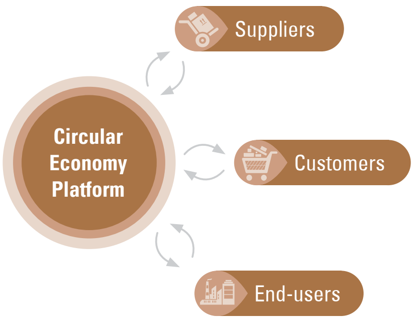
❸ Closed-loop Steel Platform

It is essential to establish a closed-loop steel platform, meaning data/digital infrastructure that increases resource flow efficiency.

Many global companies are emphasizing how intelligent collection of information and digital infrastructure fall at the heart of the transition to a circular economy. In this context, a closed-loop steel platform would allow steel companies to capture circular opportunities and create new value. Furthermore, it is a must for ensuring that the steel industry is moving towards a circular economy.

Four core pillars are necessary to establish a digital data platform for a circular economy initiative. A material registration platform provides

Figure 8. Circular Economy Platform



Material Registration Platform	Materials information e.g. key characteristics including usage, availability, other pertinent qualities
Material e-Marketplace	Buying and selling of waste streams, idle or end-of-life assets among players at scale - scrap, by-products, obsolete equipment etc.
Resources Statistics	Usage of resources registered in the system and their associated flows
Environmental Performance Data	Lifecycle environmental impacts e.g. carbon and water footprints

Source: Compiled by POSCO Research Institute

materials information with key characteristics including usage, availability, and other pertinent qualities. A materials e-marketplace connects buyers and sellers of waste streams and idle or end-of-life assets. Resources statistics need to be linked, as well as environmental performance data and information such as lifecycle environmental impact.

Overcoming challenges in achieving a circular economy

There will be many stumbling blocks along the way to achieving a closed-loop system of the steel industry, which will bring enormous changes to its value chain. While steel has many circular advantages in terms of recycling, reuse, and remanufacturing, there remains a considerable potential for improvement and transformation

When responding to challenges and opportunities in the circular economy, there are three key areas of focus:

- Process innovation for reducing energy and resource intensity; eco-friendly steelmaking processes with Carbon Capture, Utilization & Storage (CCUS)
- Product innovation for maximizing circularity and minimizing lifecycle impacts
- Creating a 'closed-loop platform' across the supply chain for the steel industry to increase resource flow efficiency

In order to push these innovations, there is a need for deeper collaboration across the supply chain and among sectors based on a circular economy platform, such as raw materials suppliers, steelmakers, steel-consuming industries, end-users, and recyclers. Moreover, the steel industry has to make long-term strides to decouple industry's growth from its energy and resource consumption, which will make steelmakers continuously to remain competitive and sustainable in the future. In the due course to reach the circular economy era, steelmakers will naturally become more innovative in green technology that will generate unimagined circular business opportunities as well.