DECARBONIZATION PROCESS: CHANGE of EAF STEEL PRODUCTION PROCESSES in the TRANSITION TOWARDS SUSTAINABLE STEEL PRODUCTION

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Abstract

Climate change has prompted a radical transformation in all industrial activities, transportation, lifestyles, and consumption patterns that rely on fossil fuels, the cornerstone of our civilization. Due to the predominantly carbon-based nature of classical steelmaking processes, "Decarbonization" processes pose one of the most challenging hurdles for the steel industry. There is a vast gap in carbon footprint between the two primary steel production methods, with the BOF (Basic Oxygen Furnace) route, accounting for approximately 70% of total steel production, being the most problematic in terms of carbon emissions. However, this observation is often incomplete, and the decarbonization transformation in scrap-based EAF (Electric Arc Furnace) steelmaking processes is considered an unquestioned and seamless steelmaking process. This study focuses on examining what the decarbonization goals of EAF processes using scrap and various ore derivatives as raw materials will be, what kind of challenges will arise, and how these will be addressed in terms of production, quality, metallurgical processes, costs, and emission values.

The topics covered in this study include:
i. General definition of the carbon footprint of the EAF steelmaking process and possible decarbonization processes.
ii. Assessment of the current status and evaluation of energy and mass balances in EAFs.
iii. Changes in chemical energy use, alternatives, problems, and causes in EAFs.
iv. Examination of decarbonization in scrap-based EAF processes, problems with metallic and energy efficiency, and analysis from the perspective of the circular steelmaking process.
v. Metallurgical implications of using hydrogen instead of fossil fuels in DRI production and EAF's.
vi. Possible changes and effects in the application of fundamental metallurgical instruments such as carbon boiling, carbon injection, decarburization, and slag practice.
vii. Relationships between metallic efficiency, metallurgical balance, cost, emissions, and product quality parameters with oxidation and chemical energy use.
viii. Proposals for changes in the EAF process from the perspective of circular steelmaking principles.

This study aims to provide insights into the challenges and potential solutions for achieving decarbonization goals in the steel industry, particularly in EAF processes.

1. Introduction

The fight against climate change is fundamentally an issue of energy transformation. The transition of a civilization built on fossil fuels over two to three centuries to completely eliminating fossil fuels from social and economic life in about 35 years is a highly challenging yet inevitable process. In this process, the decarbonization of the steel production sector, which accounts for 7-9% of global emissions, and its ability to be carbon neutral by 2050, will require a very challenging transformation, similar to other sectors. The steel industry, encompassing various energy types, metallic raw materials, and metallurgical processes, is an energy and thus emission-intensive sector, making its decarbonization one of the most difficult. Given its composition as an alloy of carbon (C) and iron (Fe), defining the steel production process as "carbon-free steelmaking" is technically problematic. A more accurate term would be "carbon-neutral" or "low-carbon steel" production. While the decarbonization of the BF-BOF route, which constitutes 70% of global steel production, is a major focus in the steel industry, the decarbonization transformation of scrap-based EAFs, which have a relatively lower carbon footprint (approximately 1/4), is not discussed as much.

EAFs, which have varying levels of carbon emissions depending on the amount and type of scrap used and the type of steel produced, have a significantly lower carbon footprint compared to fossil fuel-based BF-BOF processes. However, the ultimate goal for the entire world is net zero by 2050, and achieving net zero in the EAF process involves a long journey. For the steel sector, the decarbonization transformation will be dictated by the type of energy and the new types of energy that will be introduced, leading to changes in raw materials and metallurgical processes.

As the name suggests, the most important transformation in the EAF process, which is an electric furnace type, is related to the carbon footprint caused by the production of the electricity used. In countries like ours, high grid emissions contribute significantly to EAF emissions. However, the use of electricity produced from renewable sources alone will not solve the problem, as Scope 1 process emissions and Scope 3 ecosystem emissions also constitute significant portions in many cases.

The relatively relaxed perspective towards EAFs will change as 2030 approaches, the tangible effects of climate change become more apparent, and environmental regulations become stricter. Carbon-free steelmaking technologies and processes will be increasingly discussed.

1.1. EAF energy profile

The energy balance of a typical scrap-based EAF is shown in Figure 1. In this example, 48.5% of the total energy is electrical energy. Electrical energy emissions are evaluated within Scope 2 and depend on the average g CO_2/kWh emission value of the national grid and the proportion of renewable electricity produced at the production site, if any. The average emissions vary in parallel with the types of fuels and technologies used in electricity production. Figures 2 and 3 provide the average values of these technologies and the variations between countries.

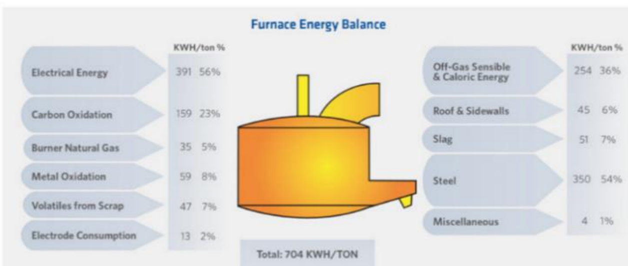

Figure 1. Energy balance example of a scrap-based EAF

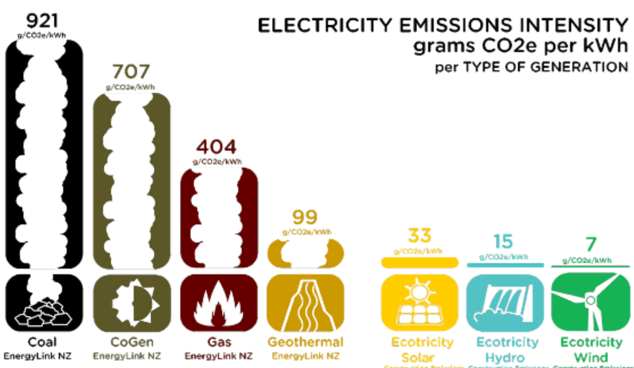

Figure 2. Emission values of electricity generation types

The average value of our country is 484 g CO_2/kWh in 2022, which is well above the EU average and close to the world average.

As the proportion of electricity produced from renewable sources increases over time, the share of Scope 2 emissions in the total EAF emissions, which is around 40-50%, will decrease. The solution is clear: intensive investment and transformation will have an impact on EAFs, just as in all other sectors. The share of Scope 2 emissions will decrease depending on electricity consumption and the average grid emission factor. Undoubtedly, the most effective method is to reduce the energy requirements of the process and its auxiliary applications. This area should be noted as having significant potential for development. In the decarbonization transformation of EAFs, the most challenging and yet less discussed issue is the use of low-carbon/low-footprint raw materials and energy, and the development and implementation of a new metallurgical process designed for these conditions, which pertains to Scope 1 emissions.

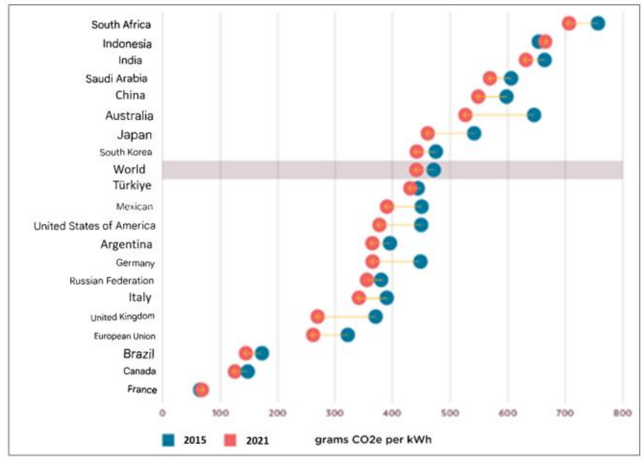

Figure 3. Emission values of national power grids

1.2. Energy use transformation in EAFs

Transformation & Recommendations for Energy Use in EAFs:

i. EAFs have become melting furnaces that utilize both electrical and chemical energy in equal measure. The primary factor contributing to Scope 1 emissions in EAFs is the use of natural gas, carbon injectants, and oxygen applied through various technologies. The main element of the journey to net zero is the complete elimination of fossil fuels. In EAFs, chemical energy, which is preferred due to its lower cost compared to traditional electricity, will undergo changes both proportionally and in type. The extensive use of chemical energy is driven by economic advantages rather than metallurgical reasons. However, as emission costs become a significant factor, the use of high-emission chemical energy in EAFs is expected to decrease and eventually be phased out.

ii. Although relinquishing high-emission chemical energy will increase unit electricity consumption, affordable and low-emission green electricity will mitigate the potential rise in emissions due to this increased usage.

iii. The issue of reducing energy consumption in conjunction with the change in energy types is highly debated. Energy and material efficiency determine the amount of energy needed and the consumption of other materials. Energy type and EAF metallic efficiency are interconnected issues, with the most critical metallurgical concern being metallic oxidation in EAFs. The use of fossil fuel-based chemical energy is the main cause of oxidation losses in EAFs. The levels of dissolved oxygen in liquid steel, the amount and composition of slag, heat losses from flue gas and cooling water systems, and the consumption of electrodes, refractories, and ferroalloys are all determined by the intensity of oxidation. Lower-cost green electricity will eliminate the need for the intensive use of chemical energy.

iv. EAF efficiency should be reevaluated metallurgically in light of the laws of thermodynamics and with a focus on minimizing carbon footprint. This evaluation and implementation should be supported by digitalization, modeling, and process control sensorization. This is one of the most crucial areas of study for research institutions and steel producers.

v. The use of chemical energy in EAFs contributes to heat losses. Increasing the proportion of chemical energy to speed up production uncontrollably leads to an increase in the volume and temperature of combustion products. The resulting high gas volumes necessitate high-capacity dust collection and water cooling systems. As shown in Figure 1, 36% of the input energy is lost with the flue gas. Preheating scrap and utilizing waste heat recovery technologies are measures to recover this lost heat, but any energy conversion involves a factor of efficiency and loss. The types and proportions of EAF energy should be reassessed considering all these parameters.

vi. With the economic and renewable production of H_2, it is very feasible to replace natural gas with H_2 as a combustion energy source. Undoubtedly, regardless of whether it is natural gas or H_2-based, alternative technologies such as induction or direct electric heating will come into play. Any energy conversion will require efficiency and cycle losses; hence, the direct and optimized electrification of all combustion processes is very likely.

1.3. Raw material transformation in EAFs

i. The scrap-based EAF process has the lowest carbon footprint, making the transition from ore-based to a recycling-based industry essential. However, scrap is limited in quantity and not suitable for producing certain types of steel.

ii. Therefore, iron ore-derived raw materials, such as DRI, which can be used in EAFs, are seen as the only solution to bridge this gap. DRI, once an alternative steel raw material used under specific conditions, has now become an unavoidable option.

iii. However, traditional natural gas-based DRI has a much higher carbon footprint compared to scrap and a lower footprint than BF-BOF routes. With CO2 emission values of 0.3-0.6 tons/ton for scrap EAF, 1.4-1.6 tons/ton for DRI EAF, and 2.2-2.6 tons/ton for BF-BOF, DRI is still an insufficient alternative for decarbonization. Therefore, using H2 produced from renewable electricity as a reductant instead of natural gas in DRI production is an option with zero emissions. The main challenge is the intensive electricity requirement for H2 and ensuring that this electricity is produced from renewable sources. The choice of the H2-DRI-EAF route, despite the current technological infrastructure's electricity consumption of 3,48 MWh/ton of crude steel, underscores the forward-looking approach and commitment to decarbonization.

iv. Beyond the initial investment costs and the relatively high demand for green electricity, the H2-DRI-EAF process signifies an entirely new era for metallurgists. An arc furnace process based on carbon-free raw materials has not been industrially tested, except for one example, and it encompasses many new challenges. This area has not been sufficiently studied, and it is evident that the transformation process will be very challenging.

1.4. Metallurgical process transformation in EAFs

a. Carbon injection serves dual functions in EAFs: it acts as a slag conditioner and conceals the arc due to foamy slag. While the amount of carbon used is a significant energy source, it is also the primary source of emissions. Therefore, synthetic, biomass, charcoal, and recycled carbon carriers will be used for carbon injection purposes. Another function of carbon injection is to act as an antioxidant and reductant against oxidation. The amount of carbon injection material used depends on the amount of FeO in the slag, the furnace atmosphere, and the amount of chemical energy used. All these parameters will change, and in an EAF metallurgical process managed with thermodynamic modeling and digital twin applications, these stages can operate with minimal carbon footprint. Figure 5 illustrates the injection reactions in a conventional EAF process and the effects of a 1% change in carbon.

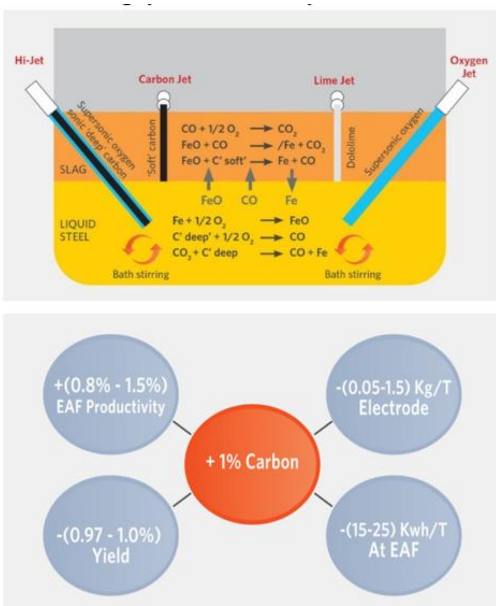

Figure 5. Importance of Carbon and Injection in EAF Process

b. While a zero-carbon EAF process remains ambitious, a reduced injection level is feasible. All types of injection will be carried out with thermodynamic modeling fed by real-time data from enhanced flue gas analysis. Thermodynamic modeling can reference a metallurgical process designed as a digital twin. Optimization of the metallurgical process and reduction of uncertainties are possible. Options include induction for bath movement, working with relatively high constant liquid metal, and adding low-carbon process product liquid metal from the primary iron production unit.

c. Classical scrap efficiency and slag quantity are direct functions of EAF chemical energy usage. Therefore, in a process with reduced and altered injection, controlling oxidation will be the primary objective. Reducing the carbon footprint involves increasing the efficiency of all inputs, including scrap and DRI, and minimizing losses.

d. The decarbonization of the metallurgical process will require more than just special investment; it will necessitate new process preferences. Establishing a balance of C between low-carbon raw materials and fuels is the most challenging aspect. Steel is inherently an alloy of Fe and C, so zero carbon is not achievable, making it a critical issue due to potential losses from low-carbon oxidation in the process.

e. Evolving the metallurgical process toward lower chemical energy usage will be an efficiency-enhancing choice in every aspect. This increased efficiency could support the financial needs arising from the transition to low emissions.

2. Results and Recommendations

The decarbonization of the EAF steelmaking process presents one of the most challenging aspects in the entire value chain's decarbonization efforts. Moving beyond the changes the EAF process has undergone in the last 30 years and designing an entirely new carbon-free process signifies a challenging period for metallurgists. When it comes to decarbonization efforts, technological change and the infrastructure investment it requires often take precedence as the primary discourse. However, the difficulties that the metallurgical process aspect will cause are equally significant. The decarbonization transformation requires a completely new perspective, primarily from process designers and implementers. The fundamental shift in the primary energy type for the entire industry and social life will inevitably necessitate a change in production processes. The most challenging aspect of this change is the limited time we have left.

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