Defossilization of Integrated Plants — Benefits and Challenges of Different EAF Designs







The global steel industry is increasing its efforts to defossilize and reduce its specific CO_2 footprint. Using electrical energy to melt iron units of scrap, pig iron, direct reduced iron (DRI) and hot briquetted iron (HBI) of various mixtures and origins is beneficial to reduce the CO_2 footprint but leads to new challenges. Different electric arc furnace (EAF) designs and process variants have been proven in the past decades and help to develop the EAFs of the future for higher input of DRI and HBI according to the steel quality demands. This article describes and discusses the technology options and their process realities for integrated plants.

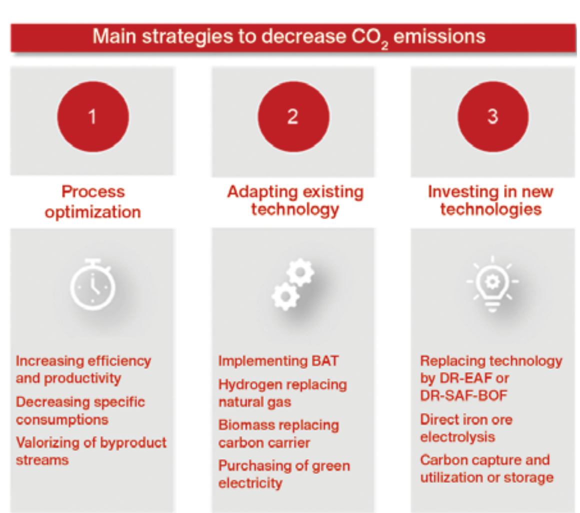
Introduction

To tackle climate change, many regions of the world have chosen to first restrict and then even zeroize the enormous quantity of CO_2 that is being emitted into the atmosphere. Since the iron and steel industry takes a non-negligible part, strategies are developed to gradually reduce CO_2 emissions in order to comply with the local governmental framework and the interests of society.

The three main strategies that each steelmaker can utilize are visualized in Fig. 1. First and foremost are process optimizations (1), which are procedures that call for direct action and some smaller fundings, but no significant investments are needed. Increased output and/or an optimized material utilization will directly result in reduced CO_2 emissions per metric ton of steel. Thereby, external expertise can help identify the quickest path to an optimal production strategy. The impact of this strategy is very effective but also limited. In reality, a scrap-based electric arc furnace (EAF) operation might reduce their emissions to below <100 kg CO_2 per metric ton steel by reducing power-on time (PON), specific electrical consumption (kWh/t) or optimizing the usage of different carbon carriers (bucket coal, injection coal, etc.). Pushing beyond the limits of process optimization, first investments are necessary to adapt existing technology (2). By replacing outdated

Figure 1

Three main strategies to mitigate CO_2 emissions in the iron and steel industry.



Authors

Felix Firsbach (top left), Head of Consulting, Badische Stahl-Engineering, Kehl, Germany
felix.firsbach@bse-kehl.de

Per Lückhoff (top right), Senior Expert Meltshop, Badische Stahl-Engineering, Kehl, Germany

Ralf Schweikle (second row left), Head of Technical Services, Badische Stahl-Engineering, Kehl, Germany

Andrea Pezza (second row right), Senior Expert Meltshop, Badische Stahl-Engineering, Kehl, Germany

Patrick Hansert (third row left), Executive Vice President, Americas, Badische Stahl-Engineering, Kehl, Germany

Peter van der Velden (third row left), Vice President Sales, Badische Stahl-Engineering, Kehl, Germany

Marcus Krause-Lehner (bottom), Vice President Sales, Americas, Badische Stahl-Engineering, Kehl, Germany

systems with more efficient machines and switching to lower-carbon (such as natural gas), carbon-free (such as hydrogen or ammonia) or nonfossil and therefore off-balance carbon sources (such as biomass), CO_2 emissions are reduced even further. This approach usually requires more investments and sometimes even research activities. Finally, carbon direct avoidance (CDA) at its final stage means investing in new technologies (3) and leads to significant investments of billions of U.S. dollars or euros. While step 1 and 2 are most suitable for EAF-based steelmakers, integrated plants cannot avoid step 3.

Numerous challenges will arise when an integrated plant chooses to proceed to step 3, which requires switching from oxygen steelmaking to electrical steelmaking while maintaining the same secondary metallurgy. In addition to requiring extensive project management, an EAF's operational and maintenance realities differ greatly from those of a basic oxygen furnace (BOF) and are covered in detail in Reference 1. The impact spreads a wide range of issues, from metallurgical questions (e.g., iron units, impurities and trace elements) that have a significant impact on secondary metallurgy, to new slag designs and recycling, offgas treatment considerations, new and varied safety risks, and maintenance issues that significantly affect the productivity of EAF-based steelmaking. A 300-ton EAF does not produce and perform like a 300-ton BOF and the majority of figures in discussion are theoretical in nature because actual industrial data are hard to come by.

Once the decision is made to produce steel using an EAF, it is necessary to select the right furnace in order to meet the demands of high productivity and low consumption, which ultimately results in low costs and low CO_2 emissions. Several EAF designs are presented in the following sections to provide a broad understanding of the capabilities and potential of the EAF technology. For the use of high amounts of virgin iron units, some of these options are theoretical exercises where entire departments and groups of educated people are guessing how an EAF would look to substitute the high-performer and high-quality producer BOF. To add value to the discussion, this article presents actual production figures for the different furnace types, to shed light on the gray outlook of theoretical EAF designs.

Different EAF Types and Their Emissions

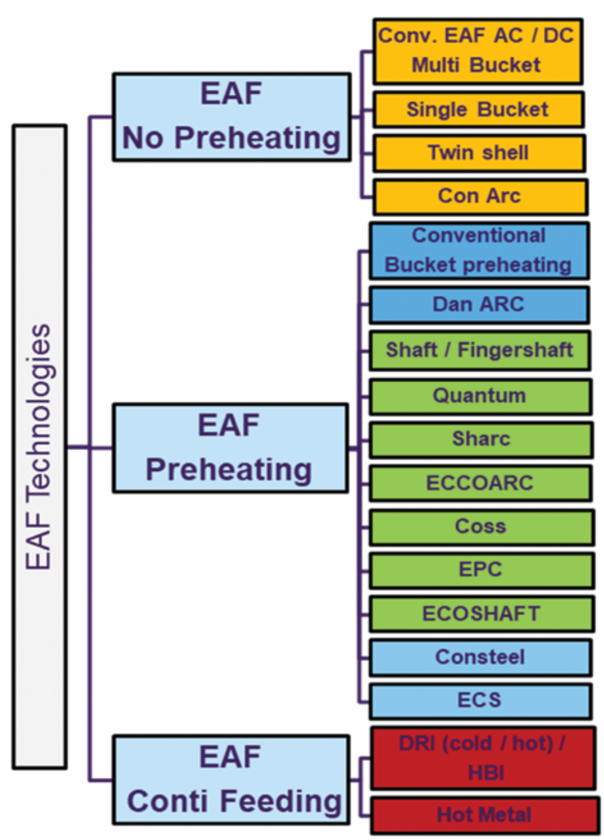
The EAF — especially when using direct reduced iron (DRI) — is expected to have a significant place in the future of steelmaking. A variety of EAF technologies have been developed and are available on the market. Three main design alternatives are visualized in Fig. 2. Of course, more design options have been developed in the past; therefore, the list is by no means complete.

The majority of these are conventional scrap-based EAFs that are charged via buckets and do not have any additional preheating technology attached. Of course, there are many different EAF designs in this category that support charging with one or more buckets and are either AC or DC powered. If two furnace shells are built in very close proximity to each other (twin-shell EAF), one set of electrodes can be used to melt the scrap in both vessels sequentially. This design allows for parallel operational activities on separate EAF vessels; however, the benefits of increased productivity may be somewhat outweighed by energy losses in the empty vessel.

Several concepts are on the market to use the lost energy that goes with the offgas. The earliest and most straightforward method of preheating was to direct the offgas into the scrap bucket (conventional scrap preheating). This approach is associated with several difficulties, such as thermal deformation of the scrap bucket, bucket logistic, and the formation of bad odors in and around the meltshop. Therefore, different technical solutions have been developed. The most common method nowadays is horizontal preheating, where a slip-stick conveyor continuously feeds scrap from the side into the EAF with a hot heel of approximately 40%, while the offgas passes in the opposite direction. Although Tenova originated the concept known as Consteel®, several original equipment manufacturers (OEMs) provide this technology.

Figure 2

Classification of electric arc furnace (EAF) technologies.



An effective preheating method is vertical (shaft) preheating since the offgas flows through the scrap pile. Over the years, numerous shaft design variations have been constructed; the most recent version uses water-cooled finger systems to guarantee preheating of the entire charge. These furnaces still operate with a batch process like conventional EAFs. Nevertheless, an extra offgas treatment is required since the scrap preheating lowers the offgas temperature.

Alternatively, a conventional EAF can also be operated with DRI, HBI, pig iron or liquid hot metal from a blast furnace, if it is necessary to guarantee specific qualities. These EAFs require a continuous feeding system through the roof (DRI/HBI) or sidewall, slag door, or eccentric bottom tapping (EBT) for hot metal.

Based on actual industrial results, a comparison is made for the three main EAF designs by selecting the most developed and proven concepts, also by the number of installations. Concerning decarbonization, the following data are examined:

- CO_2 emissions scope 1 and 2.
- Electrical energy consumption.

Yearly performance data from plants with adequate tap sizes >80 tons and high-performance levels (low power-off/high power-on time) were selected for the evaluation from the global BSE Best Practice database (benchmark). For simplicity and comparability, the same material composition of all carbon carriers was assumed for all plants to calculate the scope 1 emissions. Similarly, for the scope 2 calculation, which is based on the EAF electrical energy consumption, the same grid factor for all plants was used.

Fig. 3 shows the CO_2 emissions of scope 1 and scope 2 and the sum for the three different EAF design technologies as already explained: Conventional EAFs, scrap-preheating EAFs and DRI-fed EAFs. For the last group of DRI-based EAFs, only operations where the reduction was based on natural gas were considered. Within each group, the plants are sorted in ascending order by tap weight (size). It can be clearly seen that there is no impact of EAF size on the CO_2 emission level.

The lowest scope 1 level is reached within the group of conventional EAFs with an average of 72 kg CO_2/t and a maximum of 98 kg CO_2/t for an EAF using pig iron as charge material. However, there is an operational minimum of carbon carriers required, and therefore there are limitations to reduce further than approximately 45 kg CO_2/t.

The group of eight scrap-preheating EAFs achieves 106 kg CO_2/t as the average level of scope 1. Main drivers for the difference are higher amounts for C injection

Figure 3

Exemplary, industrial CO_2 emissions of electric arc furnace worldwide with average values as dotted lines.

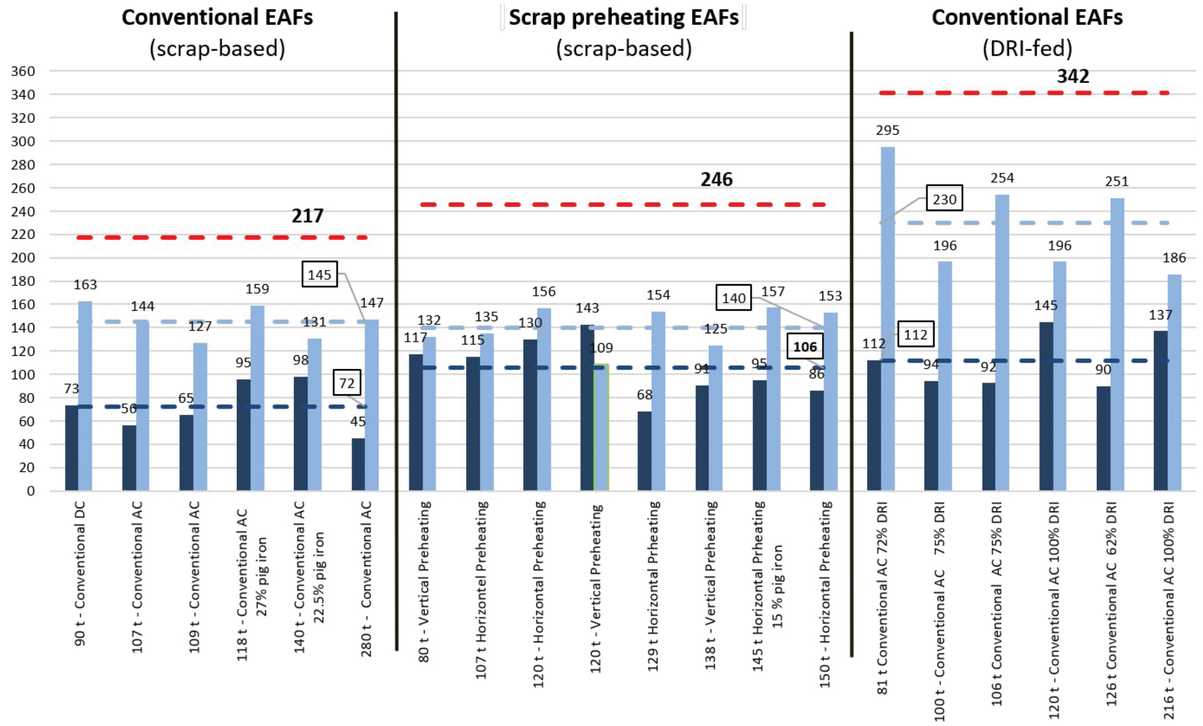
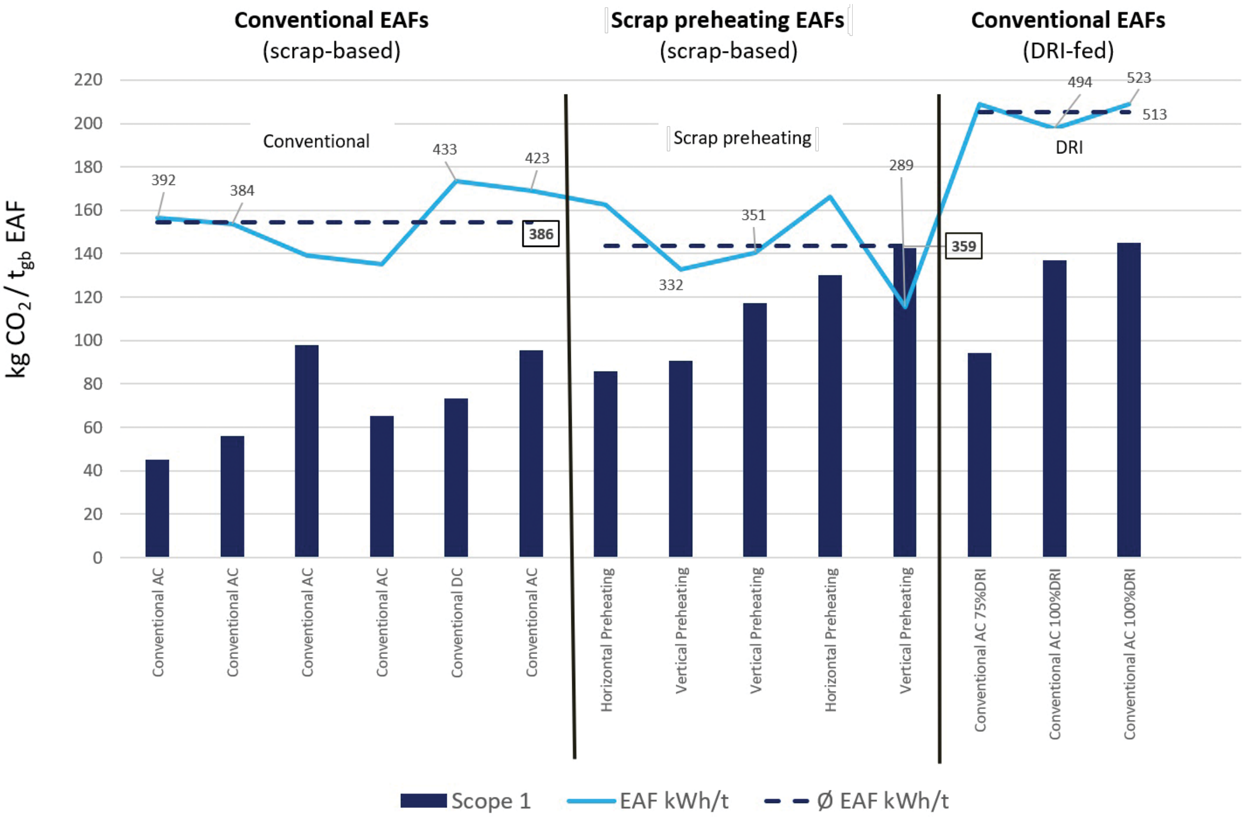


Figure 4

Exemplary, industrial electrical energy consumption vs. CO_2 scope 1 emissions of electric arc furnaces worldwide.



to keep slag foaming during flat bath and gas consumption for offgas treatment (vertical preheaters) — horizontal preheaters partially use active carbon for dioxin treatment.

DRI carbon input (in this example, 1.4% C) results in higher CO_2 levels of 112 kg CO_2/t (average). A certain amount of the DRI's carbon is required to reduce the FeO in the DRI. Any excess C is available for FeO slag reduction and combustion with injected oxygen. DRI-contained C is a more efficient carbon source than charged or injected C.

The CO_2 emissions of scope 2 are CO_2 calculated with a grid factor of 0.376 kg CO_2/kWh; logically the emissions follow according to the electrical energy consumption in each category.

Fig. 4 shows the electrical energy consumption for the three different EAF technology groups. Size has no major impact within this selection of EAFs; more important is the charge mix (scrap/pig iron/DRI/HBI/hot metal). The conventional EAFs in this database achieve 386 kWh/ton as the average electrical energy consumption. Well-managed EAFs with efficient operation can achieve 338 kWh/ton as best value in this comparison of conventional EAFs. The impact of poor melting behavior of pig iron is visible for the two plants using 22–27% pig iron. The overall effect of preheating results in a lower consumption level of 373 kWh/ton for the scrap preheating technologies, with vertical preheating EAFs being overall much more efficient. The EAFs using DRI achieve 506 kWh/ton (average). A major impact on the required electrical energy consumption is the amount of DRI charged and the melting behavior of DRI, which is strongly related to the composition of the iron ore used for making DRI and the charging temperature. Lower consumption values can only be achieved with hot DRI (hDRI).

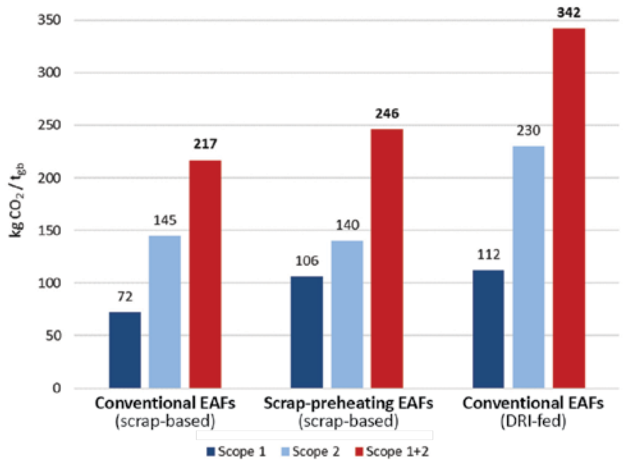
Fig. 5 shows the summary and general overview of CO_2 emissions for the three different EAF technologies. Based on the lowest scope 1 emissions for conventional EAFs and the overall good average of electrical energy consumption, the total emissions are also the lowest in comparison.

Optimal Design of Conventional AC-EAF

To achieve an optimal conventional AC-EAF, it is first necessary to ensure that the entire EAF design and control system complies with a certain safety norm.[2,3] This requires a comprehensive strategy that simultaneously

Figure 5

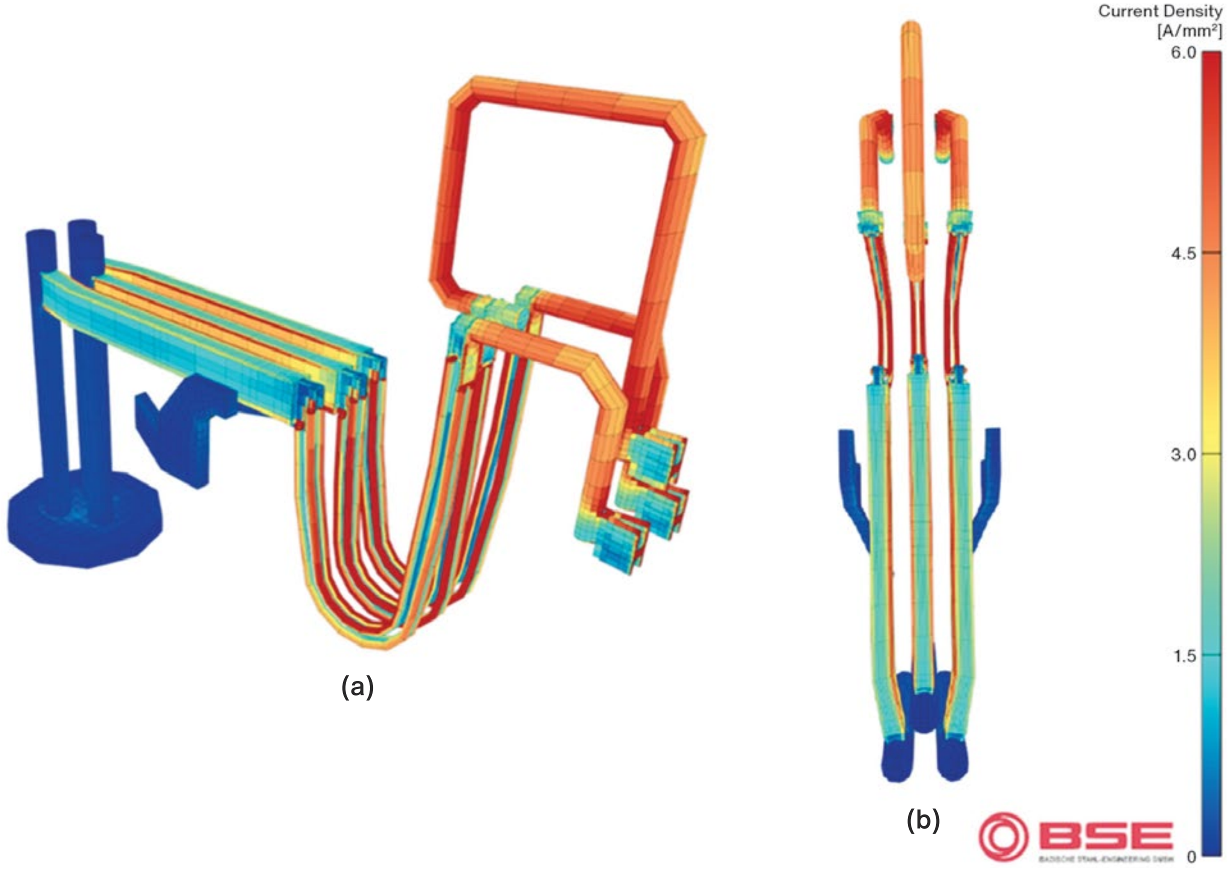
General overview of CO_2 emissions from different EAF technologies.



combines high-productivity operations with safety. To provide further information, some crucial key components of a modern, state-of-the-art EAF are briefly introduced. Nowadays, the steel grade portfolio of EAF-based production ranges from long products such as rebar up to special bar quality (SBQ) to flat products, with, e.g., transformer steel. The final product quality requirements dictate the iron feedstock, which has a significant impact on the EAF design. Rebar producers might focus on balancing scrap quality with varying densities and corresponding costs. Slab producers will need to focus on minimizing tracing elements reaching for the highest amount of virgin iron units (e.g. DRI, HBI, pig iron, etc.) necessary and the lowest amount possible.[1] Generally speaking, the EAF and its operation should be designed with as few buckets as possible — ideally only one. Since achieving a one-bucket operation is extremely difficult and seldom (except, e.g., vertical preheater with one additional bucket), a modern conventional EAF will strive for a two-bucket operation. Based on this circumstance, the buckets and EAF volume need to be designed accordingly based on feedstock and volume.

Figure 6

Finite network method (FNM) simulation of EAF high-current system (HCS) with 3D view of current density (a) and top view (b).



Continuing with this precondition, EAF high-current system (HCS), secondary delta closure, high-current cables and current-conducting electrode arms are to be designed for effective electrical energy input and reduced maintenance problems. A very important design tool is the use of finite network method (FNM) simulation for the whole system. With the FNM simulation,[4] the design is optimized to achieve the highest possible symmetry of the electrical power input during the operation of the EAF. One of the simulated parameters is the current density distribution in the system between transformer connections up to the electrode tips. The outcome of the designation for the current density distribution is shown in Fig. 6.

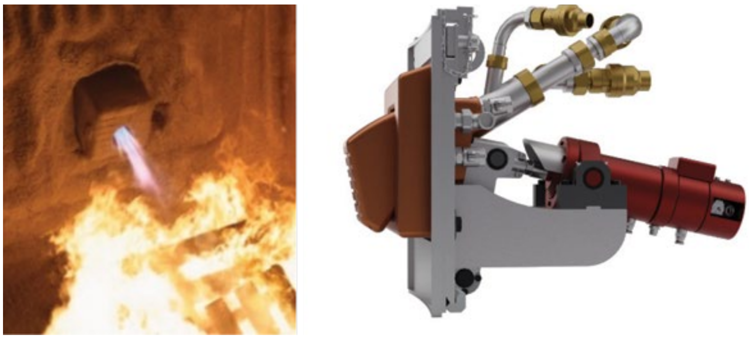
In addition, since chemical energy accounts for at least 30% of the energy input in current furnaces, the burner system that is used is an additional vital component. Tiltable oxy-fuel burners in the sidewall, as shown in Fig. 7, can reach thermal power levels up to 6 MW. For direct carbon-oxygen reactions in the bath, such as in a BOF, an oxygen lancing mode of up to 2,200 Nm^3/hour can and should be chosen in addition to the burner mode. Depending on the scrap mixtures and other factors, various operational profiles can be chosen for automatic control and power input execution in state-of-the-art burner systems. With an ideal angle for bath reactions in lancing mode and scrap heating in burner mode, the tilting feature provides more flexibility. Additionally, it aids in being adaptable to the varied melting behaviors of different densities of scrap.

The gantry design of the EAF is another special and important aspect. It should be robust, sturdy, fast moving and allow for gantry swiveling without a roof. For optimal maintenance, special attention should be paid especially to the bearing system. Furthermore, due to their leaner structure, current gantry designs can increase the furnace volume significantly. Fig. 8 visualizes the primary loads on the EAF gantry and the bearing system for a modern EAF design.

A key recommendation for any new EAF is a spray-cooled roof and elbow (Fig. 9). Pressure-less cooling results in lower maintenance requirements and furthermore is highly beneficial for safe working conditions. Since bulky cooling pipes are not required, the overall weight is decreased and the hydraulic system experiences less stress. Overall, this reduces the operation's process delays. In addition, the spray-cooled roof is lighter than other solutions and allows faster swivel movements. This reduces POFF during bucket charging and consequently reduces energy losses during open roof with a direct impact on kWh/t and productivity. However, the cooling water return requires special attention. Venturi pumps must be used to apply suction to the return collecting ring in the roof in order to guarantee a safe and

Figure 7

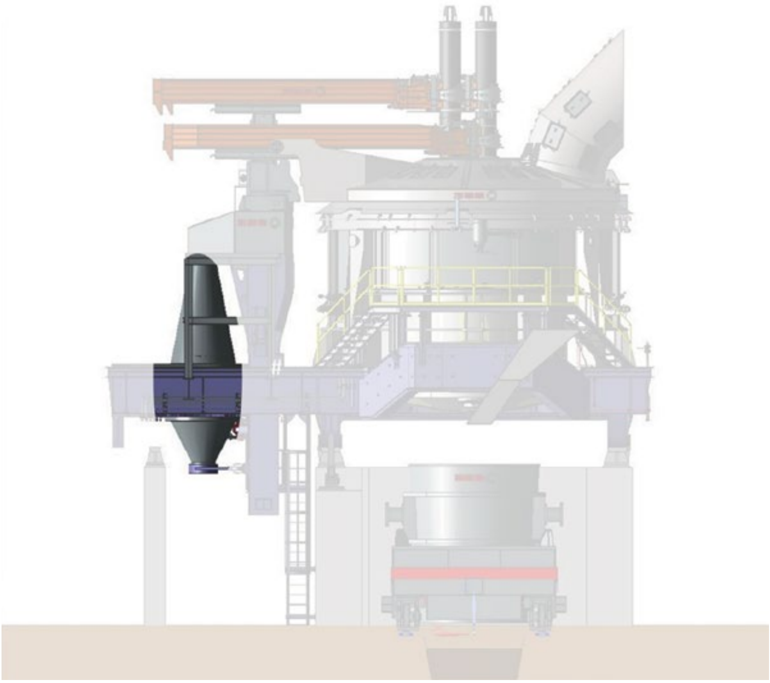
Tiltable virtual lance burner mounted in EAF with view from inside EAF (a) and view from the side (b).



(a) (b)

Figure 8

EAF with highlighted gantry.



reliable water return from the EAF roof. The benefits of the system in terms of operation and maintenance, as well as the extremely long lifespan of the installed water jet pumps — which require no maintenance at all, make the considerable installation effort for the spray-cooled roof's return water suction quickly pay for itself.

"The future is manless®," which can be seen in most U.S. steel plants. The immediate area surrounding the EAF turns into a red zone that is inaccessible during power-on time. Therefore, the implementation of automated systems becomes more important than ever. Thus, it is now more important than ever to deploy automated systems. The most up-to-date recommendations to keep operators away from the furnace are to utilize automatic taphole cleaning and changing devices in conjunction with automatic, camera-controlled taphole filling equipment, like the Tap Hole Manipulator (THM) and SandMan® for EBT. An additional technology that might be included is an automatic slag door, which has the ability to safely clean the sill and tunnel during operation and to open and close the door securely during the EAF process. In Fig. 10, a slag door concept is shown as a drawing and in a meltshop in Türkiye. These automated systems do help to standardize operation steps and consequently reduce the necessary time for those leading to increased productivity, which is necessary to counterbalance the productivity gap an EAF has in comparison to a BOF, especially when charged with cold DRI or even HBI.

Finally, much consideration should be given to the electrode regulation system. Systems like ELARC offer a highly dynamic, adaptive control concept that ensures optimal arc stability, reduced electrode consumption, and superior energy efficiency, even under challenging melting conditions. Recent tests have even shown that the simple handling in terms of parameter tuning and current set point adjustment not only increases power input (MW) but can also reduce flicker.

Figure 9

Spray-cooled roof without elbow and top plates.

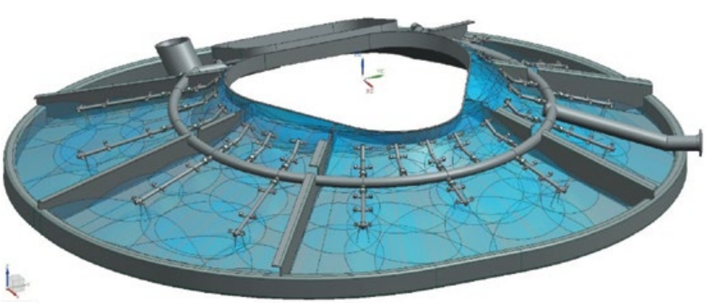
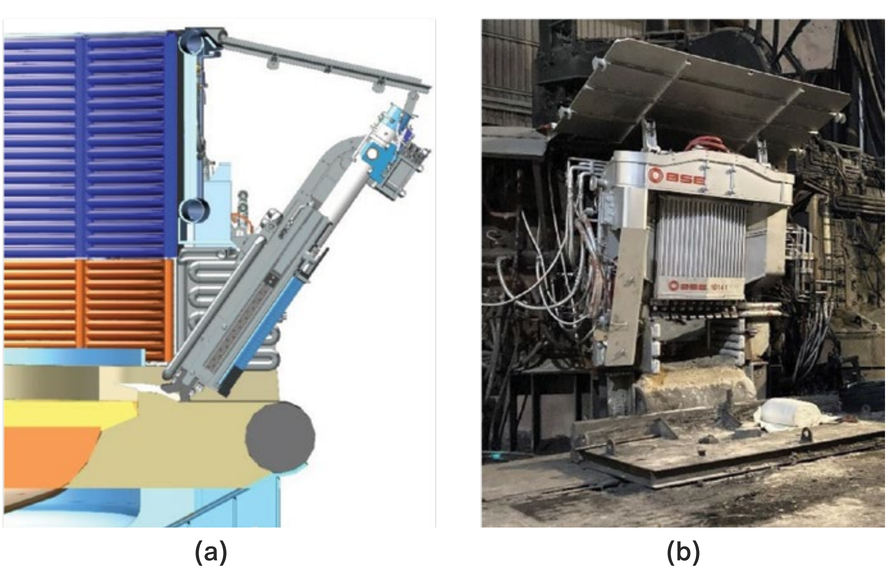


Figure 10

Automatic slag door in charging position: rendering (a) and DoorMan® at Özkan-EAF (b).[6]



Slag Volume Versus CO_2

Much thought has been put into the discussion whether DRI made from blast furnace (BF) pellets could be used or only from DR pellets as virgin iron units for steelmaking in an EAF. Usually it is said that DRI of BF pellets has too much gangue content and too less Fe, which creates too much slag in an EAF, making the steelmaking process inefficient and uneconomic. Looking into this topic, a direct comparison should shed some light. Assuming a rather representative chemical composition of both pellet types,[7,8] it can seen in Table 1 (columns named "raw") that DR pellets have a higher Fe content and all other oxides in smaller amounts. Here gangue refers to other oxides not mentioned. The carbon content of both pellets is kept the same.

When simulating direct reduction of these pellets at temperatures below melting, the following chemical compositions of DRI made of both types of pellets are presented in the column "DRI" (reduction to DRI). It can be seen that the initial 2.2% gangue in DR pellets and 8.0% in BF pellets become 3.1% and

Table 1

Chemical Composition of DR and BF Pellets in wt. % Before Reduction (Raw) and After Assumed Direct Reduction as Final DRI (DRI)

		DR pellet		BF pellet	
Component	Unit	Raw[7]	DRI	Raw[8]	DRI
Fe_2O_3	%	96.8	–	91.1	–
O from Fe_2O_3	%	29.1	–	27.4	–
Fe	%	67.7	95.5	63.7	89.8
SiO_2	%	1.6	2.3	4.2	5.9
Al_2O_3	%	0.45	0.63	3.6	5.1
TiO_2	%	0.15	0.21	0.15	0.21
Carbon	%	1.0	1.4	1.0	1.4
Sum of gangue	%	2.2	3.1	8.0	11.2
Sum total	%	100	100	100	100

Table 2

Comparison of Yield and Slag Ratio for DRI Made From DR Pellets and BF Pellets

Source	DR pellet	BF pellet	Unit
DRI feed	100		%
$SiO_2 + Al_2O_3$	28.9	110.0	kg/t_{feed}
B_2 aim	2.2		–
CaO	63.6	242.0	kg/t_{feed}
Slag	92.5	352.0	kg/t_{feed}
Yield	95	87	%
Slag	97.3	404.7	kg/t_{tap}

11.2% in DRI, respectively. For simplification reasons, the metallization is assumed to be 100%, and the iron oxide only in the form of hematite.

When designing a steelmaking slag, metallurgy suggests balancing the acidic/amphoteric oxides like SiO_2 and Al_2O_3 to the desired basicity. Which basicity is necessary to reach which quality goal is not in the scope of this article. Table 2 shows slag metallurgy considerations with resulting impacts on yield and slag ratio. For a 100% DRI-fed furnace, the sum of SiO_2 and Al_2O_3 per metric ton of charged iron units are 28.9 kg/t_{feed} and 110 kg/t_{feed}, respectively. When the B2 target $(CaO/(SiO_2 + Al_2O_3))$ is set for 2.2, the demand for pure CaO is 63.6 kg/t_{feed} and 242 kg/t_{feed}, respectively. Adding both values results in 92.5 kg_{slag}/t_{feed} and 352 kg_{slag}/t_{feed}, respectively. As the SiO_2 and Al_2O_3 are input without metallic yield and possibly further 2% yield is lost in the process, the final Fe yield for the utilization of both types of DRI are 95% and 87%, respectively. The specific slag ratio is then 97.3 and 404.7 kg_{slag}/t_{tap}. Nowadays, good EAF operations have around 150 kg_{slag}/t_{tap}, which lets the DR pellet case look appealing, and the BF pellet case inefficient — not to mention the volumes necessary inside the EAF vessel's upper shell and the amounts of slag needing transportation, processing and selling.

Integrated steel producers are considering choosing the smelter technology, known from nonferrous production, to reduce their CO_2 emissions drastically. The reason to choose smelters instead of EAFs is the assumed flexibility to use lesser quality iron ores, even not pellets but fines, therefore DRI in the form of fines. Liquefaction in a smelter is a continuous process with batch tapping. It needs carburization of 2.5–3.5% like hot metal to obtain a "synthetic hot metal." In the subsequent BOF process, oxygen blowing removes [C] to bring chemical energy, the sole energy source next to latent heat. One of the major reasons is the considered impracticality of using EAFs with high slag volumes as calculated in Table 2. Continuing this consideration and adding CO_2 emissions, which is the main and initial reason to choose the smelter technology, Table 3 shows the subsequent CO_2 emission of scope 1 and 2 in comparison with EAFs and the two kinds of iron ore pellets. This overview shows that in order to reduce the uneconomic slag volumes and ratios, the smelter technology results in higher CO_2 emissions. The still-necessary oxygen-blowing BOF removes dissolved [C] and emits 150 kg CO_2/metric ton/tap — like a scrap-based EAF. Therefore, the actual CO_2 emissions of the entire DRI-smelter-BOF-route is considerable — a conscious decision each steel producer has to make. Knowing that smelters have not been built for more than 1-million-tons-per-annum capacity but EAFs are proven technology with tap weights exceeding 300 tons, this consideration might add doubts toward the smelter technology and for sure shows the uncertainty around this strategic decision.

In addition, the slag of smelters can be designed to be similar or even identical to blast furnace slag. Here no particular metallurgical work regarding dissolved

Table 3

Comparison of EAF and Smelter Technology With Different Pellet Types and Their Respective CO_2 Emissions[9]

Case	Unit	1	2	3	4	Ref.
Melting unit	–	EAF	EAF	Smelter	Smelter	9
Pellet type	–	DR pellet	BF pellet	DR pellet	BF pellet	
DRI	kg/t_{tap}	973	1,270	932	1,123	
Carbon	kg/t_{tap}	10	10	42	49.4	
Scrap	kg/t_{tap}	210	210	210	210	
Electrode	kg/t_{tap}	1	1.4	2.4	2.6	
Scope 1 CO_2	kg/t_{tap}	126.4	155.3	244.1	239.5	
Electrical power	kWh/t_{tap}	380	406	540	582	
Scope 2 CO_2*	kg/t_{tap}	114	122	162	175	calc. **
Scope 1 + 2 CO_2	kg/t_{tap}	240	277	402	419	calc. **

* assumption: 0.3 kg/kWh CO_2; ** calc.: Values calculated based on the above values

elements in the steel is to be conducted. Thus, the basicity of "synthetic blast furnace slag" can be defined and targeted around 0.9–1.3, giving it the opportunity to be used in cement applications after grinding, as is the case for today's blast furnace slag. What is not fully understood is the role of FeO in such slag. FeO, or possibly even higher oxidation stages of iron oxide, are coming from less than 100% DRI metallization. Reduction of FeO to Fe in the smelter is suspected to be incomplete. There are OEMs claiming that all FeO and even some SiO_2 are reduced to create [Si] in the synthetic hot metal coming from the smelter. If this is not the case, the effect of FeO in this synthetic blast furnace slag on utilization in cement needs evaluation.

Conclusion

Reducing CO_2 emissions in steelmaking is a crucial and strategic decision that profoundly impacts the business and profitability of steel producers. The decision for the right technology down to certain details cannot be overrated and needs in-depth analysis. This article compares different EAF designs that might be of consideration for integrated plants and mini-mills for future profitable production with their respective implications on scope 1 and 2 CO_2 emissions.

Different industrial solutions are presented and compared. Among them, the feedstock preheating units are not more CO_2 efficient. Well-operated and maintained conventional EAFs with either scrap or virgin iron unit feedstock can have the lowest emissions and are most cost-effective with well-trained personnel and know-how. Some crucial details of a conventional EAF are highlighted and described. A minor comparison to the alternative smelter technology shows that, indeed, the slag ratios are smaller and a clear advantage, but with the disadvantage of significantly higher CO_2 emissions. Based on the strategic targets of the transforming steel producer, different solutions might be chosen. If the major and overall target should be the least CO_2 emission, then the conventional EAF seems to be the most profitable option.

This article is available online at AIST.org for 30 days following publication.

References

1. F. Firsbach, P. Lückhoff, P. Hansert and P. van der Velden, "The Road Map From BOF Toward EAF Operation — A Concept Study for an Exemplary European Integrated Plant," *Iron & Steel Technology,* Vol. 20, No. 8, 2023.
2. Deutsches Institut für Normung (DIN e.V.), DIN EN 14681, released October 2010.
3. R. Schweikle and C. Pfundstein, "Integrated EAF Safety Concept of Badische-Group," *SEAisi Conference,* Singapore, 2017.
4. D. Riedinger, P. Hansert, M. Frank, T. Thompson and D. Kakas, "Efficient Power Input Into EAFs With Optimized HC-Systems, Using the Finite Network Method (FNM) and a New Generation of Copper-Steel Arms," *AISTech 2016 Conference Proceedings,* 2016.
5. D. Riedinger, A. Vogel and D. Kakas, "A New Dimension of Designing Arc Furnace Hugh Current Systems," *Arc Furnace Conference,* Venice, Italy, 2016.
6. G. Gürler and R. Schweikle, "Introducing 1st EAF Doorman at Özkan Steel," *7th International Steelmaking Symposium,* Offenburg, Germany, 2022.
7. J. Poveromo, "DR Grade Pellet Quality, Supply and Prices," *Steel Times International Webinar,* 2020.
8. A. Babich, D. Senk, H.W. Gudenau and K. Mavrommatis, *Ironmaking,* Mainz Scientific Publishing House, Aachen, Germany, 2008.
9. B. Belford, "The Open Bath Furnace for Steel Production," (in German) Transformation of the Steel Industry Seminar, Düsseldorf, Germany, 2022.

This paper was presented at AISTech 2024 — The Iron & Steel Technology Conference and Exposition, Columbus, Ohio, USA, and published in the AISTech 2024 Conference Proceedings.