Chapter 16
Electric Arc Furnace

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Abstract In this chapter, electric steelmaking is introduced with a short review: share, raw materials, operation, typical equipment, off-gas treatment, emissions. Electric-based steelmaking enjoys a much comfortable position than integrated classical blast furnace—oxygen steelmaking facilities, regarding greenhouse emissions. This is compared both for regions and for the world. For instance, the mostly EAF-based NAFTA countries are nowadays the region where the production of steel generates lower specific emissions. This said (and detailed), the chapter continues with a discussion of the CO_2 emissions of the electric arc furnaces. A reference is be made to the use of alternative raw materials, as DRI/HBI, pig iron and hot metal. In relation with the EAF design, factors to be analyzed are the effects of different furnace designs on emissions: conventional, twin shell, conveyor scrap preheating, and shaft scrap preheating are considered. The use of chemical energy is reviewed, as well as the effect of an external factor: how electric energy is generated.

16.1 Electric Steelmaking

The electric arc furnace applied in steelmaking was invented in 1889 by Paul Héroult. Emerging new technology started in the beginning of the twentieth century when wide-ranging generation of relatively cheap electric energy started at that time. First-generation furnaces had a capacity in between 1 and 15 t. The EAF had Bessemer/Thomas converters and Siemens Martin furnaces as strong competitors, initially. But its niche was the production of special steels requiring high temperature, ferroalloy melting, and long refining times. In the 1960s, with the advent of billet casting, the EAF occupied a new niche: the melting unit of choice for the so-called minimills, feeding billet casters for the production of rebar and wire rod (Madias 2014).

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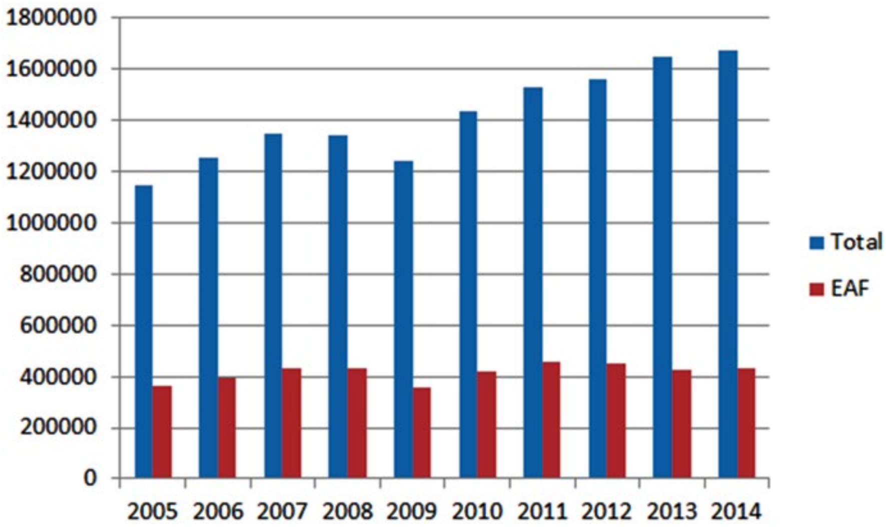

Fig. 16.1 Worldwide crude steel production (EAF vs. total) 2005–2014 (Worldsteel Association 2015)

Table 16.1 Ten top producers of steel through electric arc furnace in 2014 (Worldsteel Association 2015)

Country	EAF production (t)
United States	55,174,000
India	50,211,000
China	49,938,000
Japan	25,679,000
South Korea	24,197,000
Turkey	23,752,000
Russia	21,852,000
Italy	17,200,000
Iran	13,607,000
Mexico	13,311,000

In the following two decades, to better support the short tap-to-tap time required by billet casters, the EAF reinvented itself as a melting-only unit. Steel refining was left for the recently introduced ladle furnace. Large transformers were introduced; ultrahigh-power furnaces developed, which were made possible by adopting foaming slag practice. This way, tap-to-tap time became close to casting time.

By 1985, a new niche for electric steelmaking began to be taken: flat products, through thin slab casting, and direct rolling.

This process route has achieved a significant role in world steel production, being close to 26 % share by 2014 (Fig. 16.1). The three top producers are the United States, India, and China (Table 16.1).

Table 16.2 Estimation of raw materials for EAF steelmaking for 2014

	Annual production/ consumption	% share	Assumptions
EAF crude steel production (t)	430,251,000		From [2]
Estimated metallics required (t)	478,056,667	100	90 % yield
Scrap (t)	382,425,834	80	Balance
DRI/HBI production (t)	73,209,000	15.3	All DRI/HBI production consumed in EAFs
Hot metal + pig iron	22,421,833	4.7	BOF mix 85 % hot metal, 15 % scrap, 90 % yield

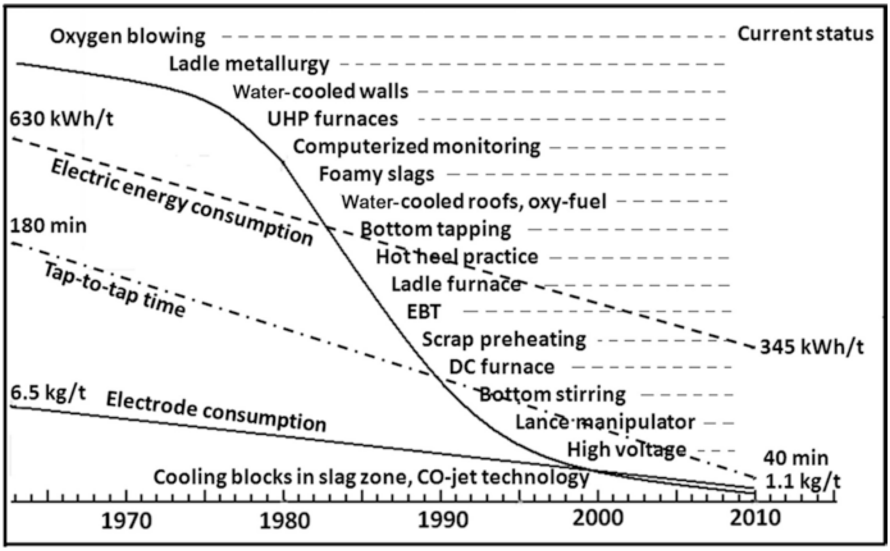

Fig. 16.2 Evolution of EAF technology 1965–2010

Most of the ferrous scrap worldwide is recycled and refined to steels via electric furnaces. EAFs are versatile, charging everything from all sorts of scrap to hot briquetted iron (HBI), direct reduced iron (DRI), pig iron, hot metal (Table 16.2).

EAFs may produce all type of steels: long and flat, carbon and alloyed, merchant and special products.

The developments in the EAF technologies since 1965, promoting lower electric energy consumption, shorter tap-to-tap time, and less electrode consumption, are shown in Fig. 16.2 (Lüngen et al. 2013). Furnace size enlarged up to 350 t maximum, which together with the shortening of tap-to-tap time made possible to have more than 1 Mtpy capacity with just one furnace. Electric energy consumption decreased down to 350 kWh/t for 100 % scrap operations. Chemical energy increased at levels not far from those of Basic Oxygen Furnace (BOFs). Refractory consumption fell down due to the replacement by cooled roof and panels, slag foaming, and refractory quality improvement. Power-off time is now of <10 min for the best operated furnaces. For a large number of ArcelorMittal group meltshops, average electrode consumption was 1.43 kg/t.

16.1.1 Equipment

The increase in furnace electric power has been the key factor in the development of EAF technology during the past 50 years. As in the 1960s, a common EAF power was 250–300 kVA/t liquid steel; today standard ultra-high-power EAFs have 900–1000 kVA/t steel available in the transformers. These furnaces are equipped with water-cooled panels and EBT tapping. EBT stands for eccentric bottom tapping, a tapping system that yields a uniform steel jet falling into the ladle, with slag carry over controlled to a certain extent. In Fig. 16.3, a scheme of such state-of-the-art EAF is presented.

The current furnace includes three water-cooled parts: roof, panels, and off-gas duct. Although some heat is lost due to the heat extraction by the cooling

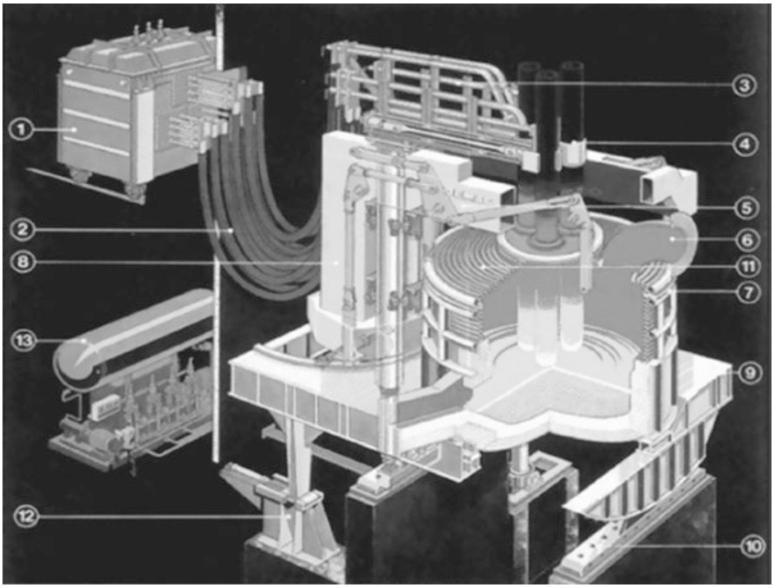

Fig. 16.3 Current EAF standard design. (*1*) Transformer, (*2*) flexible cable connection, (*3*) electrode arms, (*4*) electrodes clamping, (*5*) arms, (*6*) cooled off-gas duct, (*7*) cooled panels, (*8*) structure, (*9*) basculating structure, (*10*) rack, (*11*) cooled roof, (*12*) basculating device, and (*13*) hydraulic group

water, this design makes possible less refractory consumption (because they replace refractory linings) and the use of high power. At the time the panels were first introduced, some fears arose on safety risks, but after realizing the cost advantage, almost all EAF adopted them. They may be made of steel or copper (much longer life) and with different designs (conventional, flip and turn, etc.). Recently, more attention has been paid to safety with water cooling. First, to detect, limit, and avoid the possibility of water leakage, and second, to cut the need of repairing work in the hot furnace. Off-gas analysis, when hydrogen is included, is a useful tool to detect leakage. To limit leakage and maintenance work, solid cast or machined water panes have been introduced. Split shell, with spray-cooled upper shell means less risk as non-pressurized water tends to penetrate less in case of leakage.

There are variations on the standard design:

- Use of direct current instead of alternative current, with one large electrodes (or two) instead of three, and a refrigerated anode in the hearth bottom. Main aim is to decrease electrode consumption and flickers.
- Use of scrap preheating on a continuous scrap transporter, using the off-gas heat, in counter-current. Main aim is to decrease energy consumption and to avoid bucket charging.
- Use of scrap preheating in a shaft, using the off-gas heat. Main aim: to decrease energy consumption.
- Twin shell.

16.1.2 Melting Practice

The basic principle of electric steelmaking today is that the furnace is a “melting machine” that produces liquid steel with required chemistry, temperature, and mass in time to feed steel to successive ladle treatments and continuous caster, which finally determines the production rhythm. Typical tap-to-tap times are in the range of 40–60 min, which is also the total furnace time per heat.

Although Ultra High Power (UHP) furnaces are used, fast melting by using only electric power is difficult and not the most economic practice either. Importing extra energy and assisting melting technique can greatly accelerate scrap melting and bring economic benefits. Accordingly, the current state of the art in EAF steelmaking is to use as much as possible chemical energy, besides electric energy, to accommodate tap-to-tap times to the pace of the downstream continuous caster.

Regarding the application of electric energy, at the start of melting, after basket charge, not all the available power can be applied, as the electrodes may be still in a high position, too close to the roof. Then, when the melting operation has advanced further, changing to the tap maximum power may be applied. This is not the case for 100 % flat bath operations like in Consteel EAFs or 100 % DRI/HBI charging through the fifth hole. Chemical energy is introduced by oxygen, carbonaceous materials, and natural gas, more and more through injectors rather than lances. The energy generating reactions are:

$$C + \frac{1}{2}O_2 = CO \rightarrow 2.55\,\text{kWh / kg}\,C$$

$$C + O_2 = CO \rightarrow 9.1\,\text{kWh / kg}\,C$$

$$C + \frac{1}{2}O_2 = CO_2 \rightarrow 2.81\,\text{kWh / kg}\,C$$

$$Fe + \frac{1}{2}O_2 = FeO \rightarrow 1.32\,\text{kWh / kg}\,Fe$$

The refining step usually does not require full power, which with already flat bath could be dangerous for the lining. At that time, the foaming of the slag is a must. For the slag to foam, the production of CO gas is necessary, by means of the injection of carbon and oxygen through lances or burners. For foaming purposes, several carbonaceous materials are useful, depending on local cost and availability: anthracite, petroleum coke, coke breeze.

16.2 EAF CO_2 Emissions

There is a specific methodology to calculate GHG emissions from EAF steel facilities (Climate leaders 2003). It includes calculating emissions from carbonate flux and use of carbon electrodes. Emissions of CO_2 from use of carbonate flux are calculated based on the amount of flux used and the stoichiometric ratio of CO_2 to $CaCO_3$ and $MgCO_3$. The emissions from use of electrodes are estimated based on the number of electrodes used and the carbon content of the electrodes. CO_2 emissions from any coke or coal used in the process are estimated using the Climate Leaders Stationary Combustion guidance. The steps involved with estimating iron and steel process related CO_2 emissions from EAF facilities are shown below.

Step 1: Determine the amount of carbonate flux used. This should be in terms of pure $CaCO_3$ and $MgCO_3$. Therefore, the total amount of flux used needs to be adjusted for purity.

Step 2: Calculate the flux carbon factor. This is based on the stoichiometric ratio of C to $CaCO_3$ and $MgCO_3$. Default values are given in Climate Leaders 2003, Sect. 3.2.

Step 3: Determine the amount of electrodes used. This could be based on the actual amounts used or could be estimated based on the amount of steel produced.

Step 4: Determine the electrode carbon factor. This is based on the carbon content of the electrode

Equation 16.1 represents the method used to calculate CO_2 emissions from steel production at EAF facilities. More explanation of emission factors and default values is provided in Sect. 16.3 of the reference.

$$\text{Emission} = \left[\left(\text{Flux} \times \text{CF}_{\text{Flux}} \right) + \left(\text{Electrode} \times \text{CF}_{\text{E}} \right) \right] \times \frac{\text{CO}_2 \left(\text{m.w.} \right)}{\text{C} \left(\text{m.w.} \right)}$$

$$\begin{aligned}
&\text{where :}\\
&\text{Flux} = \text{mass of flux used}\\
&\text{CF}_{\text{Flux}} = \text{flux carbon factor} \left(\frac{\text{mass C}}{\text{mass flux}} \right)\\
&\text{Electrode} = \text{mass of carbon electrode used}\\
&\text{CF}_{\text{E}} = \text{electrode carbon factor} \left(\frac{\text{mass C}}{\text{mass of electrode}} \right)\\
&\text{CO}_2 \left(\text{m.w.} \right) = \text{molecular weight of carbon}
\end{aligned} \tag{16.1}$$

If the CO_2 emissions related to the production of electric energy are considered, the source of this energy has a very strong influence. A case study has been carried out for a conventional EAF in Canada and an EAF equipped with shaft preheater in the UK (Thomson et al. 2000). Both countries have a different profile of electricity sources (see Table 16.3). In Fig. 16.4 the share of GHG emissions (including the generation of electricity) is shown for the two cases.

It is well known that emissions from EAF-based steelmaking are much lower than for integrated plants. Electric steelmaking represented in 2013 29 % of the world steel production, but only 1 % of the energy consumption and just 12 % of CO_2 emissions (see Fig. 16.5).

Worldwide figures have been collected by Worldsteel in 2013 from 72 BF/BOF mills and EAF plants, to benchmark emissions. Results are presented in Fig. 16.6. In weighted average, for BF/BOF plants CO_2 intensity is 2.26 t CO_2/t crude steel, while for EAF plants the figure is 0.62 t CO_2/t crude steel (Reimink 2015).

In Table 16.4, a comparison is made for the case of the USA, where the dominant process route is electric steelmaking.

Thanks to its higher share of EAF, NAFTA (Mexico, USA, Canada) has the lower specific energy consumption and CO_2 emissions in comparison with other OECD countries (Europe 27+TK and Australasia), see Fig. 16.7.

Recycling scrap in EAFs is the most efficient available technology, not just for energy. Steel, like all metals, is indefinitely recyclable without loss of properties. Steel is not "consumed" but "used," over and over again. The energy needed to

Table 16.3 Electricity generation source distribution

	Canada	UK
Coal (%)	25	50
Fuel (%)	3	5
Natural gas (%)	4	13
Nuclear (%)	30	29
Hydroelectricity (%)	38	3

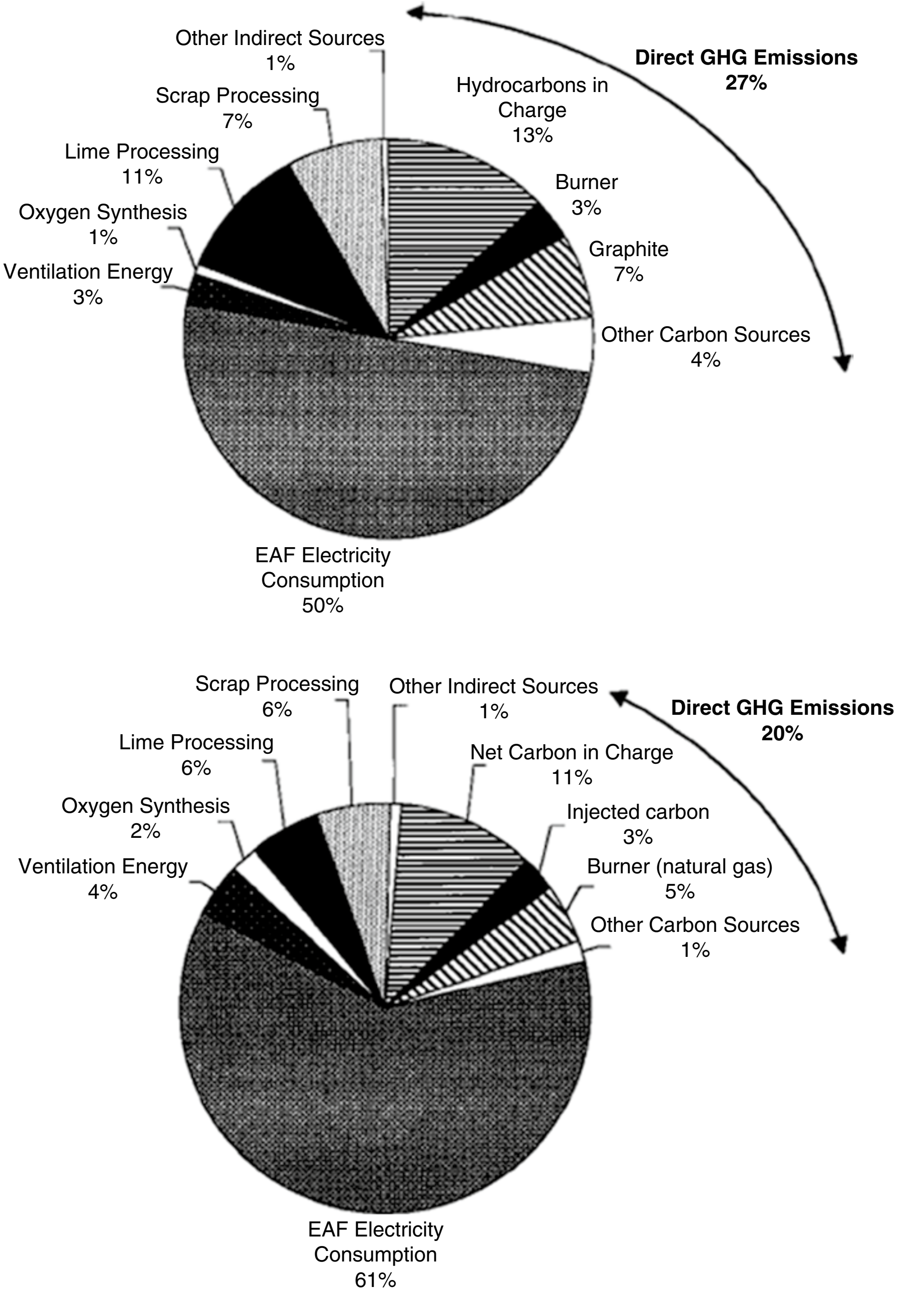

Fig. 16.4 Direct and indirect GHG sources for two cases. *Top*: convention EAF using Canadian electricity generation source distribution; *bottom*: scrap preheating EAF with UK electricity generation source

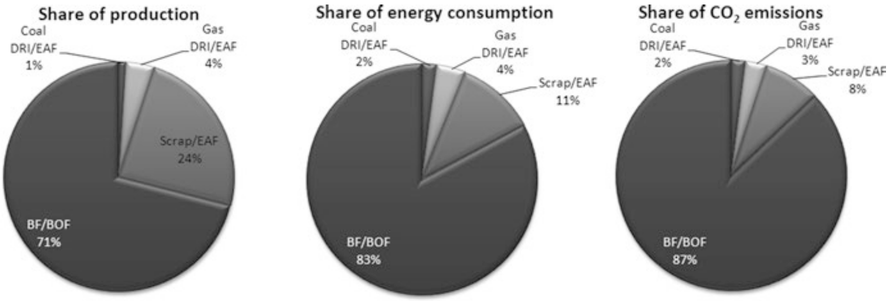

Fig. 16.5 EAF vs. BF/BOF route worldwide: a comparison of production, energy consumption, and CO_2 emissions (Laplace Conseil 2013). * Includes share of CO_2 from electricity needed; assume same mix of primary energies for electricity production

melt scrap represents 40 % of the energy and 30 % of CO_2 to smelt iron ore in a modern BF/BOF integrated mill. In addition, capital cost per ton of capacity is 60–70 % lower; maintenance costs are decreased in the same proportion. Labor productivity is twice as high and smaller size of mill usually leads to better social relationship.

16.3 Technologies to Decrease EAF CO_2 Emissions

In Europe, some technologies are being considered as Best Available Technology to decrease energy consumption and CO_2 emissions. In Table 16.5 those BAT are listed, taking into account if they are add-on, process control, or new technology (Pardo et al. 2012). Those selected as the most promising are scrap preheating and oxy-fuel burners.

In the USA, several technologies have been identified to decrease energy consumption and in consequence CO_2 emissions in EAFs (EPA Office of Air and Radiation 2012), see Table 16.6.

In the following, a short discussion of the two more promising technologies mentioned above is carried out.

Scrap Preheating Some 20 % of all the energy input for melting the scrap in an EAF disappears in the form of waste gas. Preheating of scrap is a technology that can reduce the power consumption in the EAF process by using the waste heat of the furnace to preheat the incoming scrap charge. There are 99 Scrap Preheating systems currently installed in the EU. In the case of adoption of this technology, total and direct CO_2 emissions should decrease by 0.037 t CO_2/t crude steel.

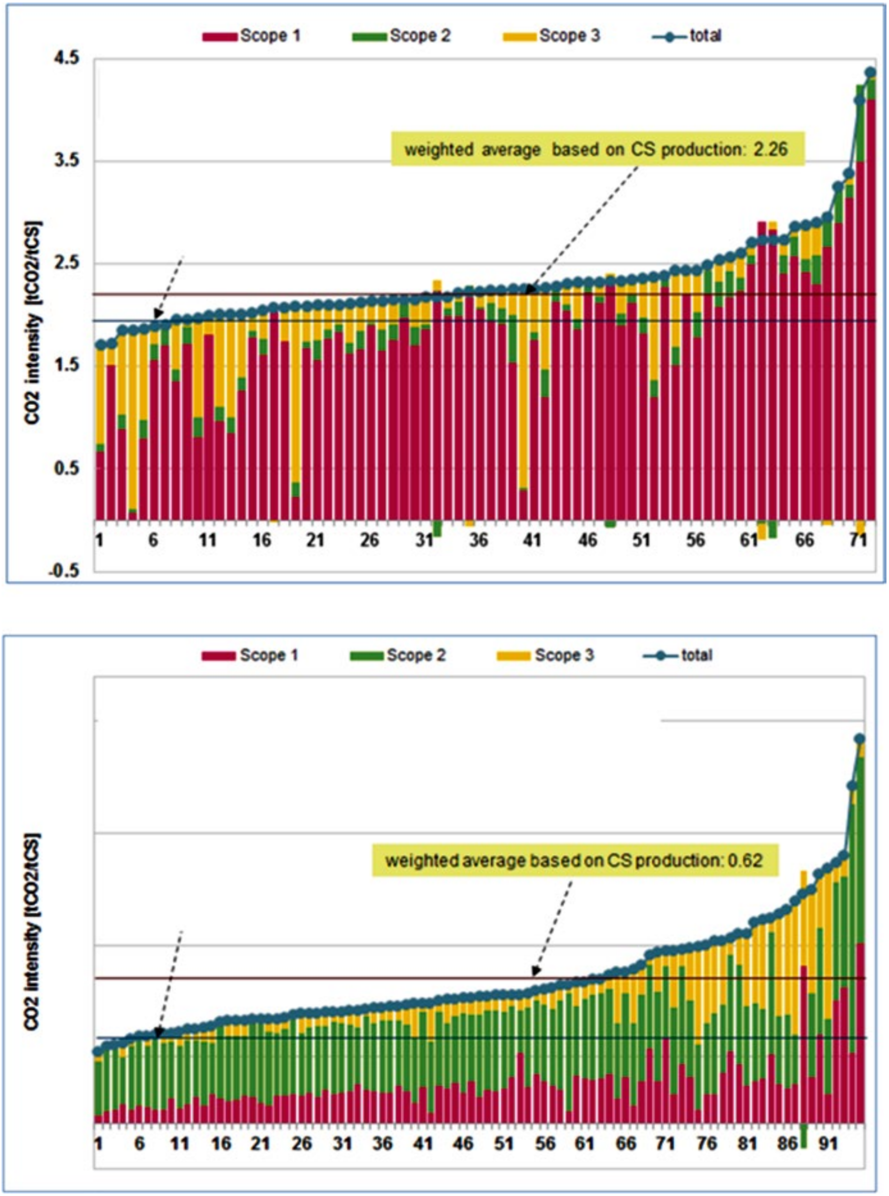

Fig. 16.6 2013 CO_2 intensity for BF/BOF (*top*) and EAF (*bottom*) plants

Table 16.4 Estimates of GHG emissions for iron and steel sector using emission factors (million tons of CO_2/year)

	Number of facilities	Process units	Miscellaneous combustion units	Indirect emissions (electricity)	Industry total	Average per plant
All EAF	87	5.0	19	24	48	0.6
All integrated	17	33	17.5	6.8	57	3.4

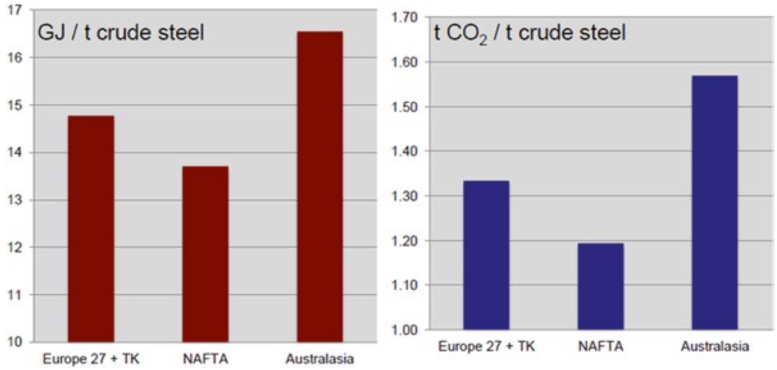

Fig. 16.7 Energy consumption and CO_2 emissions per ton of crude steel in OECD regions (Laplace Conseil 2013)

Table 16.5 Best available technologies to decrease energy consumption and CO_2 emissions being considered in Europe

Best available technology	Feature
Scrap preheating	Add on
Oxy-fuel burners	Add on
Bottom stirring/gas injection	Add on
Foamy slag practices	Process control
Improved process control	Process control
Eccentric bottom tapping	New technology
Twin shell furnace	New technology
Direct current (DC) arc furnace	New technology

Table 16.6 Energy efficiency technologies and measures available for electric arc furnace steel production in the USA

Option	Applicability and feasibility codes	Payback time (years)
Improved process control (neural network)	EX	0.5
Adjustable speed drives	EX	2–3
Transformer efficiency—ultra high power transformers	C, EX	5.2
Bottom stirring/stirring gas injection	C, EE, N	0.2
Foamy slag practice	C, EX	4.2
Oxy-fuel burners	C, EX	0.9
Post-combustion of the flue gases	C, EX	
DC arc furnace	C, EE, S	
Scrap preheating—tunnel furnace (Consteel)	C, EE, N, S	
Engineered refractories		
Airtight operation	P	
Contiarc furnace	C, N, S	
Flue gas monitoring and control	C, EX	4.3
Eccentric bottom tapping on existing furnace	C, N, S	6.8
DC twin shell with scrap preheating	C, EE, N	3.5

C = Site-specific variables may affect costs and/or practicality of use of the option at all facilities. EE = Options that could improve energy efficiency and potentially lower GHG emissions but may increase other pollutants. EX = Process already widely implemented at many existing facilities. N = Only feasible for new units. P = Immature process that is still in research and/or pilot stage as applied to Iron and Steel. S = Specialized process only technically appropriate for some equipment configurations or types

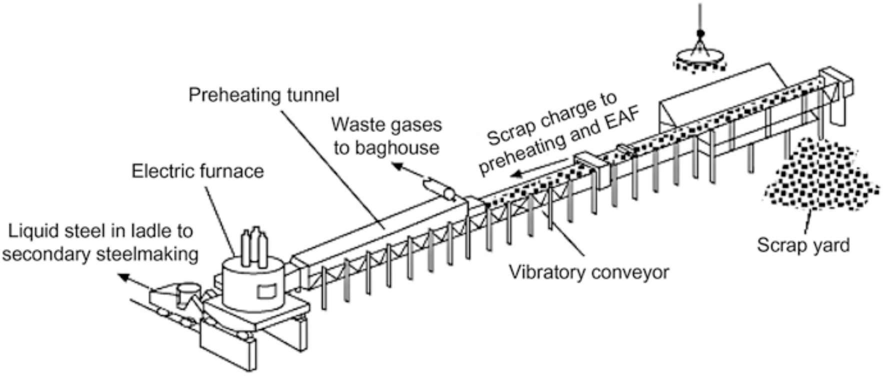

Fig. 16.8 Continuous scrap charging and off-gas energy recovery with Consteel EAF

Basically, there are three ways of preheating the scrap that are being used currently: in a conveyor, using continuous charging (Consteel EAF), or in a shaft, with batch charging.

In the Consteel EAFs, preheating is carried out continuously with the off-gas exiting the furnace over a conveyor feeding the scrap to the EAF (Fig. 16.8). The upper part of the scrap enters the furnace hotter than the lower part, which is not so much exposed to the heat. Most advantages of the furnace type come from the full flat-bath operation, although energy recovery through preheating is even significant. A current trend in these furnaces is to have a large hot heel, even 50 % of the heat weight, thus favoring heat transfer from liquid to solid steel, as long as there is bottom stirring. Here the mechanism of radiation from the electrodes to the scrap around the electrodes does not exist. More than 40 Consteel EAFs have been built and more than 30 are in operation, with some more under construction. The emphasis in the first decade of this century has been more on high productivity, large EAFs installed in Asia, rather than in the energy recovery feature. Here there is potential for more efficiency (Jones et al. 1998).

As previously mentioned, continuous charging lets us use maximum power from the start of the heat, as a difference with batch charging, where lower tap is applied after charging of each bucket to avoid damage to the roof. Obviously, power-off time for bucket charging is avoided. Recently, the Consteel Evolution concept has been proposed, including natural gas burners for charge preheating before entering the off-gas preheated tunnel, and off-gas analysis to improve post-combustion in the tunnel (Memmoli et al. 2012).

Preheating in Shaft The other industrially applied way of preheating the scrap is the shaft furnace. They are often DC EAFs with one central electrode and some of them operating in twin mode. Currently, more than 20 such furnaces are in operation (Fuchs, Eco-Arc, and Quantum type). In Fig. 16.9, a scheme of a Fuchs shaft furnace is shown, together with the typical charging/melting cycle.

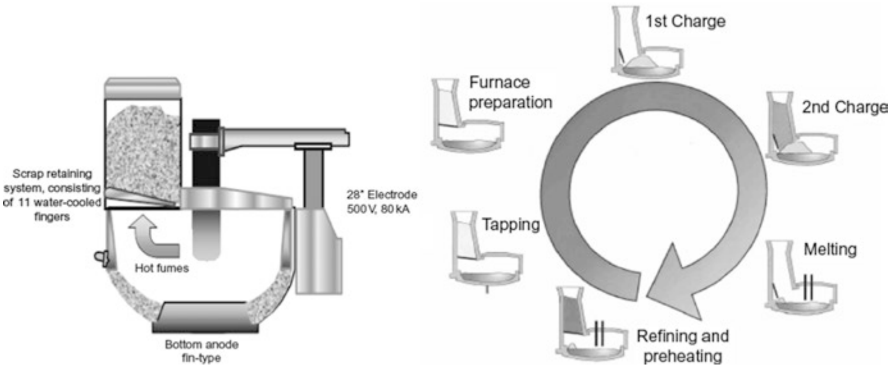

Fig. 16.9 Electric furnace with off-gas energy recovery by preheating scrap in a shaft. *Left*: scheme for a DC shaft furnace, with one electrode. *Right*: Operating cycle for a shaft furnace charging two scrap baskets

Formation of dioxine has been reported for some of these operations. Main reasons for dioxine formation are (a) plastics in the scrap and (b) critical temperature range. In a Japanese version of shaft furnace (Eco-arc by J. P. Plantech), charging is performed by means of a skip car instead of a bucket. The shaft has no device for keeping the scrap inside. The off-gas treatment includes a post-combustion chamber to decompose dioxines and a fast cooling chamber to avoid De Novo synthesis.

Oxy-Fuel Burners Modern furnaces use oxygen-fuel burners to provide chemical energy to the cold-spots, making the heating of the steel more uniform. Oxy-fuel burners reduce electricity consumption by substituting electricity with fuels and increase heat transfer. Some 136 Oxy-fuel burners are currently installed in the EU. The expectation is that this technology may decrease total and direct CO_2 emissions by 0.006 t CO_2/t crude steel.

Oxy-fuel burners have a long story of optimization and enlargement. Initially, Oxygen was introduced in the furnace through the slag door to accelerate melting by cutting scrap parts. The combination of Oxygen and Carbon lances was useful then to create a foamy slag protecting panels, roof and refractories form the arc radiation. After that, lance manipulators were devised to facilitate the lancing operation. Finally, burners were introduced through the furnace walls, to inject Oxygen, Carbon, natural gas, and lately lime. This equipment resulted easy to maintain and effective for its different tasks. Besides, their operation can be automated to a large extent.

Lately, chemical energy tends to contribute with 30 % of the EAF energy input. Since the heat duration is short, the large specific oxygen consumption (40 m^3/t crude steel, in average) requires quite high-intensity injection. In modern furnaces, the specific intensity of oxygen blowing is usually 0.9–1.0 m^3/t per minute and may also reach 2.5 m3/t per minute if hot metal and reduced iron are used in large amounts (Toulouesvski and Zinurov 2010).

16.4 CO_2 Emissions and the Future of the Electric Arc Furnace

As in China and other emerging countries start to have more scrap availability, and taking into account that these countries will have a commitment to decrease their emission, it is reasonable to expect an increased EAF share in world production, instead of the decrease of recent years. The International Energy Agency (IEA) has prepared forecasts regarding process routes and consumption of metallic till year 2050 (International Energy Agency 2012). They defined three scenarios for global average temperature increase: 6 °C, 4 °C, and 2 °C. 6 °C is an extension of current trends; 4 °C takes into account commitments assumed by countries regarding emission limits and energy efficiency improvement, and 2 °C is a very restrictive scenario regarding CO_2 emissions.

In Table 16.7, the aforementioned scenarios are presented, in relation with their influence on process routes and utilization of metallics, in comparison with the base situation, year 2010.

Although this forecast has spurred controversy (Mendes de Paula 2013), it reflects the current expectations on the future growth of this process route.

16.5 Conclusions

Electric arc furnace-based steelmaking is the low-CO_2 alternative to make steel, as long as scrap is available at a competitive price. Still, this process route may advance in lowering emissions, through the spreading of several technologies that are already available and working at industrial scale.

EAF total emissions have a large dependence on the source of electricity: hydroelectric, nuclear, natural gas, wind, or coal-based.

Table 16.7 Scenarios of increased global average temperature under low and high steel demand, and its influence on process route and metallics consumption for the year 2050, according to International Energy Agency

		Year 2010	Year 2050: low demand			Year 2050: high demand		
			6 °C	4 °C	2 °C	6 °C	4 °C	2 °C
Process route	EAF (%)		50.2	51.6	50.6	50.4	51.7	51.0
	BOF (%)	71.5	49.8	48.4	49.4	49.6	48.3	49.0
Metallics	Hot metal/pig iron (%)	68.6	45.6	44.3	40.8	45.5	44.2	37.9
	Gas-based DRI (%)	3.5	7.0	7.0	9.5	7.0	7.0	9.7
	Coal-based DRI (%)	1.3	4.8	4.8	0.0	4.7	4.7	0.0
	Smelting reduction (%)	0.0	0.5	0.5	4.8	0.4	0.4	7.4
	Scrap (%)	26.6	42.1	43.4	44.8	42.4	43.7	45.0

It is expected that in the future there will be more availability of scrap. This situation, together with the already mentioned low emission, and other advantages like lower investment, less manpower, more flexibility, easier maintenance, would make EAF the route of choice for the following decades.

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