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EU coordinated **ME**thods and procedures based on **R**eal **C**ases for the effective implementation of policies and measures supporting energy efficiency in the **I**ndustry

HORIZON 2020 Project Nr. 693845

Technical analysis –Iron and Steel sector (NACE C24.1-24.2-24-5)

WP4: Picture of efficiency projects implemented by the Industry sector-by-sector and process-by-process

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1 Introduction

Iron and Steel production covers some subsectors of NACE Sector C24 (Manufacture of basic metals):

- C24.1 Manufacture of basic iron and steel and of ferro-alloy
  - 24.10 Manufacture of basic iron and steel and of ferro-alloy
- C24.2 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel
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Considering the relevance of the European Union in the steel market (the EU is the world's second largest steel producer after China, accounting for 10% of global crude steel production in 2013), it has been chosen to treat this separately from the other metals sectors, covered however by different subsectors of NACE C24.

Although there might be different processes and subprocesses combinations, steel production can be performed through three main processing routes:

- *In Blast Furnace (BF)/Basic Oxygen Furnace (BOF) route*, pig iron is produced using primarily iron ore (70-100%) and coke in a blast furnace and then turned into steel in a basic oxygen furnace. Due to the inclusion of coke making and sintering operations, this route is highly energy intensive.
- *Scrap/Electric Arc Furnace (EAF) route* is primarily based on scrap for the iron input and has significantly lower energy intensity compared to the BF/BOF route due to the omission of coke making and iron making processes;
- *Direct Reduced Iron (DRI)/EAF route*, based on iron ore and often scrap for the iron input. Energy intensity of DRI production can be lower than BF route, depending on the size and fuel and ore characteristics.

The main steelmaking processes will be analysed in the next paragraphs.

The production of iron and steel could be categorised in the following key categories:

- *Crude steel*. Crude steel is defined as steel in its first solid state after. Crude steel are semi-finished products where further downstream processing is required to form finished products for the consumer market. Crude steel is categorized into 3 main quality levels: non-alloy; other alloy; and stainless steel. Crude steel production is split between EAF technologies (40%) and BOF technologies (60%).
- *Semi-finished products*. Semi-finished products include steel shapes (blooms, billets or slabs) that are later rolled into finished products such as beams, bars or sheet. Continuous casting is the process whereby molten metal is solidified into a semi-finished billet, bloom, slab or beam blank.
- *Finished products*. Finished products are subdivided into two basic types, flat and long products: flat products include slabs, hot-rolled coil, cold-rolled coil, coated steel products, tinplate and heavy plate. They are used in automotive, heavy machinery, pipes and tubes, construction, packaging and appliances. Long products include billets, blooms, rebars, wire rod, sections, rails, sheet piles and drawn wire. The main markets for these products are construction, mechanical engineering, energy and automotive.

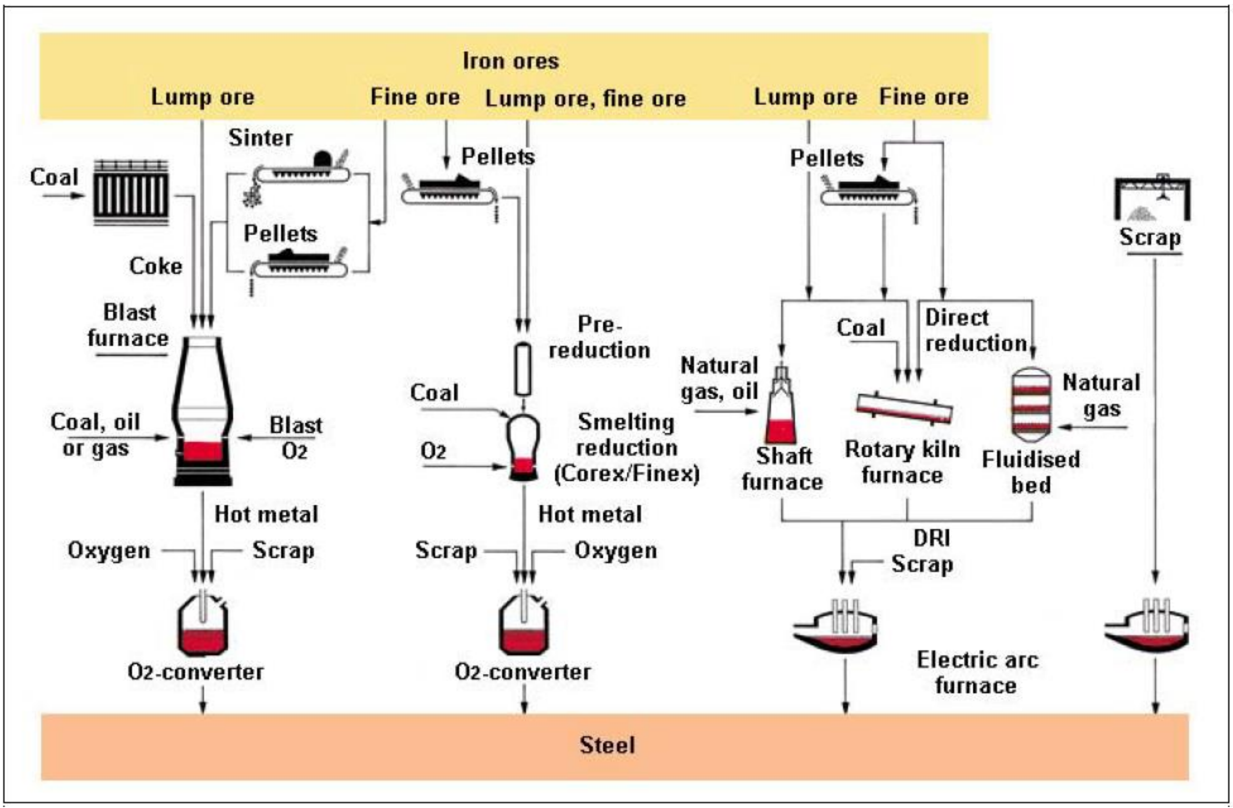

Figure 1: Alternative routes for Steel making.

2 Blast Furnace Route

Approximately 70% of the global steel production involves the use of Blast Furnaces. This route is also known as Basic Oxygen Steelmaking process, as alternative to secondary steel making process that usually exploits the Electric Arc Furnace route with scrap smelting.

2.1 Raw material preparation

Raw material preparation goal is to obtained the correct input materials to easy the reduction process from iron ore to pig iron and then steel.

One of the most important processes is the conversion of Coal into Coke, that is used in the blast furnace as a reducing agent, a source of thermal energy and a physical support for the burden in the blast furnace. Coking coals are heated up to 1,150-1,350 °C for several hours, in order to induce pyrolysis. Besides coke, the byproducts of it are coke oven gas (that might be cleaned and used as fuel gas later) and liquids.

The second main process in raw material preparation is sintering, that is performed in order to process fine grained raw materials into a coarse grained iron ore sinter, ready to be charged to the blast furnace. The final product (sinter) is a porous clinker, that increases the permeability of the burden and makes reduction with coke easier, so lowering coke demand. In the sintering process a blend of different ores, ferrous containing materials – such as flue dust – and fine coke particles (known as coke breeze) is deposited on a large travelling grate. The coke at the top of the blend is ignited by gas burners, that can be fueled by coke oven gas, blast furnace gas, or natural gas. As the grate moves, air is sucked from the top through the mixture, enabling combustion through the entire layer and complete sintering – where the temperatures may reach 1,300 – 1,480 °C. At the end of the strand, the material is cooled by air and finished sinter is size-screened. An alternative to sintering is pelletisation, a process of forming raw material mixture into 9 – 16mm spheres through high temperature process, that consists of grinding and drying or dewatering, wetting and mixing, balling and induration followed by screening and handling. However, this process is less spread than sintering.

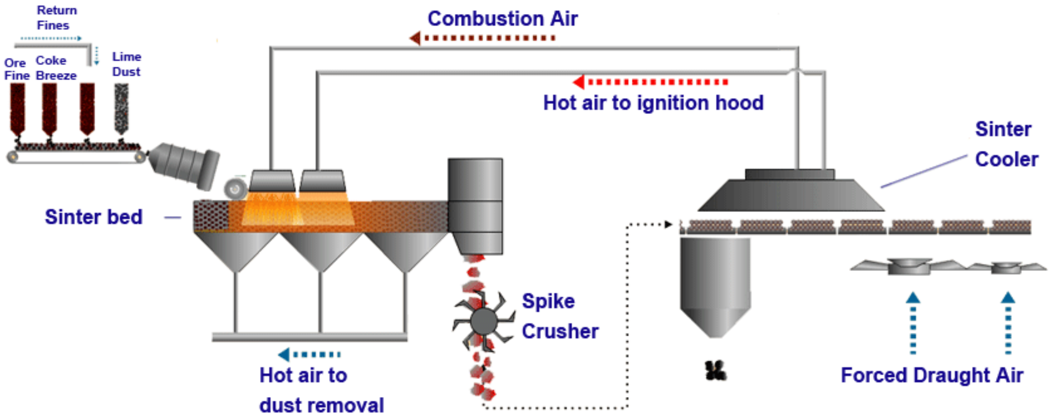

Figure 2: Schematic of sintering process.

2.2 Blast Furnace (BF)

The raw material (coke, sinter / pellets, lump ore) is fed into the Blast Furnace (BF) which reduces the iron oxides to metal iron. The liquid iron (hot metal or 'pig iron') is collected and continuously casted. This process also produces BF gas which is collected and treated before being used as fuel.

The functioning of a Blast Furnace is shown in Figure 3.

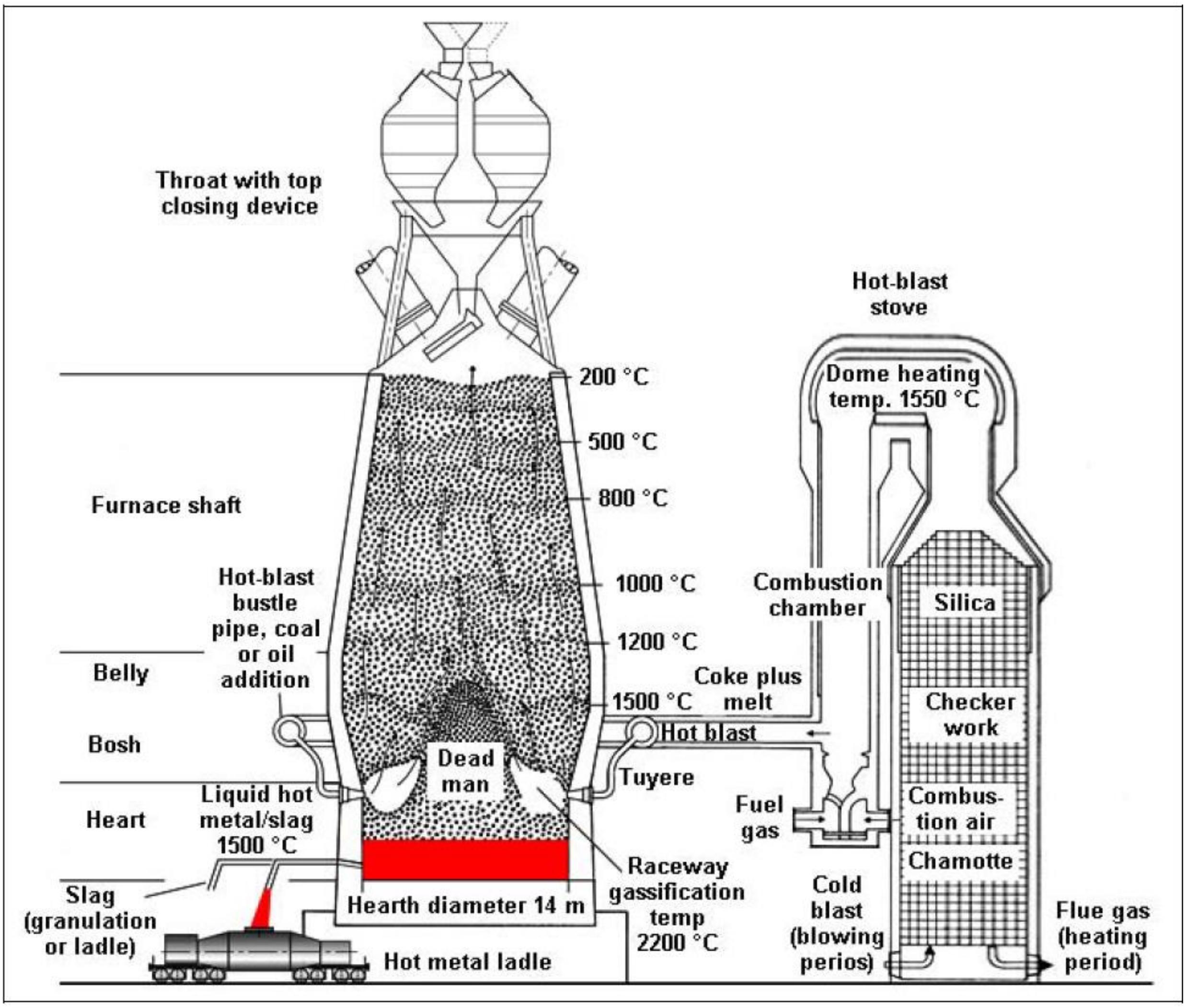

Figure 3: Blast furnace schematic.

The blast furnace is charged from the top with a burden, that consists of alternate layers of coke and a mixture of sinter and/or pellets, lump ore and fluxes. In the furnace, the iron ore is increasingly reduced and liquid iron and slag are collected at the bottom of the furnace, where they are tapped from. The slag from the blast furnace is granulated, pelletised, or tapped into slag pits. The slag granules or pellets are usually sold to cement manufacturing companies. Slag from pits can also be used in road construction.

Cold blast blowers and hot blast ovens are important elements of the BF system. While the former provides the necessary air flow at 3–5 bar pressure, the latter increases the temperature of air to 900–1,350 °C. Ore, sinter or pellets, coke and lime (that removes impurities and acts as flux) are added to the blast furnace from the top, whereas hot blast (compressed air) is introduced from tuyères at the lower part. Auxiliary reductants/fuels – like coal, fuel oil, natural gas, or other alternative sources – can also be injected from the bottom of the furnace. At lower parts of the furnace coke is gasified and the resulting CO reduces ironoxides as it ascends in the furnace. The molten iron trickles down and collects at the bottom. The impurities that are removed by the aid of CaO form a slag that floats on the molten iron. The hot gases leaving the blast furnace still maintain a pressure of 2–3 bar. In addition, a gas with low calorific value (~3 MJ/Nm^3) is produced at a rate of 1,300–2,200 Nm^3/t-pig iron. After cleaning, this gas can be used as fuel.

2.3 Basic Oxygen Furnace (BOF)

The liquid iron from the blast furnace (hot metal) is transported to a basic oxygen furnace, where the carbon content (approximately 4%) is lowered to less than 1%, in order to obtain steel.

The objective in oxygen steelmaking is to burn (i.e. oxidise) the undesirable impurities contained in the hot metal feedstock. The main elements thus converted into oxides are carbon, silicon, manganese and phosphorus. Sulphur content is mainly reduced during pretreatment of the hot metal.

Basic Oygen Furncace (BOF) is a pear shaped vessel where the pig iron from blast furnace and ferrous scrap, is refined into steel by injecting a jet high-purity oxygen through the hot metal (see Figure 4). More specifically, in a BOF:

- the carbon content of pig iron, which is typically 4-5%, is reduced to varying levels below 1% (usually 0.01-0.4%) depending on the product specifications;
- unwanted impurities are removed;
- concentration of desired components is brought to product specifications.

Scrap, or scprap substitutes, that meet purity requirements are often added to control excessive temperature rises. However, the pig iron input stays at the levels of 65 to 90% for every ton of steel produced. Impurities are dissolved by the added limestone and fomed into a slag. During the BOF processes a gas with high CO content is formed. If no gas recovery is exercised, CO is converted to CO_2 by combustion at the mouth of the furnaces with open hood and through flaring after gas cleaning in furnaces with a closed hood.

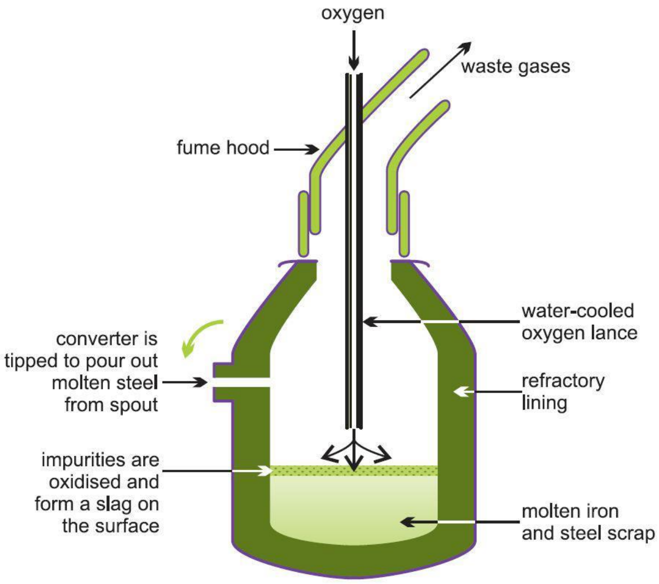

Figure 4: Schematic of a BOF.

2.4 Secondary metallurgy

BOF shops are often followed by secondary metallurgy processes, that include a number of diverse metallurgical operations. They can occur in laddle or in vacuum: upstream ladle desulphurisation of the hot metal and downstream ladle metallurgy of the steel is generally applied in order to produce steel with the required quality. On leaving the basic oxygen furnace, the liquid steel is cast either into ingots or by means of continuous casting. In some cases vacuum degassing is applied in order to further improve the quality of the steel.

The main objectives of secondary metallurgy are:

- mixing and homogenising
- adjustment of chemical compositions to close analysis tolerances
- temperature adjustment in time for the downstream casting process
- deoxidation
- removal of undesirable gases such as hydrogen and nitrogen
- improvement of the oxidic purity by separating non-metallic inclusions.

A summary of secondary metallurgy processes is reported in Figure 5.

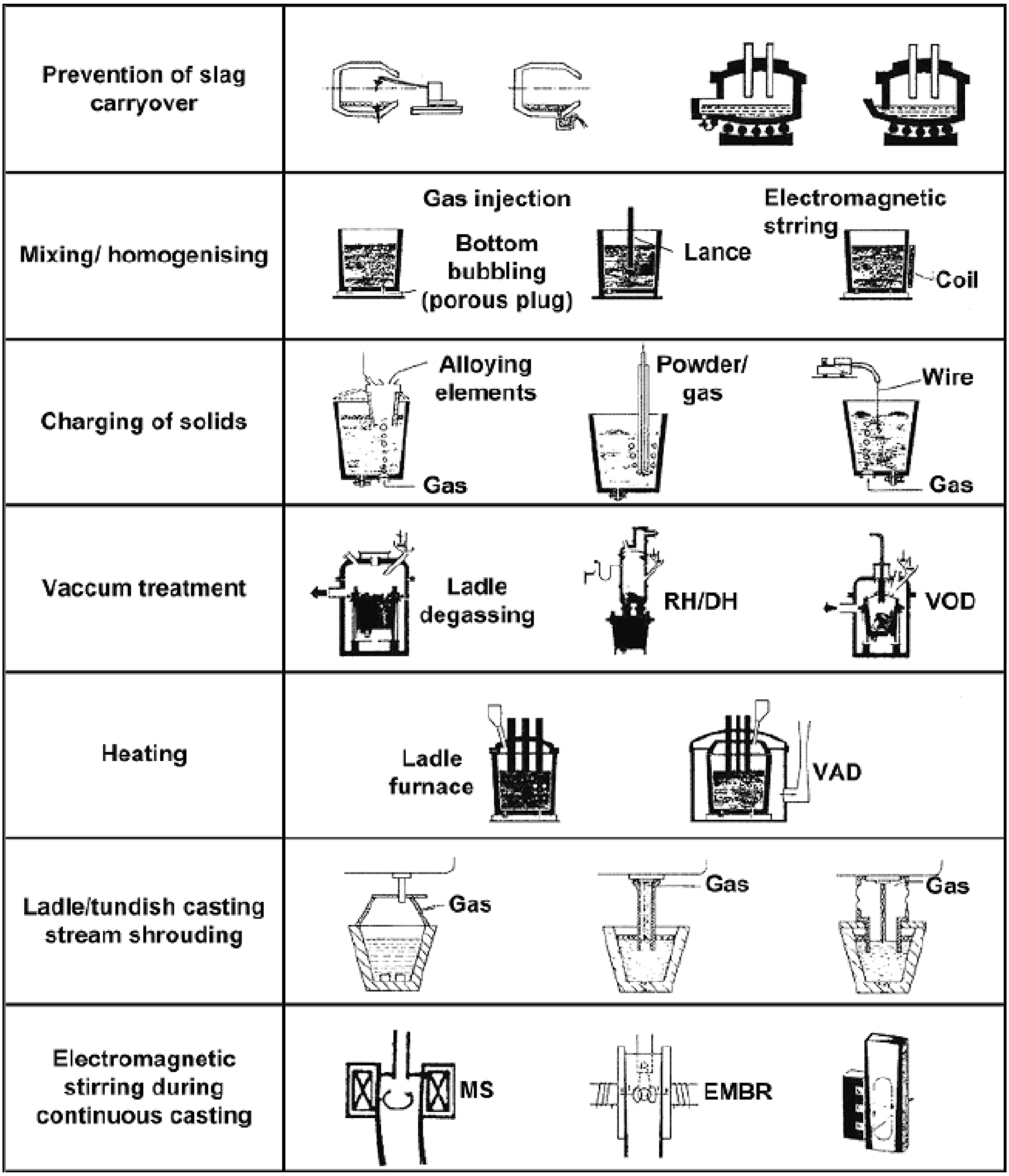

Figure 5: Secondary metallurgy processes.

3 Electric Arc Furnace Routes

Electric Arc Furnaces (EAF) allow to melt iron-containing scrap or raw material obtained through DRI in order to produce carbon steels and alloy steels.

3.1 Scrap preparation

When scrap is used as raw material, it is usually loaded into baskets with the use of magnets or grabs. The important requirement for scrap use is a requirement of minimum non-metallic inclusions, especially of non-magnetic materials and non-ferrous metals. In order not to include hazardous contaminants or radioactive material, before loading it is necessary to perform some scrap sorting. Scrap might also be pre-heatd (often using waste heat from the process) in order to reduce the energy requirement for melting inside the furnace.

3.2 DRI preparation process

In DRI, iron ore is reduced in its solid state – unlike BF process where a liquid metal is formed during reduction. There might be different types of reactors:

- shaft furnaces;
- rotary kilns (SL/RN process);
- rotary hearth furnaces;
- fluidised bed reactors.

The main differences with BF process or EAF process are:

- no melting and no slag phase are performed for reduction;
- contaminants and gangue elements, that usually are removed during melting and slag, remain inside the DRI and need to be separated into the EAF, leading to a higher energy consumption thant with scrap melting.

A way to reduce energy consumption in the EAF might be to send directly DRI from reduction to EAF, by exploiting at least partially the heat still in the material after reduction.

3.3 Electric Arc Furnace (EAF)

In an EAF scrap and/or manufactured iron units – such as DRI, pig iron, iron carbide – is melted and converted into high quality steel by using high-power electric arcs formed between a cathode and one (for DC) or three (for AC) anodes (a schematic is shown in Figure 6). Scrap is by far the the most important resource, accounting for about 80% of all electric arc furnace metal feedstock. This technology allows to omit the energy intensive process of coal pyrolysis and iron ore reduction process.

The iron units are loaded in a basket together with limestone – for slag formation – and charged into the furnace. The main task of most modern EAFs is to convert the solid raw materials to liquid crude steel as fast as possible and then refine further in subsequent secondary steelmaking processes. After melting and before secondary steelmaking operations, a flat bath operation period is kept, when most metallurgical operations may be performed.

The energy use is highly dependent on product mix, local material and energy costs and is unique to the specific furnace operation. Factors such as raw material composition, power input rates and operating practices – such as post-combustion, scrap preheating – can greatly influence the balance.

Melting in EAF starts at low power in order to reduce radiation to furnace walls and the roof. Once the scrap is sufficient shield for the arcs, power is increased and sometimes oxygen lances and/or oxyfuel burners (fuelled with either natural gas or fuel oil) are used to support the early stages of melting. Oxygen is preferred to air due to different reasons:

- Supports the shielding of the furnace walls from the radiation of the arc and increases the energy transfer from the arc to the bath, thanks to the formation of a “foamy slag” (CO bubbles in the slag generated by the presence of carbon and oxygen);
- Supports decarburisation of the melt and removal of phosphorus and silicon;
- If injected at the top of the furnace, reacts exothermically with partially-burnt gases (CO) and hydrocarbon and helps keeping as much heat as possible within the furnace.

Oxygen injection, however, results in an increase in gas and fume generation from the furnace. Fumes and gases generated from the melting operation are processed in a flue-gas treatment plant which includes the collection and treatment devices aimed at reducing pollutant emissions.

At the exit of the EAF, the metal slag can continue towards the casting process, that is the same as the one at the exit of BOF.

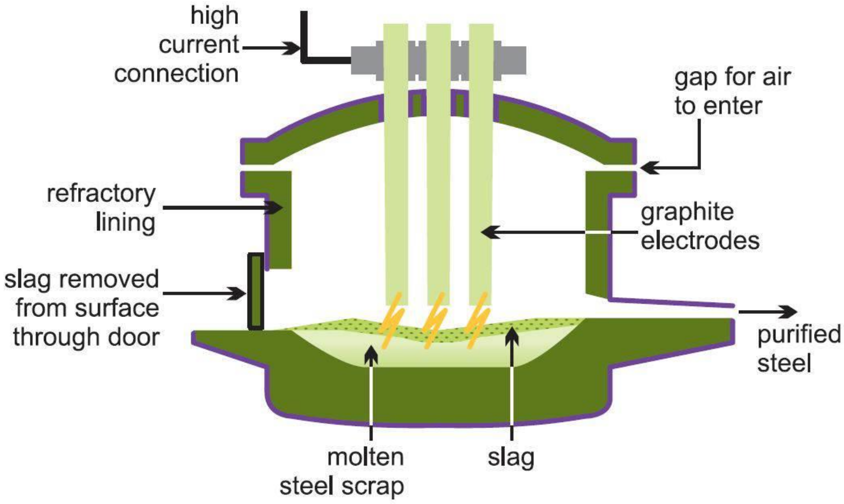

Figure 6: Schematic of an Electric Arc Furnace (EAF).

4 Casting

Casting comprises a wide variety of processes that have the goal to turn the hot metal with the right properties into intermediate, marketable products. The main types of casting are:

- Continuous casting, in which molten metal the steel is cast in a continuous strand and solidified into a "semifinished" billet, bloom, or slab for subsequent rolling in the finishing mills;
- Near Net Shape casting (NSC), a special continuous casting used mainly for flat products, is a family of techniques where the initial part production provides a quality surface finish and is close to the final (net) shape, so reducing the need for machining and grinding. NSC techniques include thin slab casting, near net shape strip casting also known as direct strip casting (DSC) and thin strip casting;
- Ingot casting, in which the liquid steel is cast into casting moulds. Depending on the desired surface quality, degassing agents (such as NaF) can be added during casting in the ingot mould. After cooling, the ingots are taken out of the casting mould and transported to the rolling mills. Subsequently, after preheating, the ingots are rolled into slabs, blooms or billets.

Continuous casting is almost universally widespread and covers 97% of Europe casting capacity. A schematic of the process can be seen in Figure 7.

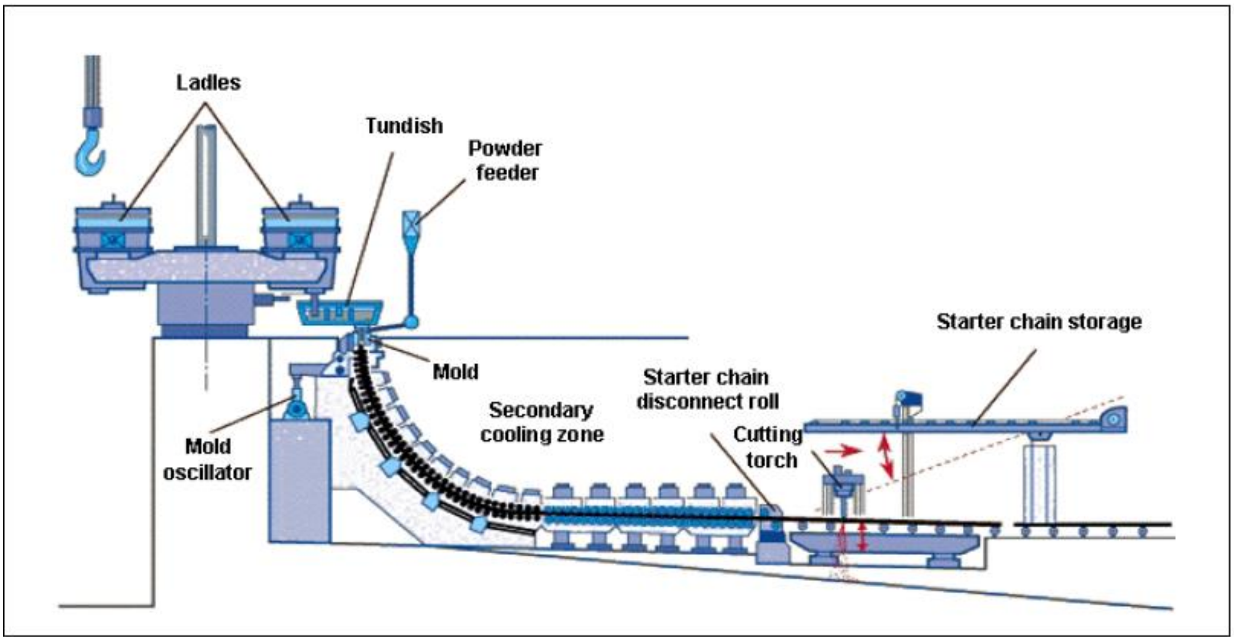

Figure 7: Continuous casting schematic.

Steel from the electric or basic oxygen furnace is tapped into a ladle and taken to the continuous casting machine. The ladle is raised onto a turret that rotates the ladle into the casting position above the tundish. Liquid steel flows out of the ladle into the tundish and then into a water-cooled copper mold. Solidification begins in the mold and continues through the First Zone and Strand Guide (together referred as Secondary cooling zone). The product, solidified and cooled, is then cut and ready to be sent to rolling mills.

5 Rolling

After casting, intermediate steel products are sent to rolling mill, where they are given their final shape and dimensions in a series of operations. First the slabs are heated in re-heating furnaces and then they are rolled in hot- or cold-rolling or finishing mills, depending on the final product (e.g. reinforcement bars only require hot rolling, while steel for cars requires bot hot- and cold- rolling). Hot rolling is performed with the metal near eutectic temperatures, so requiring a high amount of energy and the re-heating furnace is the critical factor to determine the end-product wuality and the energy consumption (and costs) of the operation.

The basic principle of rolling is that metal is passed through a pair of rolls. Rolling has 2 main classifications. Flat rolling, in which the product is typically a sheet, or profile rolling, in which the product is typically a rod or bar. Rolling is also classified according to the recrystallization temperature of the metal.

Hot rolling uses large pieces of metal, such as slabs or billets and heats them above their recrystallization temperature. The metal pieces are then deformed between rollers creating thin cross sections. These cross sections are thinner than those formed by cold rolling processes with the same number of stages. Hot rolling also reduces the average grain size of metal but maintains an equiaxed microstructure. A schematic of hot rolling process is reported in Figure 8.

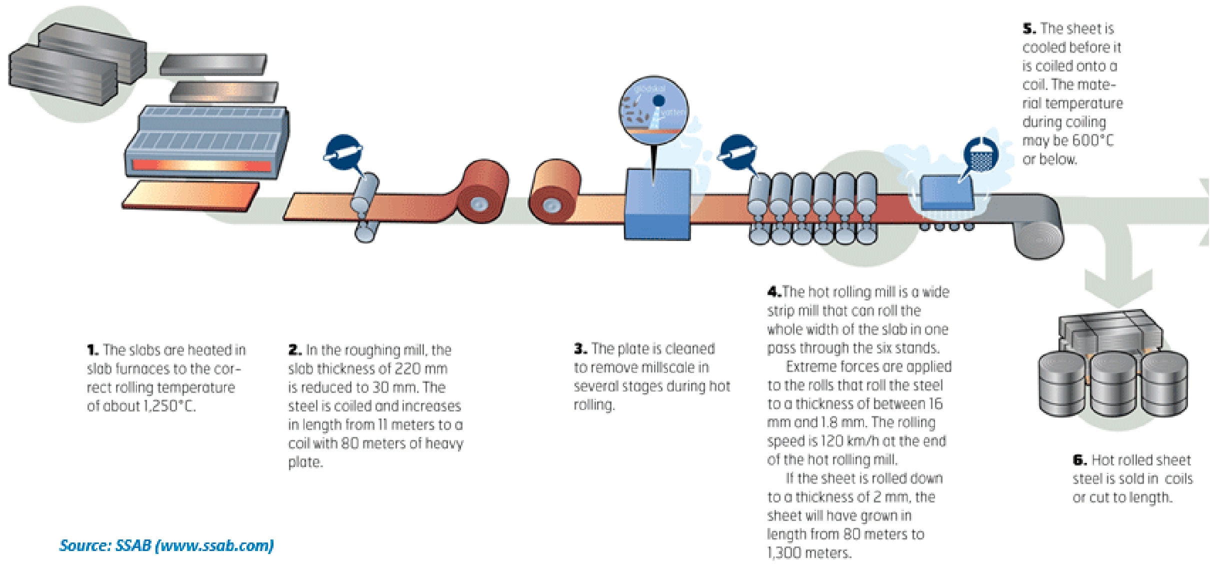

Figure 8: Hot rolling mill schematic.

Cold rolling is a process which passes metal through rollers at temperatures below its recrystallization temperatures. This increases the yield strength and hardness of the metal. This is done by introducing defects into the crystal structure of the metal creating a hardened microstructure which prevents further slip. Because the metal is at room temperature, it is less malleable than metal above its recrystallization temperature. This makes cold rolling a very labor-intensive and expensive process.

6 Cast iron production

Cast iron is commonly used for engine blocks, machinery, fences, buildings and construction. It is produced mainly by remelting scrap of iron (pig iron), together with limestone and carbon (coke), in cupola furnaces, taking various steps to remove undesirable contaminants (e.g. phosphorus and sulfur) and increasing desired elements (e.g. carbon and silicon).

In modern applications, cast iron is often melted in electric induction furnaces or electric arc furnaces.After melting is complete, the molten cast iron is poured into a holding furnace or ladle and then into moulds.

7 Energy intensity of key processes

After elaboration of data contained in BREF about steelmaking, the following energy intensity of the processes has been obtained:

Table 1: Energy intensity of key processes in Iron and Steel industry.

Process	**Electric energy** [kWh/t]		**Thermal energy** [kWh/t]	
	MIN	**MAX**	**MIN**	**MAX**
Primary route (BF/BOF) (sum of the processes below)	73	405	3,517	9,117
Coke production	6	64	906	1,306
Sintering/pelletising	25	44	358	561
Blast Furnace	31	236	2,236	6,783
BOF	11	61	17	467
Secondary route	403	747	22	517
EAF	403	747	22	517
Hot rolling	103	136	306	611
Cold rolling	164	267	283	467

As already anticipated, for primary route the highest consumption is of thermal type, related to the furnaces. The peak of thermal consumption is in Blast furnace. EAF reduces widely the thermal energy consumption and does not increase proportionally the electric energy consumption, so making it less energy-intensive and preferable (when possible, due to availability of scrap and the quality of the final product).

Both hot rolling and cold rolling require high amounts of electric energy, higher for cold rolling due to the lower malleability of the material. However, its thermal consumption is significantly lower than the one for hot rolling, where the re-heating furnace plays a very important role.