

History, developments and processes of direct reduction of iron ores

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Abstract

Blast furnaces need coke for iron ore reduction and melting of the ores to liquid hot metal whilst separating a part of the gangue components of the blast furnace charge materials via a liquid slag from the hot metal. Coke has been rated as the necessary evil of the blast furnace especially in those years, when cokemaking facilities had problems with environmental protection.

Reduction of iron ores in direct reduction processes occurs done in the solid stage without the need of coke. Just most of the oxygen is removed from the iron ores without melting and without slag metallurgy. This means, that all the gangue materials remain in the product sponge iron, called Direct Reduced Iron (DRI). Direct reduction processes can be classified by its kind of used reducing agent in gas-based processes and coal-based processes. Gas-based processes are shaft furnaces, retorts and fluidized beds. Coal-based processes are rotary kilns, rotary hearths and the multiple hearth.

The advocates of the direct reduction technologies have forecast a quick penetration of these processes from the 1970ies on and a replacement of blast furnaces by especially the gas-based reduction processes. This never occurred. The worldwide production of DRI was 114 mill. t in 2021 and the hot metal production of blast furnaces was 1,340 mill. t which is more than ten times of the DRI production. The gas-based direct reduction processes have a share of 75% at total DRI production and this is mainly done in regions with low natural gas prices. The main processes are the Midrex and the HyL/Energiron shaft furnace technologies. These have been developed to high level and most efficient processes with an industrial scale-up to 2.5 mill. t DRI production per year in a single module.

In Europe a Midrex direct reduction plant was built at a very early stage as the third industrial unit worldwide in 1971 in Hamburg, Germany, with a capacity of 400,000 t DRI/year. With respect to the high gas prices in Europe and the steady increase of blast furnaces size and efficiency it was the only DR installation by now. Due to its use of natural gas as reductant the direct reduction electric arc furnace route has lower CO₂ emissions compared to the blast furnace converter route. On the background of the current European target to become a climate neutral region by 2050 the direct reduction technology based on natural gas and hydrogen used in direct reduction shaft furnaces for DRI production currently gain huge importance.

Key words: Direct reduction of iron ores; natural gas, hydrogen and coal as reductant; Midrex, HyL/Energiron, Finmet, Circored, SL/RN, ITmk3; worldwide production of DRI/HBI; briquetting of DRI

Introduction

The name “direct reduction” is misleading because these reduction processes are not a “more direct” route to steel than the blast furnace. Nor does the term have anything to do with direct reduction in the blast furnace. Despite all these objections, the term is accepted in international usage [1].

Iron ore reduction in the blast furnace for the production of liquid hot metal needs coke. The coking plant was rated in the 20th century to be the necessary evil of the blast furnace especially in former years, when the coke plants had environmental problems. Processes for iron ore reduction without the need of coke were developed in the early decades of the 20th century, but the first important industrial applications took place in the 1960ies and 1970ies.

The principles of all direct reduction processes are equal: iron ores are reduced (removal of oxygen) in the solid stage producing a solid product sponge iron or direct reduced iron (DRI), which contains all gangue materials of the iron ores.

Direct reduction processes

Processes for reduction of iron ores as alternative to the blast furnace were developed in a large number since the beginning of the 20th century [2]. One of the first development with a patent from the year 1918 was the Högånäs tunnel furnace process for fine ore reduction with carbon [3]. In the beginning of the 1930ies the Krupp-Renn process was developed, which reduce iron ores with carbon as reductant in a rotary kiln [4]. In the year 1932 the gas-based reduction of lumpy iron ores was realized in the Wiberg process in Söderfors, Sweden [5]. The plant produced 25,000 t sponge iron per year.

The industrial technical application for direct reduction processes started from the end of the 1950ies [6, 7, 8]. Table 1 shows a sum-up of direct reduction processes to be rated of great technical importance in the middle of the 1970ies [2].

1.	Allis-Chalmers-Process	rotary kiln, natural gas (Allis-Chalmers)
2.	Armco-Process	shaft furnace, natural gas (Armco Steel)
3.	Esso-Fior-Process	fluidised bed, natural gas (Esso Research)
4.	HIB-Process	fluidised bed, natural gas (US Steel)
5.	HyL-Process	retorts, natural gas (Hojalata y Lamina)
6.	Kawasaki-Process	grate kiln, coke (Kawasaki Steel)
7.	Kinglor-Metor-Process	outside heated chamber furnace, coal (Monteforno, Danieli)
8.	Koho-Process	grate kiln, C-containing pellets (Nippon Steel)
9.	Krupp-Eisenschwamm-Process	rotary kiln, coal (Fried. Krupp)
10.	Midrex-Process	shaft furnace, natural gas (Midland-Ross)
11.	NSC-Process	shaft furnace, natural gas (Nippon Steel)
12.	Purofer-Process	shaft furnace, natural gas (Thyssen Purofer)
13.	SDR-Process	rotary kiln, fine coke (Sumitomo)
14.	SL/RN-Process	rotary kiln, coal (Lurgi)
15.	SPM-Process	rotary kiln, coal (Kubota, Sumitomo)

Table 1: Processes that were predicted to be of great technical importance in 1976

Just three of these 15 processes reached industrial application. The retort process HyL I of the company Hojalata y Lamina S.A., Monterray, Mexico, reduces iron ores with cracked natural gas and was initially for some time successful. The most important pulse was released with the development of the shaft furnace direct reduction technology by the companies Midland Ross Corporation, USA, and Korf Stahl, Germany, which implemented first industrial Midrex plants 1965 in Portland, Oregon, 1971 in Georgetown, South Carolina, and 1971 in Hamburg, Germany. The third process is the coal-based rotary kiln SL/RN (Stelco-Lurgi/Republic Steel-National-Lead). Because of the disadvantages of the HyL I retort process regarding economy and product quality the company Hojalata y Lamina developed in the beginning of the 1980ies the HyL III shaft furnaces process.

Direct reduction plants or technologies can be subdivided by the kind of reductant in use, that means gas-based or coal-based, and by the use of lumpy or agglomerated iron ores or iron ore fines, **table 2**.

Gas reduction		Coal reduction	
Shaft furnace:	Midrex HyL III/Energiron Pered Danarex	Rotary kiln:	SL/RN Jindal DRC Others
Retorte:	HyL I,II	Rotary hearth:	Inmetco Fastmet ITmk3
Fluidised bed:	Fior Finmet Circored	Multiple hearth:	Primus

Table 2: Industrial methods of direct reduction

The industrial achieved production capacities of single modules of iron ore reduction processes differ in a wide range, **Figure 1** [9]. Blast furnaces operated have a capacity range of 250,000 t hot metal to 5.3 mill. t hot metal annually. This high production level is not reached by any of the others reduction processes. The gas-based direct reduction shaft furnace processes Midrex and HyL/Energiron reach capacities of 2.5 mill. t DRI/annum followed by the smelting reduction processes Corex/Finex.

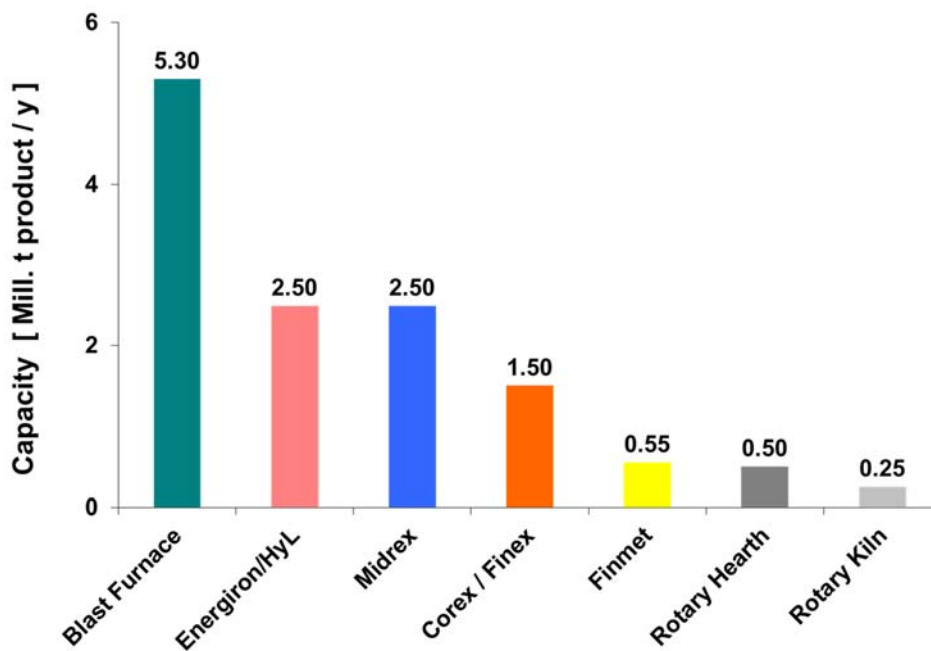


Figure 1: Production capacities of industrial iron ore reduction processes

Gas reduction processes using lumpy iron ores

In the gas-based **HyL I** retort process lump ores and fired pellets are reduced in four fixed-bed retorts by reformed natural gas. Many plants employing this HyL batch process were built until 1981 before the HyL III shaft furnace processes became established [1]. The development of this technology began in

1951 at the company Hojalata y Lamina S.A., Monterrey (Mexico). The first commercial plant was installed in Monterrey and started production in 1957 with a capacity of appr. 70,000 t DRI/year. Later plants had a capacity of 0.6 mill. t DRI/Year.

HyL I operates with four reactors simultaneously, each of which is at a different point in the reduction cycle at a particular time. **Figure 2** shows the stage at which fully reduced DRI is cooled with cold reducing gas in retort I. At this point, the carbon content of the DRI is adjusted to appr. 2%.

After cooling and water vapor condensation, the off-gas from this retort is reheated to reduction temperature and passed through retort II, where prereduced material is fully reduced. The gas is then recooled to remove any newly formed water vapor, reheated, and fed to retort III containing freshly charged ore, which is then prereduced. The off-gas from this stage is cooled and freed from water vapor. It is then available for use as fuel gas for steam raising. Retort IV is simultaneously emptied from DRI and charged with ore.

As lump ores or pellets are stationary in the retorts during reduction, the risk of sticking is high. Sophisticated removal devices are required for emptying the retorts.

The degree of metallization of the produced DRI is often lower at the bottom of the retorts than in the upper layers. Thus, the average degree of metallization is often only ca. 86%. As gas generation is carried out with a large excess of steam and cooling, and reheating of each retort is very costly, an energy consumption of around 15 GJ per tonne DRI must be taken into account. The cycle of the process from unreduced iron ores to final reduction lasts about 12 hours. In general, the HyL retort process had economic and DRI quality disadvantages.

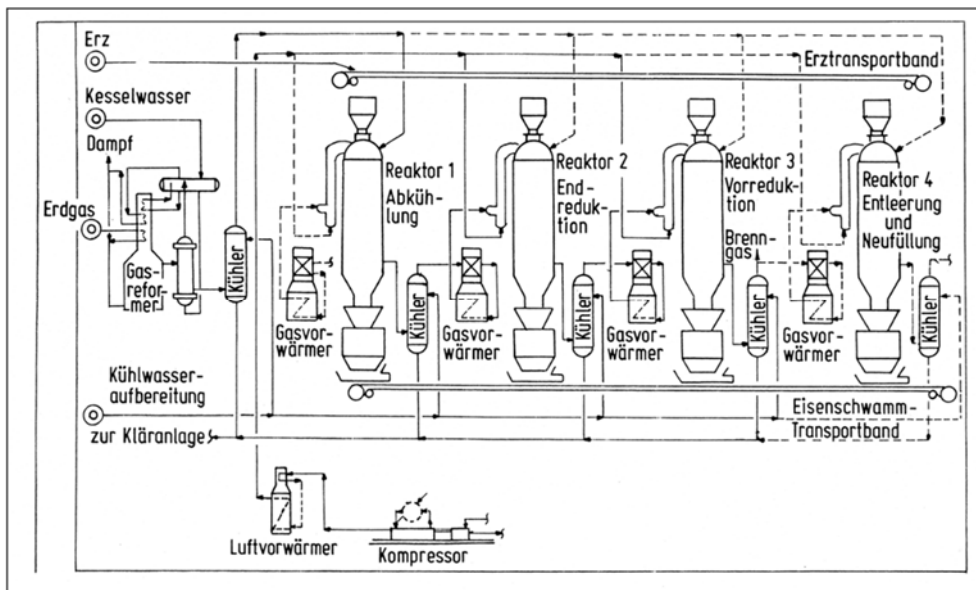


Figure 2: Scheme of HyL retort process

(Translation: Erz=ore; Kesselwasser=boiler water; Dampf=steam; Erdgas=natural gas; Gasreformer=gas reformer; Kühler=cooler; Kühlwasseraufbereitung=cooling water generation; zur Kläranlage=to clarification plant; Gasvorwärmer=gas preheater; Luftvorwärmer=air preheater; Reaktor=reactor; Abkühlung=cooling; Endreduktion=final reduction; Vorreduktion=prereduction; Brenngas=combustion gas; Entleerung und Neubefüllung=discharging and new charging; Erztransportband=ore conveyor belt; Eisenschwamm=sponge iron (DRI); Transportband=conveyor belt)

A successful gas-based direct reduction process is the **Midrex** shaft furnace process developed by Midland-Ross Corp of Toledo, Ohio in 1967 [10], **Figure 3**. The main facilities of a Midrex direct reduction plant are the shaft furnace, where lumpy iron ores are reduced to DRI, and the reformer, in which the reducing gas is reformed. The Midrex reformer is characterized by a unique catalyst design. In the reforming process, natural gas continually undergoes catalytic conversion by comprising tubes filled with

nickel to hydrogen (55%) and carbon monoxide (ratio ca. 1.5:1) at ca. 900°C. The reducing gas is injected at a temperature of 750 to 900°C and an operating pressure of 1.5 bar in the bottom of the reducing zone of the shaft. The process is able to use pellets and lump ores, which are charged at the top of the furnace and pass through the furnace countercurrent to the reducing gas.

The CO and H₂ rich top gas leaves the shaft at a temperature of up to 400°C and is re-used after cleaning in a scrubber as reducing gas again as well as to preheat and maintain the temperature of the natural gas in the reformer. In Midrex plants, gas reforming is performed as a rule using the CO₂ content of the top gas to crack CH₄ into 2CO and 2H₂.

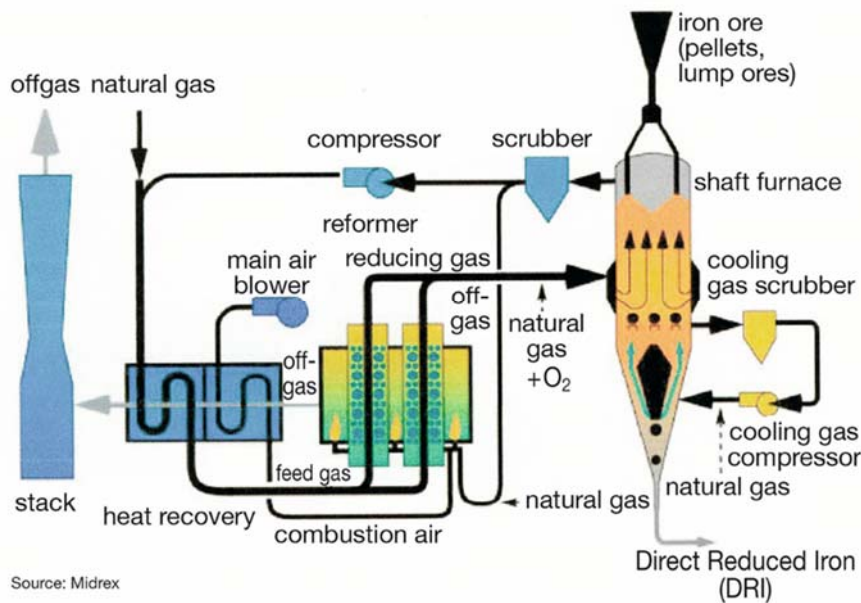


Figure 3: Midrex process flow sheet

The temperature of the reforming gas increases from 950°C to 1,000°C by the combustion of natural gas and oxygen in order to reach the desired temperature inside the shaft. The energy consumption of the Midrex process lies in the range of 9.5 to 10.0 GJ/t DRI.

Besides the reforming reactions inside the reformer, in situ reforming occurs inside the shaft furnace induced by the catalytic nature of the DRI. Several injection spots of natural gas influence the ratio of in situ reforming and carbon pick up of the DRI. The natural gas is injected in the transition zone located between reduction and cooling zones, inside the cooling gas, and inside the reduction gas. In the transition and cooling zones, the carbon content of the product can be adjusted between 1.2% and 2.5%.

For increasing the carbon content up to 4% without lowering the discharge temperature, Midrex developed a retrofittable technology: Carbon monoxide (CO), made in the Midrex reformer is added to the transition zone in the form of a CO-rich gas stream. The CO contacts the DRI bed, and the resulting exothermic reactions provide extra energy. In the transition zone, natural gas is added along with the CO-rich stream, and the CO-generated energy is used to produce additional carbon without sacrificing temperature. 85–90% of the DRI carbon is in the form of iron carbide (Fe₃C).

Several discharge options are available: Cold DRI, hot-briquetted iron (HBI), hot DRI through hot link (HOTLINK), and hot DRI through hot transport conveyor or transport vessel.

To reduce the CO₂ footprint, a Midrex process with hydrogen additions and a Midrex H₂ concept were presented in 2018 [12], which use pure hydrogen as the energy source and chemical reactant.

In 2020 77 Midrex shaft furnace plants were in operation and three under construction [11].

Hojalata y Lamina S.A. (HyL) of Mexico developed the **HyL III** shaft furnace process for the reduction of lumpy iron ores (pellets, lump ores) based on steam reforming of natural gas. The HyL III process operates at higher pressure of 5 to 8 bar. The cracking of the natural gas takes place in a catalytic gas reformer usually with the addition of steam. In order to obtain higher hydrogen contents in the reducing gas (appr. 80%) the CO₂ content is eliminated by scrubbing. After addition of water- and carbondioxide-free top gas and indirect heating to ca. 850°C, the reducing gas is fed into the reduction shaft. In the bottom section of the shaft furnace, the DRI is cooled to <50°C lower as in the Midrex process. HyL-III plants can also be operated with hot discharge and hot briquetting.

The HyL-ZR process is a variant of the HYL-III process that does not utilize an external reformer unit. ZR stands for “zero reformer”, **Figure 4**. The conversion of the natural gas is performed at the hot DRI following partial oxidation of natural gas with oxygen in the shaft. Thus, three processes take place simultaneously inside the reactor: In situ reforming using the catalytic effect of metallic iron, reduction of iron ores and carburization of DRI.

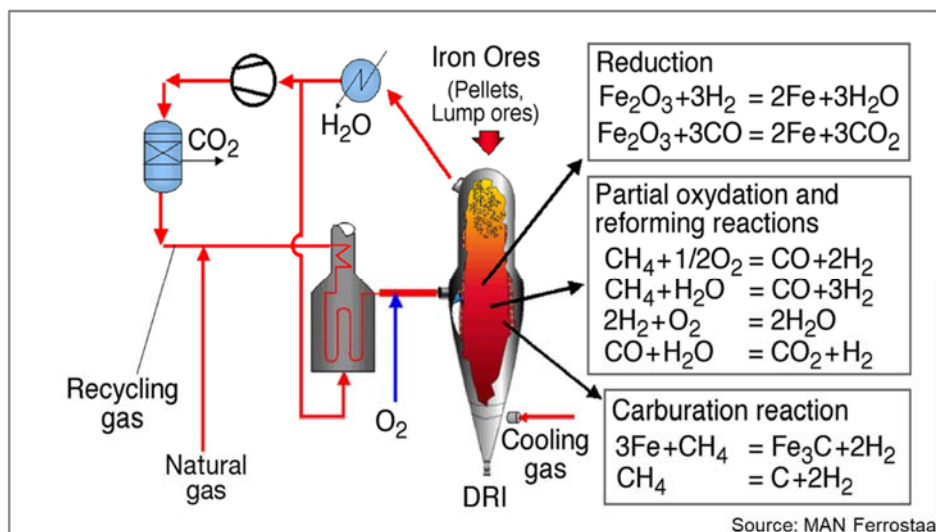


Figure 4: HyL-Zero reformer (ZR) direct reduction process

The shaft reduction reactor operates at 920–1,000°C and 5 bar. The DRI may be discharged either cold or hot. Systems are available that allow direct hot charging into a downstream electric arc furnace. The reformer-less HyL-ZR process was first applied in an industrial-scale installation at the Monterrey HYLSA 4M plant in Mexico in 1998.

In 2005, Techint Technologies acquired Mexico’s HyL Technologies. In 2006, HyL Technologies (since 2007 Tenova HyL) entered an alliance with Danieli to supply HyL direct reduction plants worldwide under the brand name HyL/Energiron.

The Energiron process is an extension of the HYL-ZR concept merged with Danarex (a direct reduction technology developed by Danieli) know-how. The Energiron technology employs a continuous shaft furnace reactor, uses a simple plant configuration, has flexibility for using different sources of reducing gases (natural gas, coke oven gas, syngas, or hydrogen from hydrocarbons or renewable energy sources), and offers the flexibility to operate with a wide variety of oxide pellets, lump ores, or mixtures of both.

Reduction gases (mainly H₂ and CO) are generated by in situ reforming within the reduction reactor, feeding natural gas as makeup to the reducing gas circuit, and injecting oxygen at the inlet of the reactor, **Figure 5**, [13]. Inside the shaft furnace, hot reducing gas is fed to the reduction zone and flows upward countercurrent to the iron ore moving bed. The gas distribution is uniform with a high degree of direct

contact between gas and solids. The exhaust reducing gas (top gas) leaves the reactor at about 400°C, where its energy is recovered to produce steam, or alternatively to preheat the reducing gas stream.

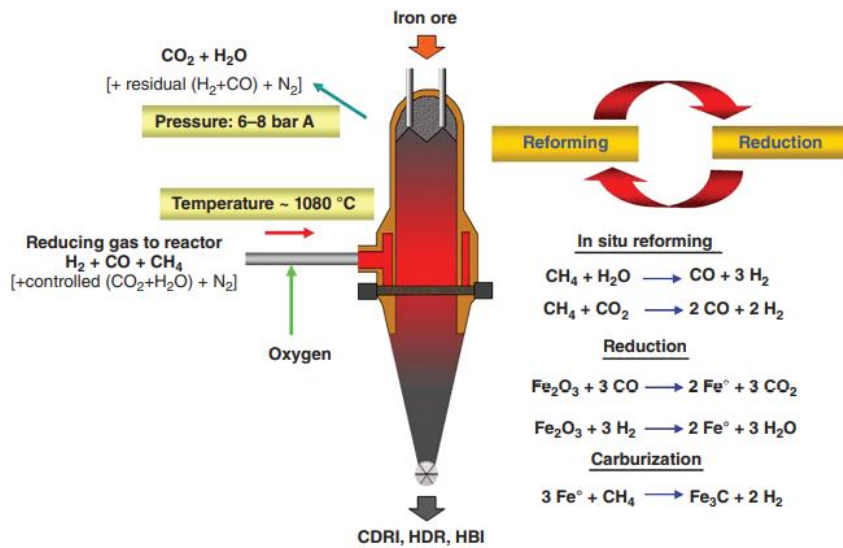


Figure 5: Energiron ZR process: In situ reforming [13]

Operation conditions are similar to the HYL-ZR process: High temperature (ca. 1,080°C) and high pressure (6–8 bar). The pressurized operation lowers gas velocities and reduces dust losses through top gas carryover. The Energiron process (**Figure 6**) is characterized by the selective removal of H₂O and CO₂ from the top gas. They are eliminated through top gas scrubbing and CO₂ removal units (e.g., by using pressure swing adsorption). DRI carbon levels from 1.5 up to 4.5% C can be obtained, regardless of whether cold DRI, hot DRI, or HBI is produced, due to the prevailing conditions in the upper section of the reactor: CH₄ concentration >20%, H₂/CO ratio of 4–5, and bed temperature >860°C.

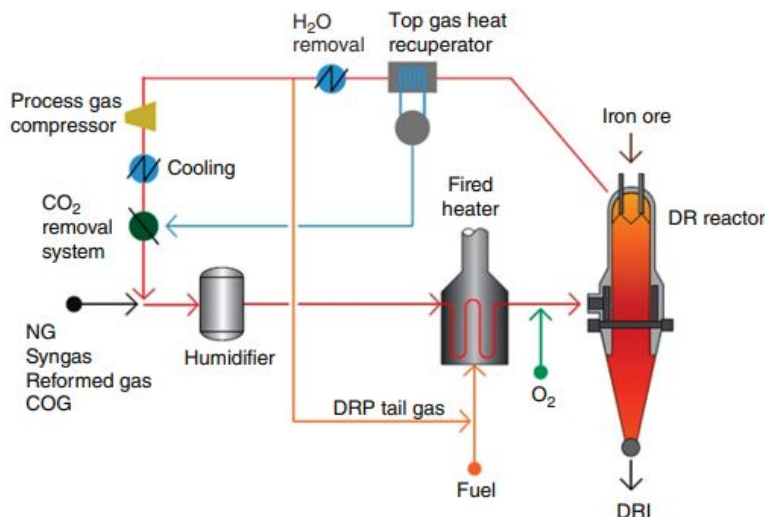


Figure 6: Standard Energiron ZR process flow sheet [14]

The energy consumption of the HyL/Energiron shaft furnace processes are in the range of 9.4 to 10.9 GJ/t DRI depending on DRI carbon content and temperature, extent of in situ reforming and power generation.

In 2020 16 HyL/Energiron plants were in operation and two under construction [11]. To reduce CO₂ emissions in iron ore reduction HyL/Energiron is also developing the use of pure hydrogen as reducing gas in the HyL/Energiron shaft furnace direct reduction technology [25].

The degree of metallization of the DRI produced by the various shaft furnace processes ranges from 92% to 95%. The carbon content is usually 1.5–2%, but the process is able to produce high-carbon DRI with up to 4% C.

Energy savings of the downstream electric arc furnace melt shop become possible by hot charging via Midrex HOTLINK or HyL/Energiron HYTEMP system (sensible heat), high degree of metallization, and chemical energy release from high-carbon DRI.

Gas reduction processes using iron ore fines

The development of the **Fior** fluidizing beds process, **Figure 7**, started in the 1950ies at Esso Research and Engineering in collaboration with Arthur D. Little. Following the building and operation of a 300 t DRI/d pilot plant in Dartmouth, Nova Scotia, Canada, from 1965 to 1969, a 400,000 t DRI/a commercial plant went into operation in Puerto Ordaz, Venezuela, in 1976, operated by FIOR de Venezuela, later (1986) by the Sidetur division of Sivena. The Sidetur Fior plant was closed down in 2000, and currently there is no Fior plant in operation anywhere in the world. The Fior plant for a long time was the only industrial used fine ore reduction process in the world.

The Fior plant consists of a series of four fluidized bed reactors in sequence, a reformer to produce fresh reducing gas, and a briquetting section. The hydrogen-rich reducing gas (90–92% H₂) is generated by cracking of natural gas with steam and oxidation of CO to form CO₂ with subsequent CO₂ scrubbing. DRI is produced by multistage reduction of iron ore fines (0–10 mm, 0.5 mm fraction <25%) in a vertical series of fluidized bed reactor vessels at a temperature of ca. 720°C.

The iron ore fines are first dried to a residual moisture content of 0.1%. The dry ore fines are then transferred by skip hoist to the charge bins located at the top of the system (80 m height), in which an operating pressure of 11 bar is maintained.

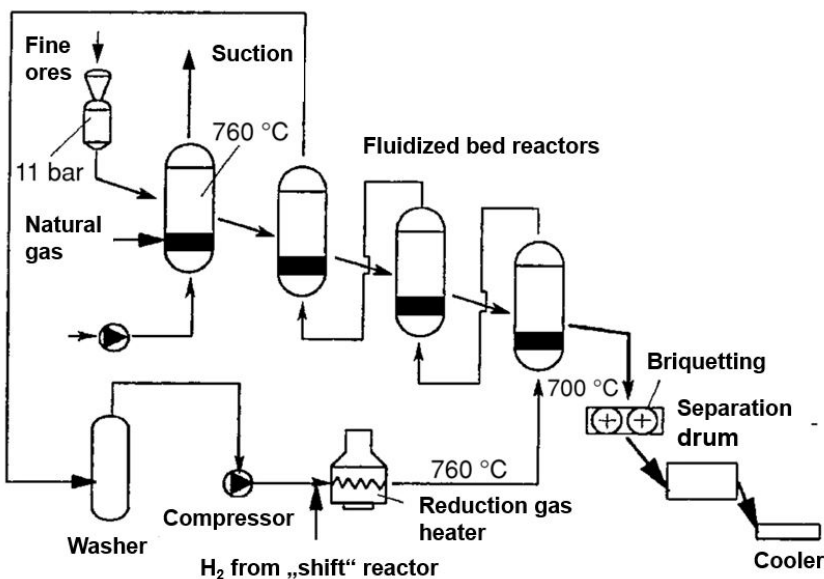


Figure 7: Fior process flow sheet

From there, the ore fines are conveyed to the first fluidized bed, where the ore is heated to operating temperature. The residence time between the first (heating) and the fourth reactor (final reducing stage) is 90 min.

Reducing gas enters the final reactor and flows countercurrent to the descending ore fines. The exhaust reducing gas leaving the first reduction reactor is scrubbed and cooled to remove dust and most of the water produced during reduction.

From the fourth reactor, the fine-grained DRI passes through a depressurizing stage, which reduces the pressure from 11 to 1 bar, and is fed to a bin from which three briquetting machines are charged. The briquettes (HBI) have a metallization degree of 93%. The carbon content can be adjusted between 0.6% and 3.0%. Sticking problems of the fine ores at high temperatures and reduction with high H₂ concentration in the reduction gas have led to accretion formation on the walls of the fluidized beds which made stoppages necessary to remove them.

The **Finmet** process is a further development of the Fior process by Siemens VAI (today Primetals Technologies) in collaboration with Fior de Venezuela. Two commercial plants were built, each featuring four reactor trains and designed for an annual output of 2.0 to 2.2 mill. t HBI per year. One plant, BHP DRI, located at Port Hedland, Western Australia, went into service in 1999 and was shut down in 2005. The second plant, Orinoco Iron at Puerto Ordaz, Venezuela, has been in service since 2000 and is located adjacent to the former Fior unit at Puerto Ordaz [15]. The HBI production of this plant was 200.000 t in 2020 [11].

The primary aim of the Finmet development is to improve energy efficiency of Fior by using top gas for ore heating and by removing CO₂ from reformed gas as well as by use of recycle gas. The Finmet process, **Figure 8**, comprises ore screening and drying, reduction of iron ore fines in a fluidized-bed cascade (reactor train), a reducing gas production system, and a briquetting unit. Reforming gas is provided by a catalytic gas reformer cracking natural gas by using steam.

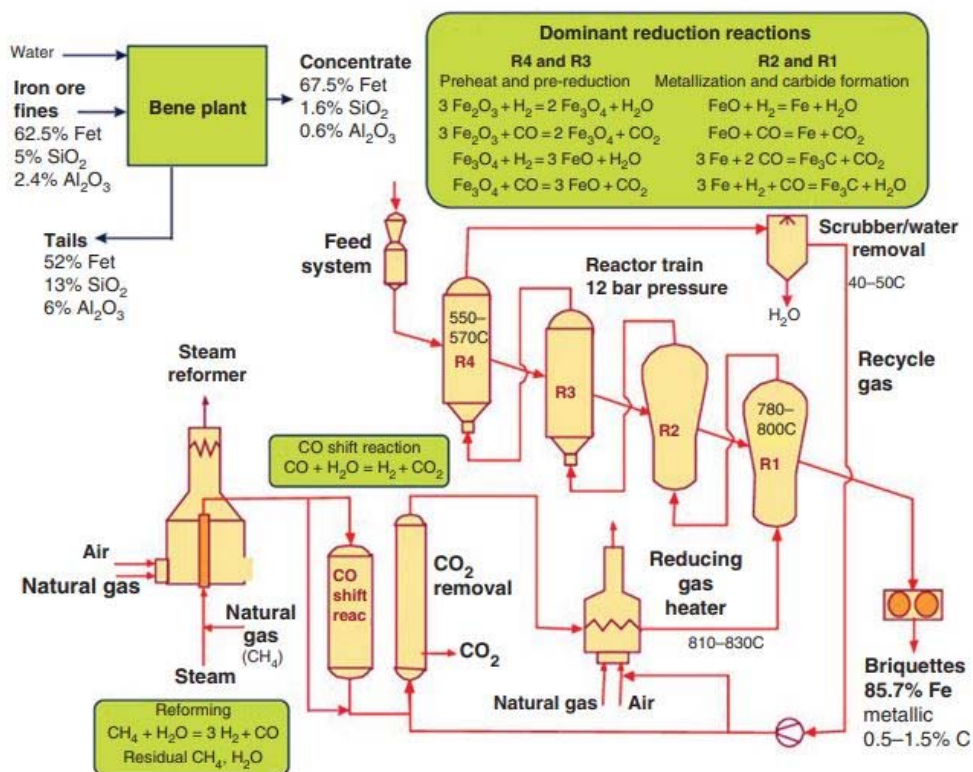


Figure 8: Finmet process flow sheet (Port Hedland HBI plant) [16]

The reactors are arranged in a stepwise fashion so that the ore introduced into the upper reactor (R4) flows downward by gravity while the reducing gas flows countercurrent upward. The iron oxide fines (<12 mm in size and up to 30% of particles <0.15 mm) are preheated to ca. 450–500°C in the first reducing reactor. The preheated ore passes down through the other three reactors in series and is further heated and reduced by the upcoming reducing gas. The reactor system operates at a pressure of 11–13 bar.

The hot reducing gas is charged at a temperature of 750–900°C into the bottom reactor (R1), is then distributed by a grid, passes through the fluid bed, and exits the reactor via cyclones, which are located inside the reactor vessel. These internal cyclones remove entrained fines from the reducing gas leaving the fluid bed before it exits the reactor. The gas passes onto the other three reactors and exits the upper reactor (R1) at a temperature of up to 450°C. The top gas is scrubbed and cooled to remove dust and water formed in the reduction process. A small amount of the CO and H₂ rich top gas is removed for fuel, and the remaining gas is compressed and recycled. The combined stream of reformed and recycled gas is then heated in a gas-fired reducing gas heater to ca. 850°C before it is introduced into the bottom reducing reactor. The DRI produced is hot-briquetted. The carbon content of the HBI is ≥0.8%, and the degree of metallization is ca. 91%. The energy consumption of the Finmet process is in the range of 13 GJ/t HBI.

In the **Circored** process, **Figure 9**, developed by Lurgi Metallurgy Germany [17] (now part of Outotec), small-size iron oxide ores (0.1–2.0 mm, 90% <1.0 mm) are reduced by hydrogen. Hydrogen-based reduction is characterized by excellent reduction kinetics at lower temperature and lower susceptibility of reduced material to sticking. Furthermore, the phenomenon of low-temperature, high-pressure methanation arising from mixed CO/H₂ reducing gases is completely avoided [18].

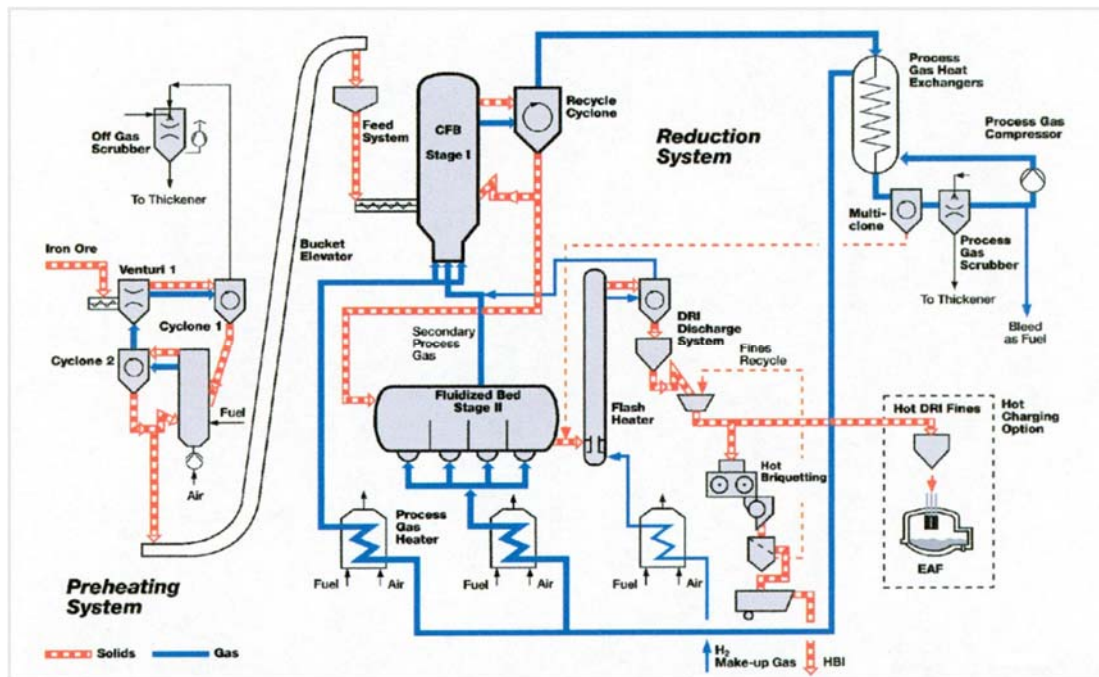


Figure 9: Flow sheet of the Circored process [18]

The main feature of the Circored process is a two-stage countercurrent reducing reactor system comprising a first stage circulating fluidized bed (CFB) and a second-stage bubbling fluidized bed enabling degrees of metallization in excess of 93%. This combination was chosen to best match fine ore reduction characteristics: the initial reduction is limited by mass and energy transfer phenomena at the particle surface and the final reduction by diffusion within the particle [18].

Iron ore fines are first preheated to ca. 850°C and prereduced to about 65% metallization in the stage 1 circulating fluidized bed at a temperature of 630°C within 20 min. Final reduction to 90–93% metallization is accomplished at lower gas velocities in a subsequent bubbling fluidized bed reactor stage II with several compartments at a temperature of 630°C. Both reactors are generally operated at temperatures below 650°C to avoid sticking of the iron ore fines.

The off-gases from the final reduction step in the stage II fluidized bed and makeup hydrogen are passed into the circulating fluidized bed reactor stage I. Most of the solids in the off-gases from the circulating fluidized bed are recovered in the recycle cyclone. The gases are then led through a heat exchanger, dedusted, cooled for condensation of water, and compressed to the plant pressure of appr. 4 bar. After heat exchange with the hot off-gases from the circulating fluidized bed the reduction gas is heated to 750°C before being reintroduced into the two reduction reactors.

Before entering the circulating fluidized bed, hot makeup hydrogen is used to transport the reduced fines from the bubbling fluidized bed to the briquetting plant and to heat them up. The reduced DRI fines are hot briquetted if the product is intended to export it. It can also be charged directly into an electric arc furnace.

The use of hydrogen as a single reductant means that no carbon is present in the Circored product. By introduction of hydrocarbons into the product stream after the final reduction stage, the Circored process can also be applied for production of a carbon containing HBI with ca.1% carbon.

A 500 000 t/a Circored plant went online in Trinidad in 1999, but was idling since the fourth quarter of 2001, mainly due to decline in the selling price of HBI. The plant restarted in 2004 and operated until 2006. At present, there is no operating Circored plant anywhere in the world. Nevertheless, the Trinidad plant proved the possibility of hydrogen-based iron production on an industrial scale. The plant produced during its operation in total 300,000 t HBI which were processed in electric arc furnaces located in the USA [19]. The natural gas consumption including hydrogen production is designed for 354 m³ (STP)/t HBI [19], corresponding to 12.4 GJ/t HBI.

For reaching the target of massive CO₂ mitigation the hydrogen based fine ore reduction process Circored process could be of interest for the future.

In the **Iron Carbide** process developed by Stephens (Iron Carbide Holding Ltd.), fine-grained iron oxides (0.1–1 mm) are reduced in a fluidized bed reactor by a gas-containing hydrogen and methane to give iron carbide [11].

A 300 000 t/a iron carbide plant was constructed in Point Lisas, Trinidad, by a joint venture of Nucor, USA, and Samitri, Brazil, in 1994. The Trinidad plant was shut down in 1999 after producing about 357,000 t of product.

Solids direct reduction processes

Solids direct reduction means reduction with coal. In the following the focus is set on rotary kiln processes and rotary hearth processes.

Many **rotary kiln processes** are in industrial application: SL/RN, Jindal, DRC, Codir, Siil, Osil, DAV, BGRIMM and others [11]. Typical features of rotary kiln processes are their high flexibility with regard to feedstocks and their capability for economic production of even small quantities of DRI. All non-coking coals ranging from lignite through bituminous coals up to anthracite or coke breeze are suitable as reductants. In addition to the pellets and lump ores, which are the main iron-bearing materials, iron sands and ilmenite concentrates are industrially used.

Of the various rotary kiln processes [21], the **SL/RN** process attained the greatest technological significance, and most of the DRI currently produced in rotary kilns worldwide is manufactured by this

process. Therefore, the principle of the rotary kiln processes is explained with reference to this process. The SL/RN process, **Figure 10**, was developed in 1964 by Lurgi (now Outotec) in collaboration with North American companies Stelco, Republic Steel and National Lead (hence the name). In the past years, it was the dominant process for the direct reduction of iron ore with coal as a reductant, with India being the most prominent market with several hundred plants installed over the last 30 years.

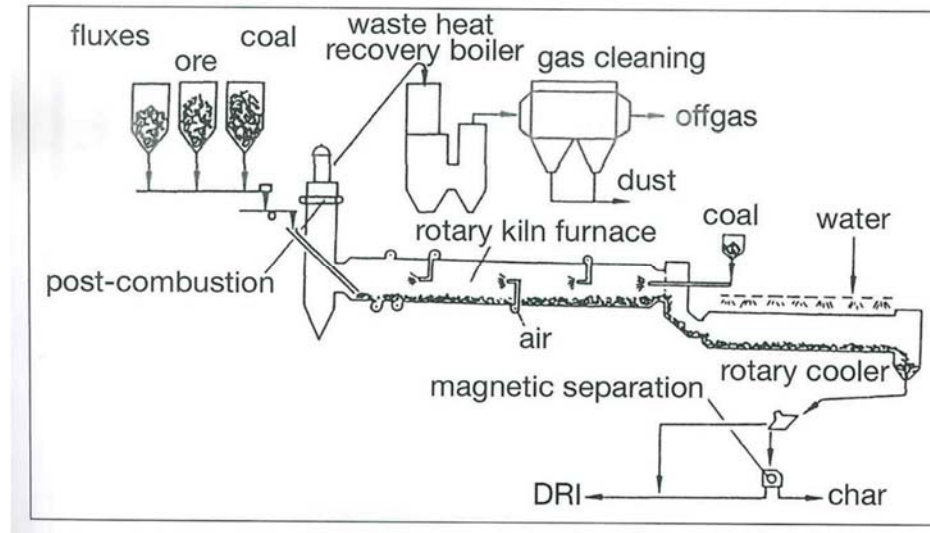


Figure 10: SL/RN rotary kiln process

The main device of the process is the rotary kiln inclined from the feed to the discharge end, in which the raw materials iron ores, additions and coal are heated up and reduced to DRI. Many fans are installed on the shell of the kiln. These fans supply the necessary process air via so-called air tubes or via air injection nozzles in the feed zone of the rotary kiln.

The internal kiln temperature is continuously recorded by thermocouples installed along the entire length of the kiln and projecting into the kiln freeboard. The power supply to the shell fans and the transmission of the data recorded by the individual thermocouples are accomplished by means of slip rings mounted on the kiln shell.

Up to ca. 35% of the total fresh coal required is fed into the kiln from the discharge end with a special pneumatic injection system. The charge passes through the kiln in 8 to 12 hours. The cooling of the DRI is done in a cooling drum. The sensitive heat of the waste gas can be recovered in a boiler and used for heating purposes or for electricity production. In simplified terms, the rotary kiln can be divided into a preheating and a reduction zone. In the preheating zone, the feed materials are dried and coal volatiles escape, and the charge is heated to reduction temperatures of 950–1,100°C. Compared to direct reduction shaft furnaces, rotary kilns are characterized by more flexibility by the use of iron ores and by a high specific energy (coal) consumption and low productivity. The energy consumption is appr. 14.8 GJ/t DRI.

Rotary hearth furnaces have been industrially applied in small production units for the processing of iron bearing residues, like the Fastmet, Inmetco and IDI processes. In these processes green pellets which contain carbon or a mixture of iron ores, oxidic residues and carbon containing reductants (coal, coke) can be used. Rotary hearth furnaces are also used in Japan and South Korea for the processing of zinc rich steel works residues.

The **ITmk3** process, **Figure 11**, (iron technology mark 3) of Kobe steel, has the target, to reduce the iron ores and to separate the gangue materials from the iron in one process step. The green iron ore

and coal composite pellets are fed to a rotary hearth furnace and heated to 1,300 to 1,450°C. At this temperature the pellets are reduced and then the iron is melted and separated from the slag to form iron nuggets which have an iron content of 97% and a carbon content of 2%. The iron and slag are subsequently cooled and separated in the form of iron nuggets and granulated slag. The ironmaking process from charge to final product takes only 10 minutes [22].

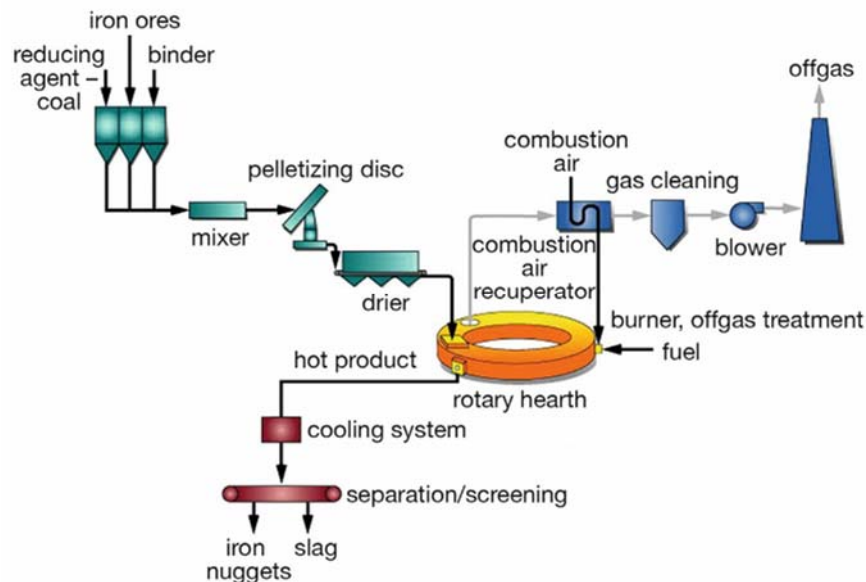


Figure 11: ITmk3 rotary hearth furnace process

Kobe Steel and Steel Dynamics have built a production plant for 500.000 t iron nuggets per year in Hoyt Lakes, Minnesota, USA, which went into service in 2010 (Mesabi nugget project).

Production of DRI/HBI

The introduction into industrial service of processes for the direct reduction of iron ores began towards the 1950ies. In the following years, they were regarded by many advocates as real alternative iron ore reduction processes to the blast furnace process and the forecast was a quick penetration in the industry and a sharp increase in worldwide production [23]. The gap between the hopes, wishes and forecasts on the one hand and reality on the other hand was wide, **Figure 12**. There were two main reasons for this shortfall:

The energy situation only allowed the operation of especially gas-based processes at locations, where cheap energy, and particularly cheap natural gas, was available.

The development of the market for steel scrap as a raw material traded on a worldwide scale has, for many years, worked against the forecast demand on high quality DRI/HBI.

In 2020 the worldwide total amount of DRI/HBI produced was 104.4 mill. t [11].

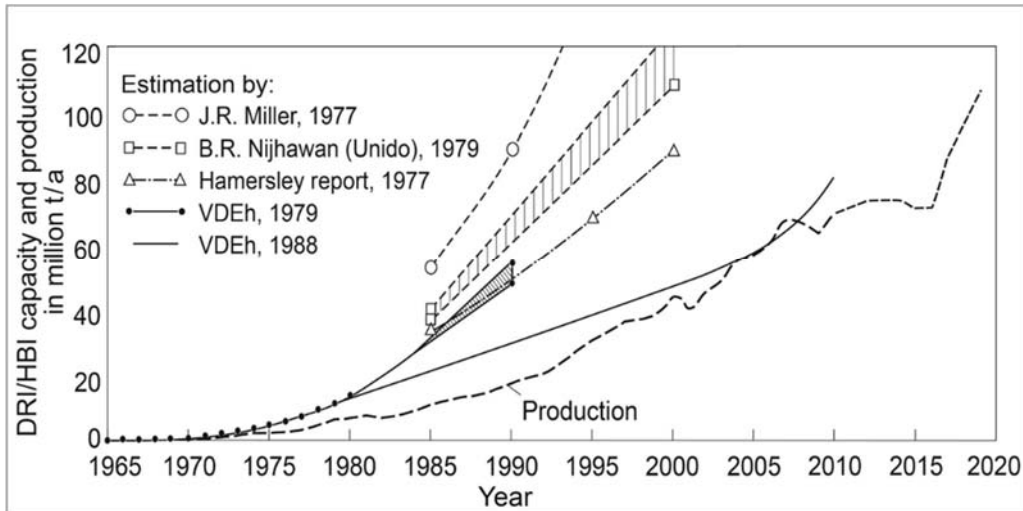


Figure 12: Evolution of DRI/HBI production around the world compared to preceding capacity forecasts

The DRI/HBI production increase mainly took place in the regions Middle East / North Africa, Asia / Oceania and Latin America, whereby in Latin America a drop in production is to be seen in the last 15 years, **Figure 13**.

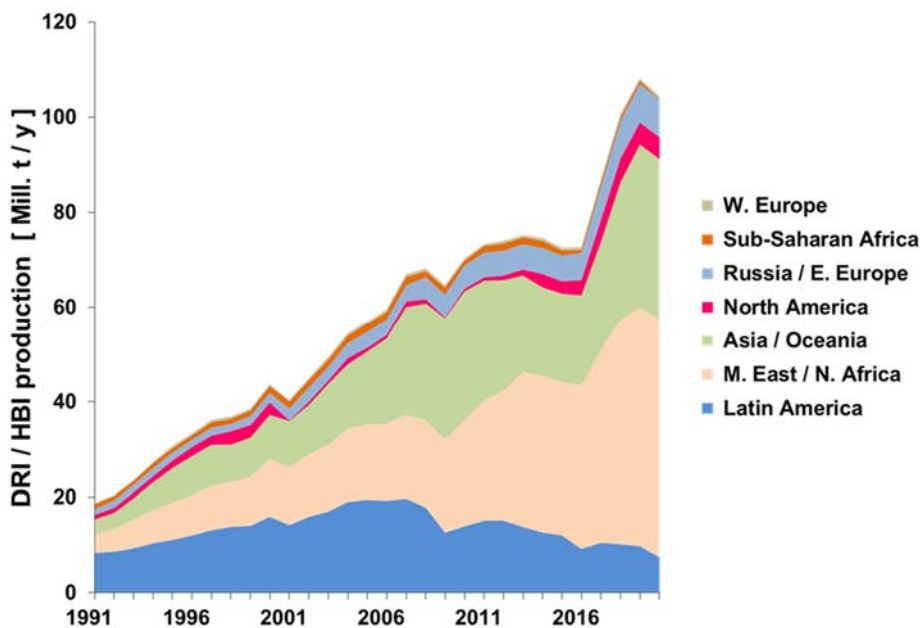


Figure 13: World DRI/HBI production by regions

The main DRI producing countries in 2020 were India with 33 mill. t, Iran with 30 mill. t, Russia with 8 mill. t as well as Saudi Arabia and Mexico with 5.2 mill. t each.

From the worldwide production of 104.4 mill. t DRI/HBI in 2020 75.6% was produced with gas as reductant and 24.4% with coal as reductant, **Figure 14** [11]. The marked leader is the Midrex shaft furnace process with 62.2. mill. t followed by the HyL/Energiron process with 12.9 mill. t.

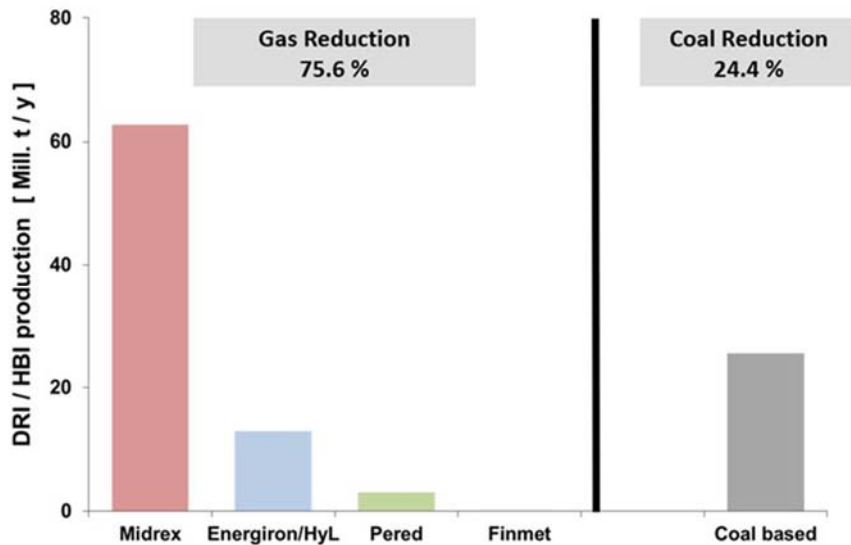



Figure 14: World DRI/HBI production by processes in 2020 (total DRI/HBI production: 104.4 mill. t)

The product DRI is characterized by a metallization of 92 to 96% and a total Fe content of 86.1 to 93.5%, **Figure 15**. The carbon content can be adjusted in a range of 1.0 to 4.5%, but using pure hydrogen as a reducing agent, it could be zero. Important is the request, to keep the gangue content as low as possible to avoid intensive slag metallurgy by processing the DRI/HBI to crude steel in the electric arc furnace.

Metallisation	92.0 – 96.0 %
Fe (Total)	86.1 – 93.5 %
Fe (Metallic)	81.0 – 87.9 %
C	1.0 – 4.5 %
S	0.001 – 0.03 %
P ₂ O ₅	0.005 – 0.09 %
Gangue*	3.9 – 8.4 %

*residual unreduced oxides, mainly SiO₂ and Al₂O₃, but also CaO, MgO, MnO, etc.



$$\text{Metallization} = (\% \text{ Fe metallic} / \% \text{ Fe total}) * 100$$

Figure 15: General specifications for DRI (by weight) based on 65.5 to 68% Fe iron ore

Therefore high-grade DR pellets and DR lump ores which have a high Fe content and low gangue content are processed in the direct reduction shaft furnaces.

The product DRI is pyrophore which means that it tends to re-oxidate in contact with air and tends to burn. The reactivity of iron with moisture or water may generate hydrogen gas which can be explosive over a very wide range of concentrations. Therefore, precautionary measures have to be taken for the transport and storage of DRI. The produced DRI has the form of the used iron ores, for example ore fines 0.1 to 10 mm or pellets with 8 to 12 mm in size. These have a large specific surface area which has an influence on the ignition temperature of the DRI. Effective measures for storing and transport of DRI is to do this under inert atmosphere or to decrease the specific surface. The most suitable technique for that is the hot briquetting of the DRI to HBI (Hot Briquetted Iron) [24], **Figure 16**. By this a clear decrease of the specific surface is achieved which avoids oxidation and ignition of DRI.

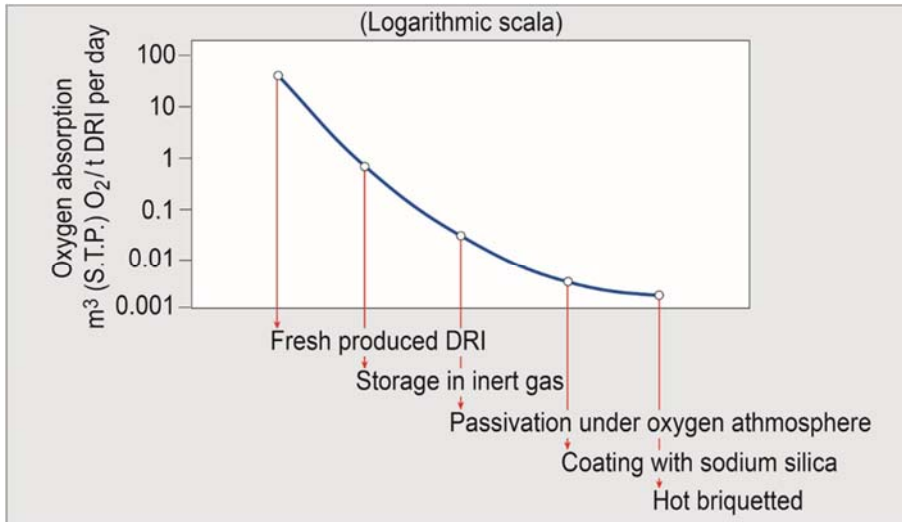


Figure 16: Reactivity of DRI depending on the treatment

The amount of DRI briquetted to HBI was just only 9 mill. t or 8.6% in 2020. Also the water and land transport of DRI/HBI to external users was only 20 mill. t which means, that most of the production was directly processed in in-plant electric arc furnaces.

Outlook

On 11 December 2019 the European Commission announced by the European Green Deal the target, that the European Union will become the first climate neutral continent and has therefore presented an action plan. The European steel industry is in line with the target, to reach greenhouse gas neutrality by 2050 and will bring substantial CO₂ mitigations on the way by 2030.

Carbon direct avoidance (CDA)

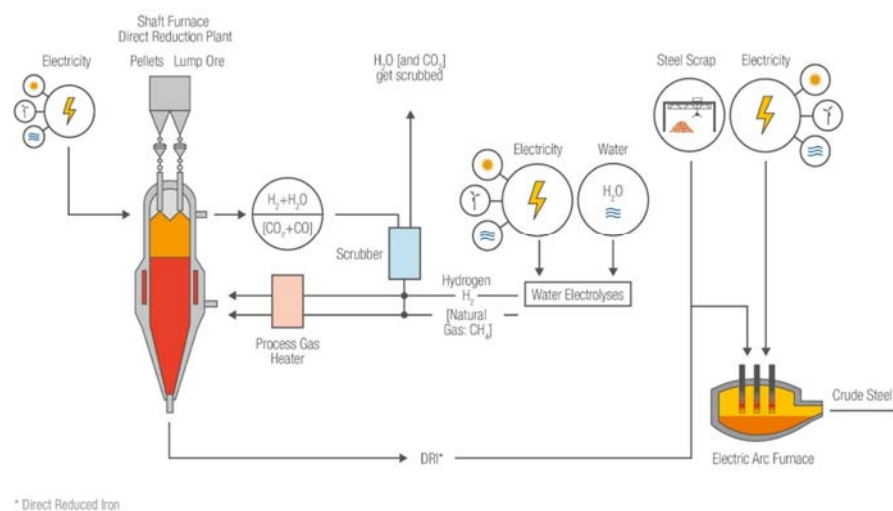


Figure 17: Production of green steel with hydrogen as reductant

To reach a nearly climate neutral level of iron and steel production it is planned to implement the direct reduction technology with hydrogen and subsequent melting of the direct reduced iron (DRI) to steel in an electric arc furnace, **Figure 17**, or in a combination of a submerged arc furnace or open slag bath furnace and a basic oxygen steel converter. This means a replacement of blast furnaces for the reduction of iron ores and the need for an immense amount of hydrogen and CO₂-free electric energy.

Both, the Midrex and the HyL/Energiron shaft furnace technology are currently further developed to be ready for using hydrogen as a reductant on the way to climate neutral iron ore reduction. Also the hydrogen based fine ore reduction process Circored could be of interest in the context of climate neutral iron ore reduction. This will be a renaissance for the gas-based direct reduction technologies in Europe and probably in other regions of the world.

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