COREX® + MIDREX AN IDEAL CONCEPT FOR ECONOMIC AND ENVIRONMENTAL FRIENDLY STEEL PRODUCTION[1]

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Abstract
The Corex process is beside the Finex technology the only economic and ecologic industrially realized alternative to the blast furnace route for the production of hot metal. Based on the nature of the Corex process using pure oxygen for the smelting process export gas with a high calorific value is produced which can be used for various purposes. Existing Corex plants at Saldanha, JSW, Baosteel and Essar have already implemented different applications for export gas utilization to fully utilize the benefits of the Corex process for economic and efficient hot metal and steel production. Current trends in iron and steelmaking clearly show an increasing demand for utilizing the Corex export gas for the production of DRI. Integrated plant concepts based on a Corex/Midrex DR plant combination offer solutions for future challenges of the iron- and steelmaking industry, which include: economical hot metal and DRI production based on coal; low raw material costs, sustainable raw material availability; integrated energy solutions; and environmental friendly high grade steel production. A further aspect of the combination is the possibility to charge the hot metal from Corex and the DRI in hot condition from the Midrex plant to a Simetal EAF for highest efficient steel production. The new Simetal Fast DRI EAF especially developed for DRI charge to an EAF is maximizing the productivity due to minimized power-off times. Many references for the input of hot metal and hot/cold DRI reflecting the market demand for increased input of scrap substitutes are available.
Key words: Corex; Midrex; Simetal EAF; Export gas utilization; Hot metal; DRI.

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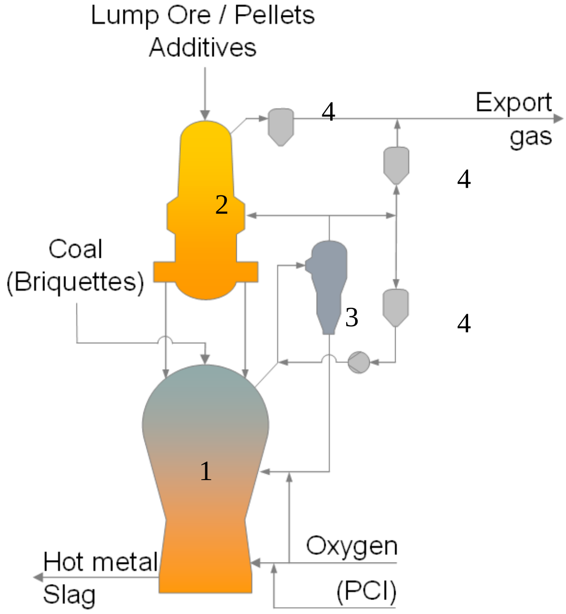
1 INTRODUCTION

1.1 The Corex Process

Corex is a commercially proven smelting reduction process that allows for cost-efficient and environmental friendly production of hot metal directly from iron ore and non-coking coal. The process was developed to industrial maturity by Siemens Vai and is beside the Finex process the only alternative to the blast furnace route consisting of sinter plant coke oven and blast furnace. It distinguishes itself from the blast furnace by:

- direct use of non-coking coal and a minimum of low quality coke as reducing agent and energy source for melting purposes;
- direct use of iron ore in form of lump ore, pellets and sinter;
- usage of pure oxygen for coal gasification.



[1] Melter gasifier *[2] Reduction shaft*
[3] Hot gas cyclone *[4] Process gas scrubbers*

Figure 1. Corex process flow sheet.

Based on the nature of the process a high valuable export gas is produced, which can be used for different applications like:

- heating purpose;
- DRI production;
- power generation;
- chemical processes.

Table 1. Typical specification for Corex C-1.0M and C-1.5M export gas

		C-1.0 M (former C-2000)	**C-1.5 M (former C-3000)**
Flow	m³ (STP)/h	~ 200,000	~ 290,000
Temperature	°C	30 – 50	30 – 50
Pressure	kPa g.	5 – 180	5 – 180
Analysis			
CO	%	38 – 45	38 – 45
CO_2	%	30 – 35	30 – 35
H_2	%	15 – 23	15 – 23
H_2O	%	saturated	saturated
CH_4	%	1 – 2	1 – 2
N_2/Ar	%	Balance	Balance
H_2S	ppmv	<100	<100
Net Calorific Value	kJ/m³ (STP)	up to 8,500	up to 8,500
Dust	mg/m³ (STP)	<5	<5

Gas volumes are based on STP (273.15 K; 1.01325 bar)

1.2 The Midrex Process

The Midrex process has been developed in the 1960's and until now more than 70 plants have been installed for DRI production. Presently the Midrex process is the dominating natural gas based DR technology. In 2011 the total world production of DRI/HBI based on natural gas was 55.5 Mio tons whereas 80% of this production was generated by plants using the Midrex process.
The typical main energy source for the Midrex process is natural gas, which is reformed and then used as the reducing agent for DRI production. But also other gases can be used as energy source in the Midrex shaft furnace for DRI/Hot DRI/HBI production.

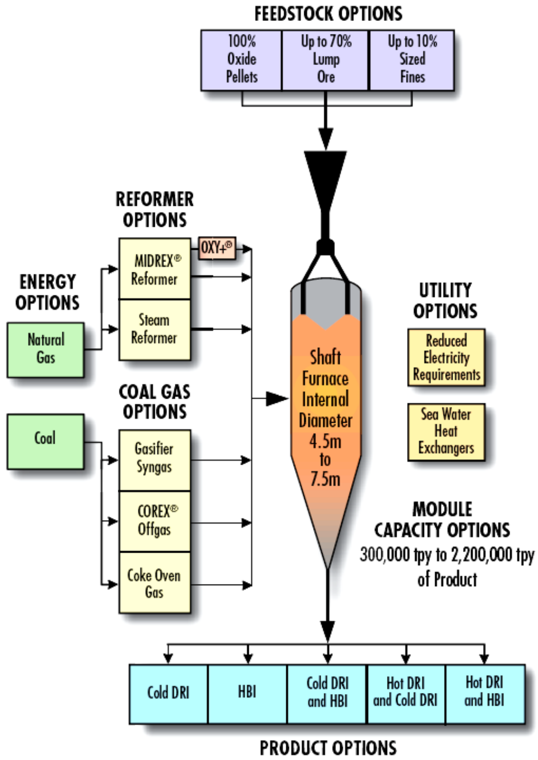


Figure 2. The Midrex process overview.

1.3 Corex + Midrex Combination Plant

Based on the cooperation between Midrex and SVAI for traditional Midrex DR plants and the development of the Corex process by SVAI it was a logical consequence to use the export gas of a Corex plant for DRI production in a Midrex shaft furnace.

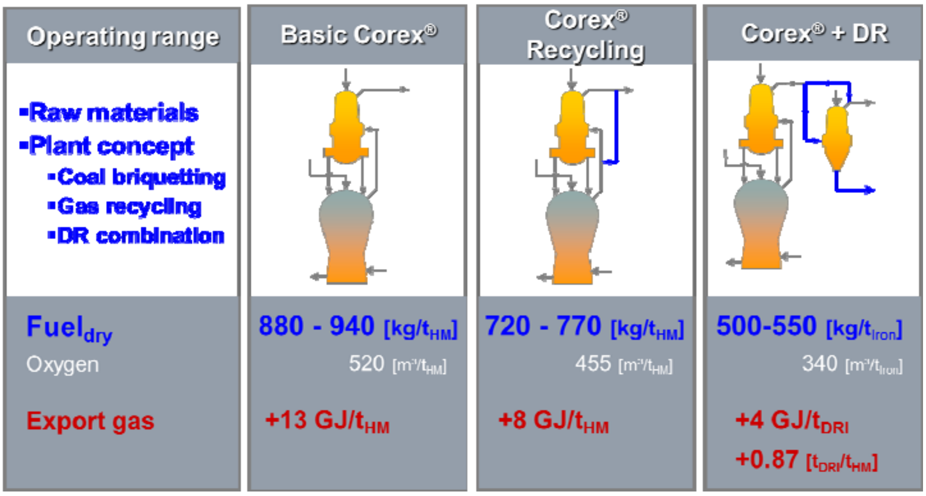


Figure 3. Basic concepts of a Corex plant including the Corex + Midrex combination plant.

At a Corex plant with a total fuel rate of approx. 940 kg/t HM approx. 13 GJ/t HM thermal export gas energy is produced. After deducting all internal power consumers approx. 1.36 MWhel/t_{HM} for export can be produced by using the Corex export gas in a combined cycle power plant. With an internal gas recycling system under consideration of coal briquetting/PCI injection system the fuel consumption can be lowered to approx. 770 kg/t_{HM}.
The Corex export gas can also be fully utilized for DRI production. Such a concept is lowering the fuel consumption to approx. 550 kg/t iron.
It is no surprise that a Corex-Midrex DR plant combined system has been considered with the development of the Corex C-2000 plant in the early 1990's already for the Corex plants at Hanbo, Korea. For the first time the concept was successfully realized at the Corex–Midrex plant combination at ArcelorMittal South Africa, Saldanha Steel Works.
Currently a Midrex shaft furnace based on the export gas from the two Corex plants at JSW, India, is under construction.
The relocated Hanbo Corex plants have been started up at Essar, India in 2011. Also there the Corex gas is used to substitute natural gas for the existing Midrex DR plants.

2 DEVELOPMENTS AND CONCEPTS FOR COREX GAS BASED DRI PRODUCTION

Depending on whether the top gas leaving the reduction shaft of the DR plant is exported or recycled to be reused for the production of DRI, there are two basic concepts for such a plant:

- the once through; and
- the recycle concept.

2.1 "Once Through" Concept

The once through concept for using Corex export gas in a Midrex shaft furnace plant is illustrated in Figure 4. This concept was developed for Hanbo Steel/Korea.

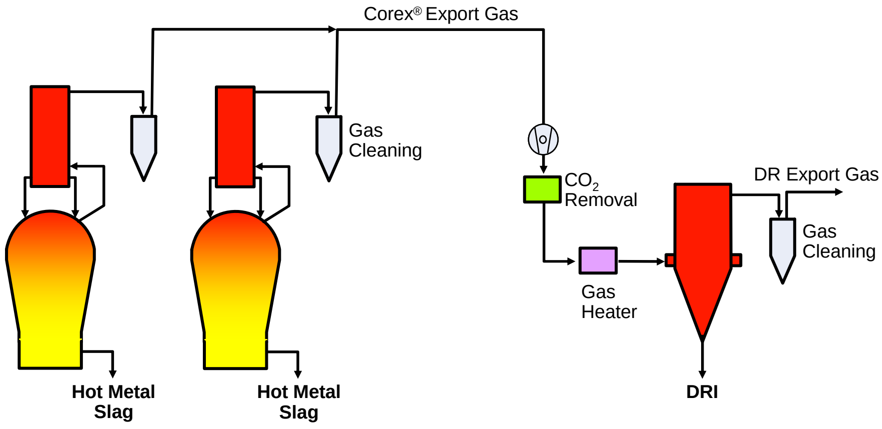


Figure 4. "Once through" concept: hot metal/DRI production at HANBO Steel.

The "once through" concept is the simplest concept for Corex gas based DRI production. Corex export gas is compressed, before fed into the CO_2 removal unit. The cold reduction gas is preheated to the required reduction gas temperature and used for DRI production in a Midrex DR shaft. The DR shaft top gas is of similar quality compared to the original Corex export gas and can be further used similar to the Corex export gas:

- heating purposes by substituting fuel gas/natural gas;
- power generation;
- chemical processes.

The advantages of this concept are:

- lower investment cost (no recycle gas compressor required);
- lower operational cost (no electric power required to pressurize the recycle gas from DR export gas).

In such a plant configuration the DR plant can produce up to approx. 0.5 t DRI per ton of HM. The hot metal and (hot)DRI produced can be processed further either in an electric arc furnace or in a basic oxygen furnace. Above concept is not focused on maximizing DRI production, but it gives highest flexibility for an integrated energy concept including DRI production for various purposes.

2.2 Recycle Concept

The recycle concept has been developed for maximized DRI production with Corex export gas. The main portion (max. 85 – 90%) of the DR top gas is recycled to the CO_2 removal system and then used again for the production of DRI. For that purpose the recycled gas is compressed and mixed with the Corex export gas upstream of the CO_2 removal system.
A small amount of the DR top gas has to be exported to avoid the accumulation of inert gas (N_2 and Ar) in the DR reducing gas. The flow depends on various parameters like oxygen purity for the Corex and the DR plant, required DRI production, or required DR export gas volume.

The advantages of this concept are:

- maximized DRI production;
- low DR export gas flow;
- lowest fuel/carbon consumption and lowest CO_2 generation per ton of iron.

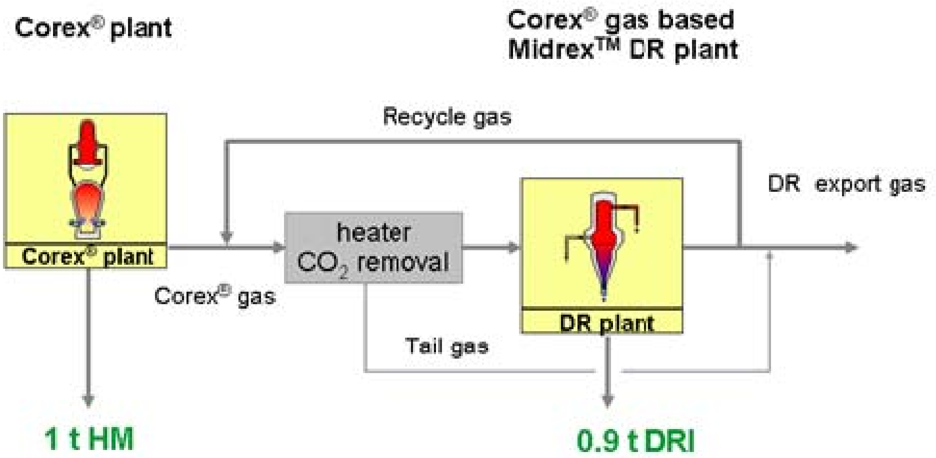


Figure 5. Recycle concept.

With this concept about 0.9 ton of DRI can be produced per ton of hot metal. The relation between hot metal and DRI production depends on the amount and quality of the Corex export gas and subsequently on the amount and quality of coal used in the Corex process.

Table 2. Production capacities of combined Corex and Midrex plants

Corex	**C-1.0 M**		**C-1.5 M**	**C-2.0 M *)**
DR plant concept	Once through	Recycle	Recycle	Recycle
Corex HM Production (t/y)	1 million	1 million	1.5 million	2.0 million
Corex export gas to Midrex plant (Nm^3/h)	200,000	200,000	290,000	385,000
DRI Production (t/y)	0.45 Mio	0.87 Mio	1.25 Mio	1.60 Mio
DR export gas flow (Nm^3/h) **)	145,000	100,000	140,000	185,000
DR export gas heating value (kJ/Nm^3)	7300	5000	5000	5000

** Based on the positive operation results of Corex C-3000 plant at Baosteel, SVAI has developed a new upgraded Corex C2.0M plant with an annual capacity of 2 million/y; ** Total gas flow exported from the Corex-Midrex combination plant, which will be available for downstream users.*

Ultimately process economics of the entire works will dictate whether the DRI production will be maximized or higher rates of the DR top gas will be used for other purposes.

2.2.1 Concept for Arcelor Mittal South Africa, Saldanha

An example for such a recycling concept is the world's first Corex+Midrex combination plant at AMSA (Arcelor Mittal South Africa, Saldanha Steel Works) producing hot metal and DRI successfully since the year 2000.

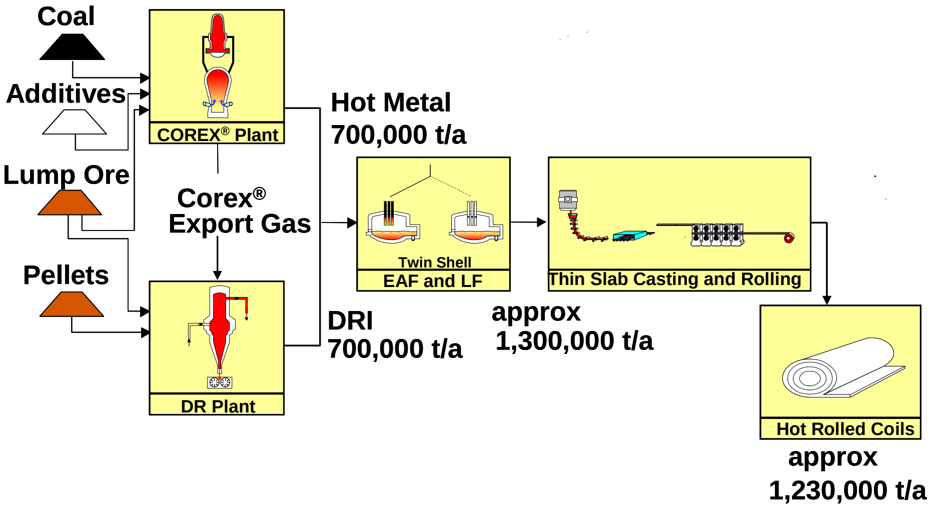


Figure 6. Hot metal/DRI production at Saldanha Steel.

The overall flow sheet of Corex-DR Saldanha represents a concept, where nearly all the DR plant top gas is recycled back to the Corex export gas.
After compressing the Corex export gas the CO_2 is removed by a vacuum pressure swing absorption plant (VPSA). The cold reducing gas from the VPSA is heated to 800–850°C. The exact reducing gas temperature depends on the properties of the DR shaft furnace oxide feed (mainly reducibility and sticking tendency). The reducing gas is heated in two steps. First, the reducing gas is convectively preheated in a heat exchanger. In a second step the gas is heated to the desired temperature by partial combustion.
At Saldanha Steel per ton of HM, additionally approx.. 1t of DRI is produced. The products of both plants (hot metal from Corex and the cold DRI from DR plant) are then charged to an electric arc furnace (EAF).

Raw Material and DRI quality at ArcelorMittal South Africa

At Saldanha it is imperative that a high percentage of lump ore can be processed in the DR plant. In the Midrex DR shaft furnace up to 70% of Sishen DR grade lump ore can be used, with the remainder being DR grade pellets. This was demonstrated during the performance test.
After the performance test the lower cost Sishen BF grade lump ore that is also fed to the Corex plant has been used. Operational experience showed that the most economic feed mix of direct reduction for Saldanha Steel consists of approx. 60% Sishen BF grade lump ore and 40% DR grade pellets.

Table 3. Analyses of the used iron oxides

		Sishen Lump Ore	CVRD DR Grade Pellets
Fe	[%]	66.6	66.6
SiO_2	[%]	3.1	1.9
Al_2O_3	[%]	1.0	0.9
CaO	[%]	0.1	1.3
MgO	[%]	0.1	0.5
Na_2O	[%]		
K_2O	[%]	0.12	< 0.05
P_2O_5	[%]	< 0.10	0.07
SO_3	[%]	0.02	0.13

From the very beginning the DRI produced was of excellent quality with regard to metallization and carbon content. The DRI quality for the steel shop has a metallization degree of 92% and a carbon content of about 1.6%.

2.2.2 Concept for JSW – Jindal South West

At JSW two Corex C-2000 plants are in operation since 1999 and 2001. Originally the export gas of both Corex plants was mainly used for electric power generation at two nearby located 130 MW_{el} power plants (**Figure 7**). Alternatively also coal can be used as energy source for the power plants. In addition some export gas is also used at the pelletizing plant.

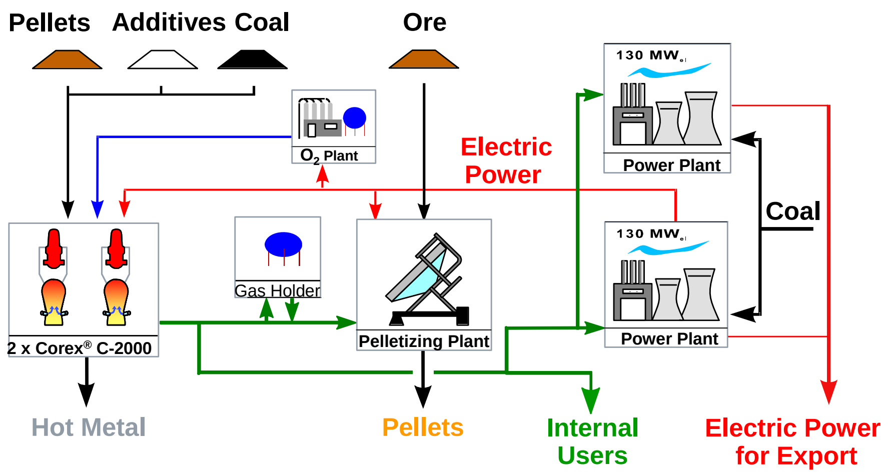


Figure 7. Overall iron making plant concept based on Corex® at JSW up to 2013.

In 2011 the consortium consisting of Siemens VAI (consortium leader), Midrex Ltd. and Linde was awarded with the contract for the installation of an additional Midrex DR plant with an annual capacity of 1.2 million ton DRI.

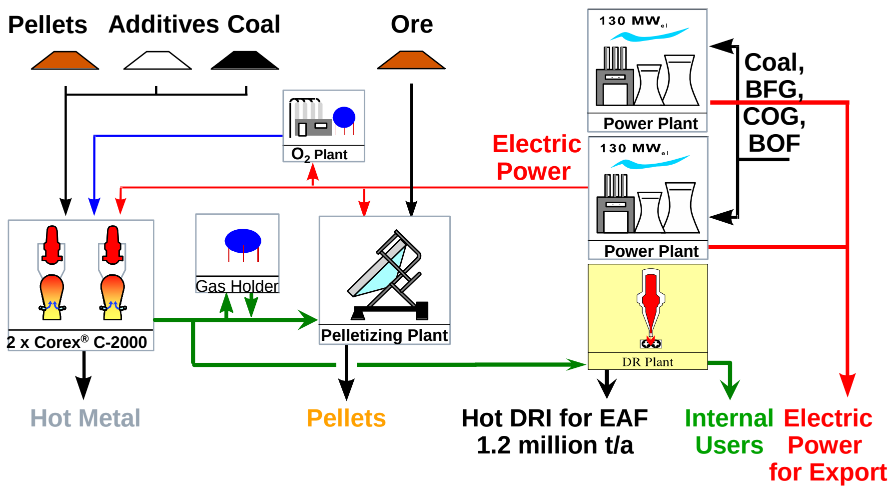


Figure 8. New overall ironmaking plant concept based on Corex® at JSW from 2013.

Similar to Saldanha also at JSW the Corex export gas from both Corex plants and re-circulated top gas from the Midrex plant are mixed and compressed, followed by CO_2 removal. The gas low in CO_2 is heated and then used for the direct reduction of iron ore in the Midrex shaft furnace. Part of the top gas is recycled whereas the rest of the

DR export gas which has a calorific value of approx. 7500 kJ/m³ will be used within the steel works for mainly high temperature heating applications (Figure 8).
For the JSW concept the CO_2 removal plant design has been changed from a VPSA system to PSA (pressure swing absorption) system due to the lower maintenance requirement. The PSA plant does not require vacuum for removal of the CO_2 captured within the absorbent.

3 COREX EXPORT GAS UTILIZATION TO MINIMIZE NATURAL GAS CONSUMPTION FOR EXISTING DR PLANTS

Recent trends for DRI production based on existing DR plant concepts using the natural gas reforming process show the need to minimize natural gas consumption. Corex export gas provides excellent possibilities to realize such concepts. At Essar Steel there are 6 existing Midrex DR plants. The integration of the two Corex C-2000 plants has significant advantages for the development of the overall steel plant complex:

- increase the liquid HM capacity for improved capacity of the existing EAF
- significant reduction of natural gas consumption at the existing DR plants

In 2011 two Corex C-2000 Modules have been successfully put into operation and the export gas is utilized at the two big DR plant modules No. 05 and No. 06 which are designed for an annual DRI capacity of 3.2 million t/a.

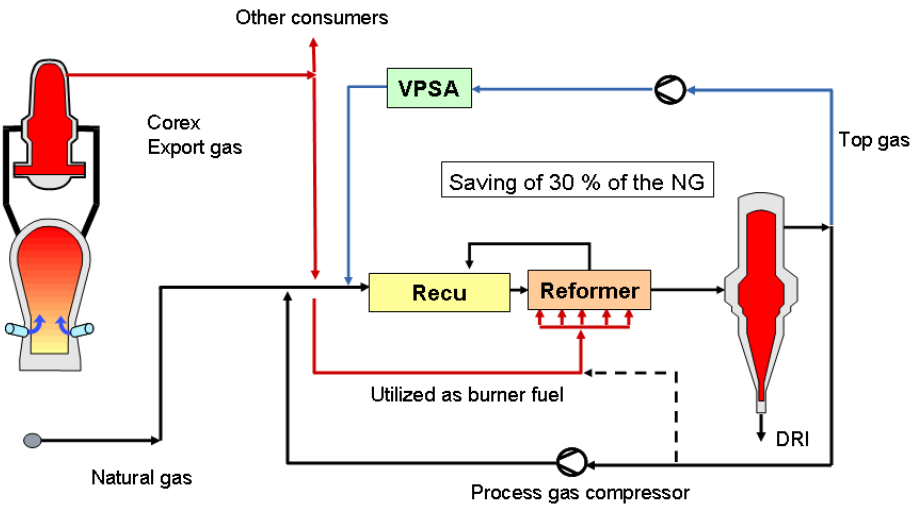


Figure 9. Corex export gas utilization at Essar Steel, India.

As shown in Figure 9 the Corex export gas is utilized to replace natural gas as a fuel for the reformer heating. In addition a part of the DR plant top gas is recycled and fed to a VPSA unit and from there the gas is mixed into the process gas flow upstream of the reformer for further reduction of natural gas consumption. Above configuration lowers the overall natural gas consumption for the Midrex plant by approx. 30%.
Considering the reduction of natural gas requirement for DRI production this system provides enormous advantages for overall DRI production costs. Allocating those savings as a benefit for Corex, the Corex hot metal production costs at Essar are considerably lower compared to the blast furnace production costs.

4 OUTLOOK / DEVELOPMENTS

4.1 Hot DRI Charging to EAF

Corex+Midrex combination plants with cold DRI (CDRI) discharge are already very well established. Recent experience gained from several Midrex projects show significant benefits for Hot DRI discharge into the EAF. For the first time a hot conveyor system was installed at the Midrex plant Module E in Hadeed (Figure 10). Main benefits compared with 100% CDRI are:

- Increased productivity determined to be 15-20%;
- Power savings of 130-150 kWh/t liquid steel;
- Electrode savings of 0.5-0.6 kg/t liquid steel.

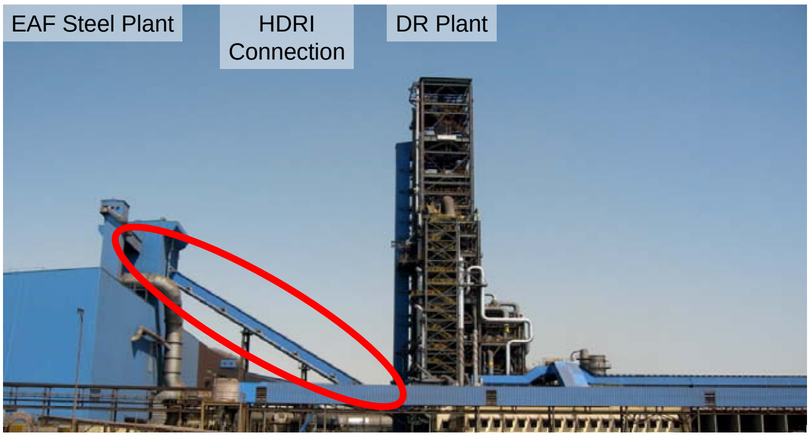


Figure 10. Hot Transport between DR plant and EAF as realized at Hadeed, Saudi Arabia.

5 BASIC CONCEPT FOR COREX HM + MIDREX DRI CHARGING INTO EAF

Table 4 and Table 5 show typical production data for a Corex C1.0M plant and a directly connected Corex gas based Midrex plant with recycle concept. Both products (hot metal from Corex and hot DRI from Midrex plant) are charged into the electric arc furnace. In Table 4 the following is considered:

- even eot DRI charging is applied a small amount of CDRI is continuously produced in parallel to keep the cooling loop on “hot” standby to be ready in case the EAF shop is shutdown.
- further CDRI is produced out of the availability difference of the Midrex plant and the EAF.
- eot metal will be continuously produced even during shutdown of the EAF. It is assumed that 40% of that HM amount can be temporarily stored in hot condition in ladles/torpedos, whereas 60% has to be granulated or cast into pig iron.

The buffered hot metal, the pig iron and the CDRI are added to the EAF charge when the EAF is in operation.

Table 4. Production data of a Corex C1.0M plant and a directly connected Corex gas based Midrex plant

	Corex C-1.0 M	**Midrex**
Hot Metal t/h	125	-
Hot DRI t/h	-	108
t/d	3000	2592
t/a	1040250	864000
Hot Metal °C	1500	
Hot DRI °C	-	550
Met%	-	92
C	4,5	1,6
Si	0,7	*)
Mn	0,35	*)
P	0,07	*
S	0,05	*
h/a	8322	8000
*depends on iron ore source		

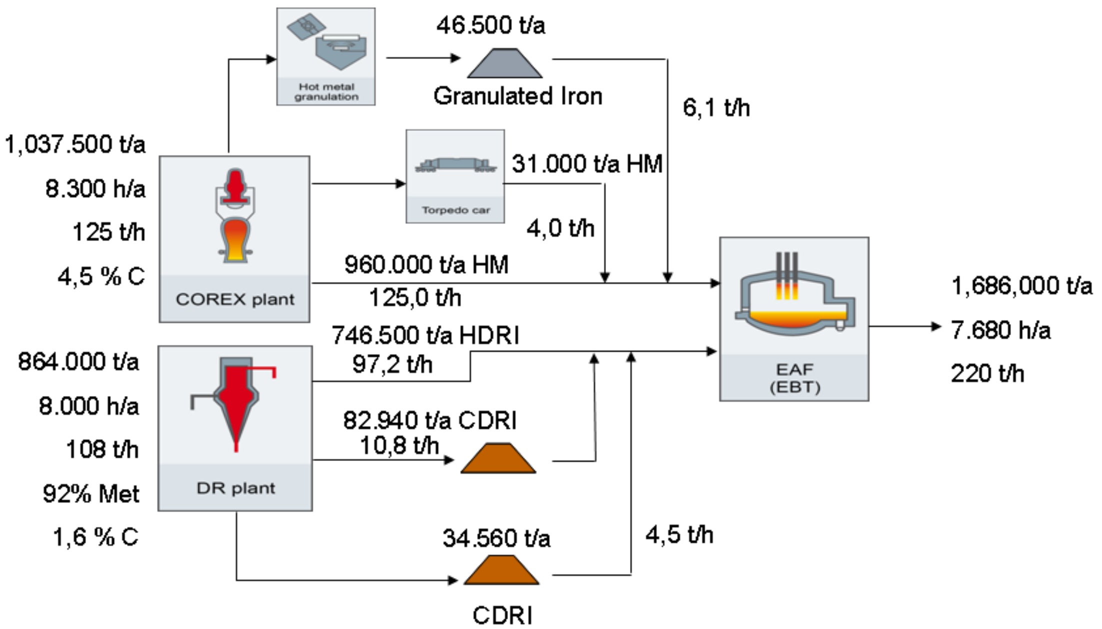


Figure 11. Process flow diagram for a Corex C-1.0M +Midrex combination plant +EAF

Table 5. Consumption and production data of an EAF based on hot metal and Hot DRI produced in a Corex C 1.0M +Midrex DR combination plant

EAF Charge *)		
Hot DRI	t/h	97.2
Cold DRI	t/h	15.3
Hot Metal	t/h	129.0
Pig Iron	t/h	6.0
EAF Consumption and Production Figures		
POWER ON TIME	min	33
TAP to TAP-TIME	min	41
Electric Power	MW	71
Electric Energy	kWh/t	260
Electrodes	kg/t	0,8
O_2 PC + Burner + RCB	m³/t	55
Natural Gas	m³/t	2.3
Carbon total	kg/t	4
Lime	kg/t	40
Dolomite	kg/t	10
Productivity	t/h	220
Yearly Prod	t/y	1,686,000
Work. Hours	h/y	7680
Metal Yield	%	88.8

***** *Note: EAF charge mix considers the different availabilities of Corex (8300 h/a), Midrex (8000 h/a) and the EAF (7680 h/a).*

6 CONCLUSION

The growing demand for steel in emerging markets is posing a challenge which is directly linked with the energy and raw material situation in these markets. Therefore solutions for alternative ironmaking routes will become more important in the near future.

DR plant technologies typically are using natural gas for generation of the reduction gas. These technologies have successfully penetrated the iron market and more than 70 plants are in operation worldwide.

Corex gas based DRI production in a Midrex shaft furnace has been considered since development of the Corex technology started in the 1980's and is a solution for countries and locations where there is a natural gas scarcity or no natural gas at all. For such locations this coal based plant combination is a proven viable alternative. As it is available in various plant concepts it can be tailored to customer needs.

By combining Corex and Midrex, synergies and advantages of both processes can be fully utilized towards:

- high raw material flexibility;
- optimum utilization of iron carrier materials;
- lowest fuel consumption;
- low coke requirement;
- high export gas revenue by producing DRI;
- environmental friendly and economic steel production.

In combination with a Circular Pelletizing Plant (CPT) in front of the Corex/DR combination and an SIMETAL EAF subsequent to the combination which processes the hot metal and the DRI/HDRI, a high energy efficient operation can be achieved.

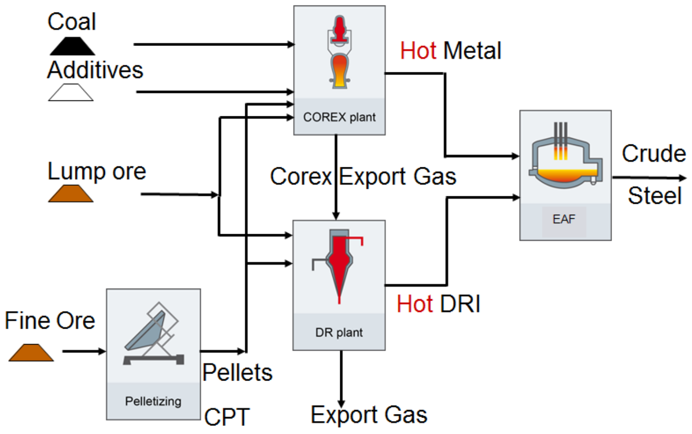


Figure 12. Process diagram for a Corex+ Midrex +CPT.

In addition by combining the processes via expert systems, it will be possible to operate the total system at its optimum point.