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TECHNICAL PAPER

# Developments in Alternative Ironmaking

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**Abstract** Alternative ironmaking processes compete with the blast furnace process route. The blast furnace, the most important hot metal producer, has improved over the years and continues to do so. Consequently replacing the blast furnace is a formidable task. The success rate of alternative processes has been low, i.e. limited to niche applications. Why do we continue to work in this field? Because the drivers to develop alternative processes are very strong. For example, the expected coke shortage has been the driver for coal based developments in Europe in the period 1980–1990. Some of the recent developments evolved from the work done in that period. In later years, around the year 2000, the Climate Change issue became the driver for development. And the high price level of iron ore of the last decade can spur a new wave of ironmaking developments. The HIsarna alternative ironmaking process is an example of a development that combines several of the drivers mentioned above. The process has the potential to considerably reduce the $CO_2$ emissions per ton. But it can also use more economically priced raw materials such as non coking coals and iron ores outside the quality range for blast furnace ironmaking. Therefore the process can offer economic benefits as well as environmental benefits.

**Keywords** Ironmaking · Smelting reduction · Sustainability · ULCOS · HIsarna

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## 1 Introduction

Alternative ironmaking is a collective name for all ironmaking production routes other than the blast furnace ironmaking route. The alternative ironmaking processes include processes using coal as well as natural gas and processes producing a solid product (HBI/DRI) as well as processes producing liquid iron. To subdivide these production routes into smaller groups the type of ironmaking furnace/reactor can be used as a criterion. The table below shows such a division. Other criteria are the reductant and the product.

This paper will focus on a smaller group of processes, named Smelting Reduction.

As the name suggests smelting takes place in the process and a liquid product is produced. A further characteristic is that these processes use coal as reductant, not coke or gas. The following processes from Table 1 can be considered Smelting Reduction processes; *Corex, Finex Tecnored, AISI Direct Steelmaking, DIOS, Romelt, Ausiron, HIsmelt, CCF and HIsarna*.

Presently from these 10 technologies, 5 have stopped, 3 are in the pilot plant stage and 2 have reached industrial status. But only 1, the Corex process, has been commercialised with several industrial applications.

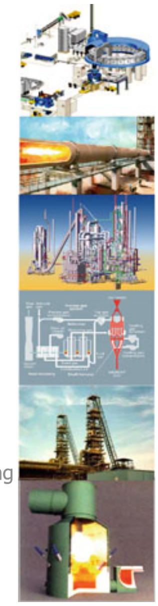
It proves to be extremely difficult to compete with a process that is so well established as the blast furnace. Even a development promising to match its performance is not good enough. In order to accept the development risk it must exceed the blast furnace performance in terms of energy efficiency, product quality and consistency. And at the same time perform in the areas of reliability, safety, maintenance performance and most of all costs.

The development of a new ironmaking process requires time, money and perseverance, and most importantly a business need that guides the project through the “Valley

**Table 1** Overview of alternative ironmaking processes

| Type of reactor | Reductant | Product | Examples |
|---|---|---|---|
| **Moving hearth furnaces** Rotary/multi hearth | Coal | Solid | Inmetco, Fastmelt, Primus Redsmelt, Sidcomet |
| **Rotary kilns** | Coal | Solid | SLRN |
| **Fluidised beds** | Coal and Gas | Solid | Circofer, Circored, Finmet |
| **Shaft furnaces** | Gas | Solid | Midrex, Hyl, Danarex |
| **Shaft furnaces** | Coke/charcoal | Liquid | Mini-BF, Oxycup |
| | Coal | Liquid | Tecnored |
| **Smelter + .....** | | | |
| • Shaft furnace | Coal | Liquid | Corex, AISI Direct Steelmaking |
| • Fluidised bed | Coal | Liquid | Finex, DIOS, HIsmelt |
| • Cyclone | Coal | Liquid | CCF, HIsarna |
| • Smelter only | Coal | Liquid | Romelt, Ausiron |

Smelting Reduction



of Death" between the research/pilot phase and the first industrial implementation. Many developments stranded when the money or the patience ran out.

The question raised and hopefully answered in this paper is: "Is it worth to continue the development of new ironmaking technologies to replace the blast furnace route and if so, why?"

## 2 Why Smelting Reduction

In 1992 Amit Chatterjee [1] wrote his book "Beyond the blast furnace" on direct reduction and smelting reduction processes. He states the following: The Blast furnace ironmaking has achieved near perfect maturity through intensive developments that have taken place around the globe. But he also mentions some threats for the blast furnace route:

- Very strict raw material requirements.
- High capital requirement.
- Lack of flexibility.
- Strict environmental policies.

He concludes that coke is the biggest threat because of the need for high quality coking coal and because of the environmental issues of cokemaking.

This was written in 1992. Now 20 years later the situation is not dramatically different. But a few developments need to be mentioned.

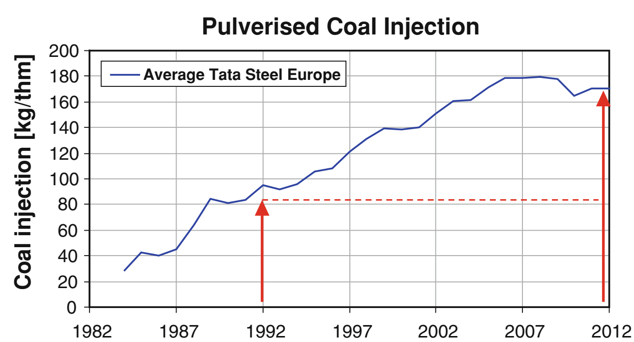



**Fig. 1** Development of the PCI rate in Tata Steel Europe reduced the dependency on coke with 35 %

### 2.1 Coke

In the period 1985–1995 there was a strong interest in smelting reduction in Europe and the USA because of aging coke ovens and environmental problems with coke production.

However at the turn of the century all the developments were stopped because of two major changes, coke became available from China at very attractive prices and pulverised coal injection in the blast furnace had been successfully introduced (van der Stel [2]). This strongly reduced the dependency on the aging coke ovens. Although there is still a cost benefit in replacing coking coal with thermal coal this is no longer the main driver for smelting reduction development (Fig. 1).

### 2.2 Climate Change and Sustainability

When there was a call from society for more sustainable products and processes, the steel industry took its responsibility and all over the world projects were initiated to investigate $CO_2$ lean production methods.

These projects quickly focussed on the ironmaking process being by far the most $CO_2$ intensive step in the production chain. The drive for sustainability caused a renewed interest in smelting reduction.

### 2.3 Iron Ores

In the last decade a period of almost 30 years came to an end in which high quality iron ores were available in large volumes and at low prices. Since the 1970s seaborne trade of iron ore grew steadily and rapidly. This trade supplies to mainly Asia and Europe; to customers in countries practically without iron ore sources—Korea and Japan—or customers in countries with a substantial shortfall in the European Union and China. (Gray [3]).

Availability of high quality ore in large volumes at low prices had a number of effects on the steel industry.

- In Western Europe Steelmakers that were (partly) self sufficient mostly abandoned their indigenous ores because the mining couldn't compete with the superior quality imports at low costs.
- No new process developments to utilise other iron ores than premium quality were initiated because it could not be economically justified.
- Blast furnace ironmaking thrived based on the constant high quality ore imports, reaching unprecedented levels of productivity and consistent high product quality. This further strengthened the previous statement.

In the last decade this situation drastically changed. Due to the rapid growth of the steel industry in Asia the demand for iron ore strongly increased and so did the price.

A process capable of using iron ores outside the standard quality range, that appeared uninteresting 10 years ago, would be a highly sought after asset today.

## 3 Status

### 3.1 Corex

The Corex process is the most successful smelting reduction development. Several industrial Corex plants are operational today, the largest with a capacity of 1.5 M thm/y. Furthermore the process is the basis for the Finex development.

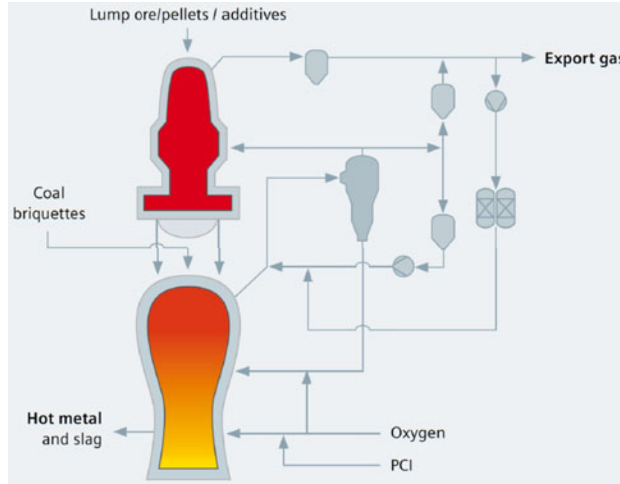



**Fig. 2** Corex process [4]

The process combines pre-reduction of ore in a shaft furnace, to a level of about 80 %, with final reduction and melting in a melter/gasifier.

The reduction shaft requires lumpy or agglomerated iron ores. The fuel rate is high and so is the amount of export energy in the form of combust able gas (Fig. 2).

The process is not completely independent of coking coals. The exact coke requirement is unclear. Agrawal [5] reported that it may range from 50 to 200 kg/thm. However, the coke addition improves the productivity (Carpenter [6]).

Another draw back of the Corex process is that it depends on efficient usage of the large amount of export gas for its economical viability.

### 3.2 Finex

In the Finex process the reduction shaft of the Corex is replaced by a series of fluidised beds. This enables the Finex process to use fine ores instead of lump ore or pellets.

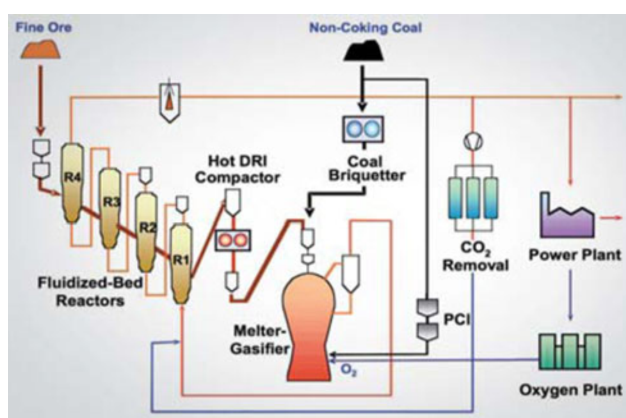



**Fig. 3** Finex process [7]

As a result the process requires neither coke making nor ore agglomeration (Fig. 3).

Briquetting of the pre-reduced ore and the coal, pulverized coal injection and controlled charging of the melter/gasifier have improved the fuel rate of the process compared to the original Corex process. The process includes a $CO_2$ scrubber. The isolated $CO_2$ can be stored geologically if such a storage is available. With geological storage a $CO_2$ emission reduction of 45 % is achieved .

Posco has operated a 1.5 Mt/y plant for several years and has recently ordered the engineering and supply of proprietary equipment for a 2.0 Mt/y plant to be constructed at Pohang.

### 3.3 Tecnored

The Tecnored process is developed in Brazil. The process uses self reducing briquettes from iron ore and fine coal. These briquettes are cold bonded. Iron ore reduction in the self reducing briquettes is very fast. As a result Tecnored can limit the height of its reduction shaft and thus limits the mechanical load on the cold bonded briquettes.

The process doesn't require coking coals. But there are certain quality requirements for the coal. The process prefers lumpy anthracitic coals. The process operates with hot blast of 850 °C generated in metallic heaters.

The furnace shape is rectangular with a fixed width and length depending on the capacity. When scaling up only the length of the furnace is increased in size while the height and width remain fixed. This furnace concept practically eliminates the risk of scale up.

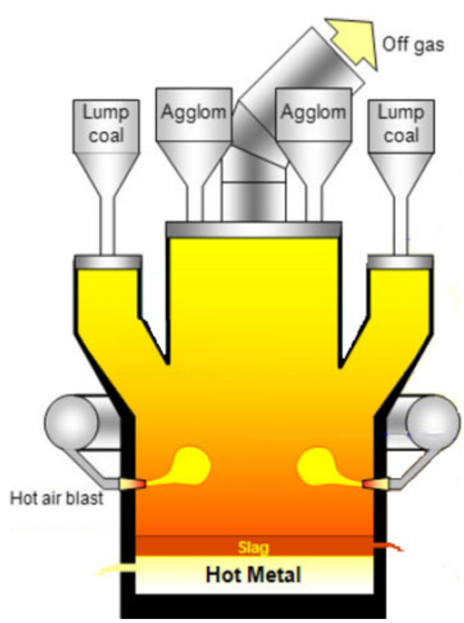



**Fig. 4** Tecnored process [8]

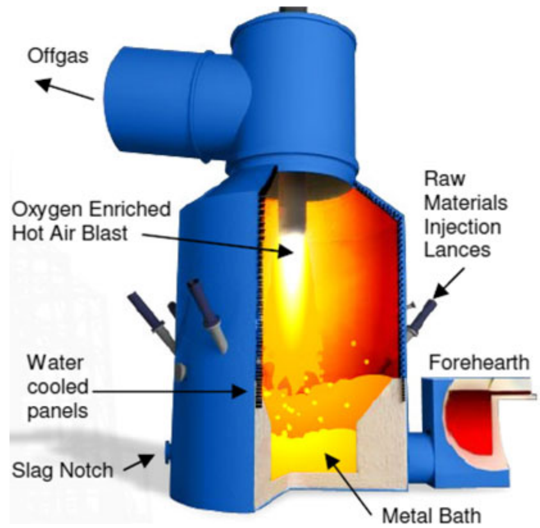



**Fig. 5** HIsmelt process [9]

In 2005 construction of a demonstration plant, with a production capacity of 10 t/h, started in Pindamonhangaba in the State of Sao Paulo in Brazil.

After a considerable delay, the first start up of the plant was carried out in 2010. Up to now the results are not published (Fig. 4).

### 3.4 HIsmelt

The HIsmelt process combines pre-reduction and preheating of fine ore in a fluidised bed with final reduction in a smelter. The smelter operates with enriched hot blast, generated in blast furnace type stoves (Fig. 5).

A unique feature of the process is the submerged injection of coal and pre-reduced ore using the so called solid injection lances (SIL).

Submerged solids injection creates a highly stirred slag phase and even throws large amounts of slag into the top space, the so called slag fountain. This promotes the transfer of heat from the post combustion zone to the bath. With respect to heat transfer efficiency the process is superior to other smelter processes. The process achieves a high post combustion ratio (PCR).

$$PCR = \frac{CO_2 + H_2O}{CO + H_2 + CO_2 + H_2O}$$

The PCR is typically 50–60 %. A drawback of the high PCR is that the pre-reduction of ore in the fluidised bed system is only to magnetite (max. 11 %).

With 4 to 5 % FeO in the slag the conditions in the HIsmelt vessel are more oxidising than in the hearth of a blast furnace. This allows the HIsmelt process to use ores with a higher P content without increasing the P in the metal. The higher FeO content also suppresses Ti reduction allowing the use of high Ti ores without running into slag viscosity problems.

## 4 HIsarna

The HIsarna process is a development of the ULCOS (Ultra Low $CO_2$ Steelmaking) project in cooperation with HIsmelt.

The ULCOS program was launched in 2004 on initiative of the major players in the European Steel Industry. The objective of ULCOS is to find innovative and breakthrough solutions for reducing the specific $CO_2$ emissions of steel by at least 50 %, by the year 2050. For integrated production sites, the Blast Furnace ironmaking route accounts for 80 % of the $CO_2$ emissions. Therefore, ULCOS is focused on ironmaking technologies.

Up till 2006, many different technologies have been evaluated, after which the four most promising ones were selected for further evaluation and testing. These four technologies are:

1. Top gas recycling blast furnace.
2. HIsarna (smelting reduction).
3. Ulcored (DR technology).
4. Ulcowin (electrolysis).

The ULCOS consortium approached HIsmelt with the objective to cooperate in the further development of the HIsarna process. An agreement was reached and as a result the HIsarna process is based on a modified version of the HIsmelt smelter technology.

### 4.1 HIsarna Process

The HIsarna process can use fine ores and fine coals directly with drying and grinding as the only pre-processing requirements. This means that neither coking nor iron ore agglomeration processes are needed.

The HIsarna process combines the HIsmelt bath smelting technology with ore smelting and pre-reduction in a cyclone. This cyclone technology originates from an earlier development, the Cyclone Converter Furnace (CCF), a development from, at that time, British Steel, Hoogovens and Ilva.

### 4.2 Smelt Cyclone

In contrast to other pre-treatments steps, such as a reduction shaft or fluidized bed, the cyclone is directly connected to the smelter and the smelter gases are neither cooled nor cleaned before they enter the cyclone. It is the only pre-reduction technology that allows integration of both stages into a single reactor vessel (Fig. 6).

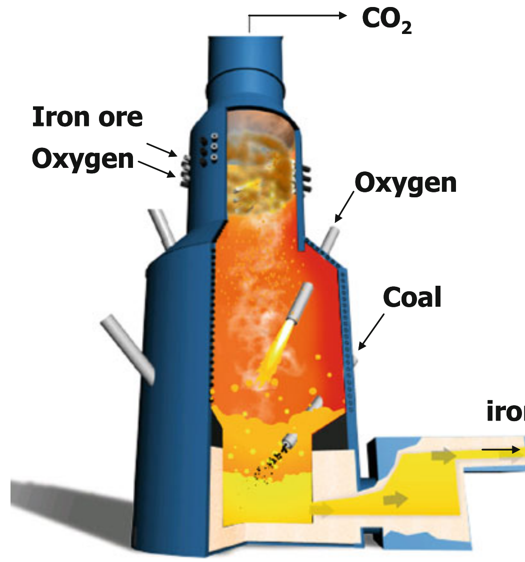



**Fig. 6** HIsarna process [10]

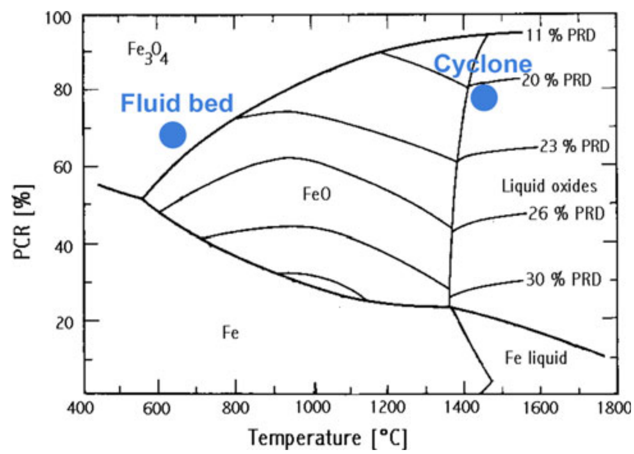



**Fig. 7** Pre-reduction of iron ore for different temperatures and $CO_2$/($CO + CO_2$) [%]

The chemical, as well as the thermal energy of the smelter gas is utilised in the cyclone.

Typical pre-reduction degrees are 20–25 % even at the high PCR of the smelter gas. This is due to the different equilibrium at the very high temperatures in the cyclone compared to a fluid bed or shaft furnace at more moderate temperatures. These reactors can not operate at higher temperatures because of the risk of sticking and softening. Figure 7 illustrates the difference in ore pre-reduction.

Oxygen is injected in the cyclone for the generation of additional heat required for the pre-reduction and the melting of the ore. The cyclone is designed to fully combust the smelter off-gases.

The molten, pre-reduced iron ore is transported by gravity as liquid droplets that fall directly into the smelter. There is no need for intermediate product handling or transport.

### 4.3 Smelter Technology

The final reduction and coal gasification stage of the HIsarna process is basically the HIsmelt process with some modifications. In order to make the combination with the cyclone possible the process is operated with pure oxygen instead of enriched hot blast.

### 4.4 Pilot Plant

Although the two parts of the HIsarna process have both been experimentally tested before, the combination of both reactors is new. Furthermore the HIsmelt operation with pure oxygen has also never been tested. Therefore a pilot plant had to be designed and constructed to investigate the new process.

A suitable location was found at the works of Tata Steel Europe at IJmuiden. A former hot metal desulphurization plant had all the required utility connections, a rail connection, and an existing baghouse of suitable capacity.

The design output of the HIsarna pilot plant is 8 t/h of hot metal. The ore injection capacity 15 t/h and the coal injection capacity is 6 t/h. The basic set-up of the pilot plant is shown in Fig. 8.

The Hisarna furnace and the casthouse are the core of the plant. Next to metal and slag tapping the casthouse has facilities for filling the furnace with a liquid charge and for draining the furnace after a trial series.

The hot top gas from the smelt cyclone is transported to an incinerator through a water cooled duct. After incineration the gas is cooled and cleaned. (Not shown in the figure are the gas cooler and the baghouse.)

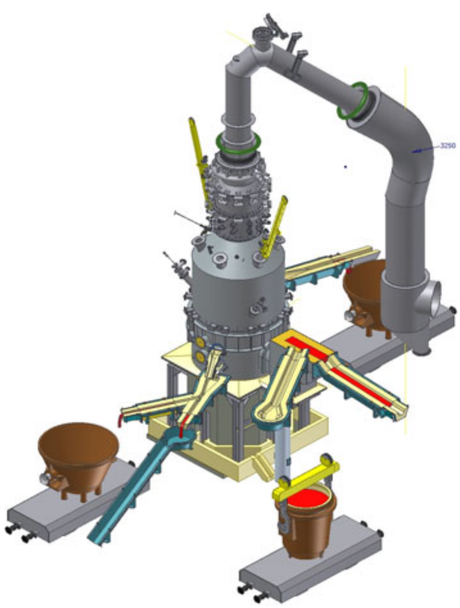


**Fig. 8** HIsarna pilot plant

**Fig. 9** Pilot plant during charging

### 4.5 Experimental Campaign

The construction of the HIsarna pilot plant was completed in April 2011. In May the first experimental campaign started. The campaign had a duration of 2 months. In this period the pilot plant was charged 4 times with 50 tons of hot metal from the blast furnace. Because the building lacked an overhead crane, mobile cranes were used for the charging of the hot metal (Fig. 9).

Once the hot metal is charged there is a time slot of several hours to get the process running. If the process is not operational within this time slot, there is a risk of a "frozen hearth".

This risk was encountered in the first start-up of the campaign. After charging the hot metal the oxygen flow could not be maintained at the required set-point because of a faulty controller. After several attempts to solve the problem the start-up was aborted and the vessel was drained to avoid the risk of solidification of metal inside the smelter.

The next 3 start-ups of the campaign were successfully carried out and on May 20th 2011 the first metal was tapped from the HIsarna pilot plant. It was a major milestone for the technology and for the HIsarna team, which had been working towards this moment for many years.

A number of important targets were met during the first campaign. All systems were hot commissioned in actual operation. 60 % of the injection capacity was achieved, although only for a short period. Parameters such as cooling losses and gas composition were in the right range. However, many more operating hours are required to draw more solid conclusions on the process performance.

After the plant had cooled down, a thorough investigation of the internal condition of the furnace was carried out. The coolers, lances and refractories in the main furnace were in good condition.

A technology like this does not achieve technical viability in one campaign. Two more trial campaigns for the pilot plant have been scheduled. The objective will be to achieve longer stable operating periods. Many improvements will be made to the installation and the operating procedures.

## 5 Conclusions

The blast furnace is still by far the dominant ironmaking technology. The dependency on coke ovens and coking coals is strongly reduced but still present.

Replacement of the blast furnace is unlikely to happen and shouldn't be the measure of success for smelting reduction. Even a niche application of smelting reduction in coexistence with the blast furnace, must be considered a success and can justify a new development.

The environmental challenges, with the exception of the $CO_2$ issue, appear manageable with improved but existing technologies.

The $CO_2$ issue is more complicated and will require substantial development efforts. This has revived the interest in smelting reduction.

For many years the steel industry has benefited from the availability of high quality iron ores for prices just slightly above mining plus transport costs. This period has come to an end in the last decade.

The high costs of high quality iron ore (high quality from the point of view of the blast furnace operator) form a new and compelling reason to investigate ironmaking processes with the capability to operate with lower grade ores.

The blast furnace will also be driven in this direction. The question remains: *Can the blast furnace reduce its dependency on prime iron ore qualities like it did with coking coals or is this the opportunity for smelting reduction?*

The HIsarna process, like the HIsmelt smelter technology it incorporates, is capable of using iron ores with higher levels of P and Ti than allowed in the blast furnace.

Other benefits of the HIsarna process are:

- Reduction of the $CO_2$ emissions per ton with 20 %.
- Reduction of the $CO_2$ emissions per ton with 80 % if the process is combined with CCS.
- Elimination of coke and sinter/pellet plant emissions.
- Use of non-coking coal qualities.
- Use of low cost iron ores, outside the blast furnace quality range.
- Economically attractive even at small unit size (0.8–1.2 M thm/y).

The first experimental campaign with the HIsarna pilot plant has been a major step in the development of this process.

It will require further campaigns at pilot plant scale and most likely one additional scale up step to bring the technology to maturity.

The challenges and development risks are high but so are the expected rewards.

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## References

1. Chatterjee A, *Beyond the Blast Furnace*, CRC Press, Boca Raton (1994).
2. van der Stel J C S, *Three decades of coal injection at Tata Steel Europe, Scanmet*' (2012), p 185.
3. Gray M, in *Building prosperity—The Australian iron ore industry in the 21st century*, (2006).
4. Siemens VAI Metals Technology, SIMETAL Corex Technology, Company Brochure.
5. Agrawal B B, and Mathur A S, *New ironmaking processes and relevance to India*, Steel Authority of India Ltd., Ranchi, India.
6. Carpenter A, *Use of coal in direct ironmaking processes*, (ISBN 92 9029 403 5) (2004).
7. The Finex Innovative Ironmaking process, POSCO, in *The Asia-Pacific Partnership on Clean Development and Climate*, (2008).
8. Noldin J H, Conttrucci M A, Meijer K, and Cox I J, *Tecnored Ironmaking process*, AISTech, Charlotte (2006).
9. Dry R J, Bates C P, and Price D P, in Proc 58th Ironmaking Conference *HIsmelt—the future in direct ironmaking,* (1999).
10. Meijer K, Guenther C, and Dry R J, *HIsarna Pilot Plant Project*, EECR, (2011).
11. FP6 Program Contract NMP2-CT-2004-515690.
12. RFCS Research Project RFSR-CT-2011-00002 HISARNA B and C.