An overview of the new and emergent ironmaking technologies

Despite the remarkable achievements of blast furnace (BF) ironmaking in recent decades in terms of energy use, productivity and environmental performance, new breakthrough developments in BF technology are becoming increasingly difficult and expensive to achieve. This means that new and emergent ironmaking technologies will play an increasingly important role in the future of the steel industry, especially due to increasing limitations in raw material quality and environmental constraints. There are many variants of these new technologies, each with its pros and cons, which indicates that BF ironmaking is likely to maintain its dominance for some time yet.

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Ironmaking is the most labour, energy and investment-intensive step in the steel production chain. Although deemed very efficient (after centuries of empirical and fundamental improvements), today's dominant ironmaking technology, the blast furnace (BF), is under increasing pressure from environmental, technical and economic perspectives[1]. However, there are areas of concern.

In particular:

- **Technical** Dependency on premium quality raw materials for a smooth operation, when raw materials are either exhausted, in very limited supply or geographically not accessible, limited flexibility in terms of production (in difficult times the operation of a BF at low throughput is very challenging, not to say, impossible), use of very complex support systems (gas cleaning, probes, stoves, etc), and 'slow' processes in which detrimental actions may sometimes only be discovered hours later.

- **Economic** Requires high capital investments (CAPEX), has typically high operational costs (OPEX); low margins (typically two-thirds of the steel cost and one-third of its value added), too much high-scale efficiency per module unit (requiring large investments and typically not allowing integration of mini-mills, which, in turn, demand higher quantities of virgin iron).

- **Environmental** It is usually very difficult to gain a permit for construction and operation; there are several undesired by-products; a major amount of make-up water is used, as well as a large area footprint (the latter two are becoming critical, even in developing economies, such as India and Brazil).

These concerns, despite significant attempts to optimise the process in recent years, continue to be the drivers behind a worldwide effort to develop new and more efficient ironmaking technologies. This movement started several decades ago, but has had limited success so far (from an industrial perspective), the exceptions being direct reduction (DR) processes (eg, SL/RN, Midrex and Tenova's HyL) and the oxygen based/coke-free Corex process.

To further complicate matters, a huge amount of money is required on the R&D, promotion and operation of pilot plants of the different new technologies. In fact, an estimated US$10bn has already been spent by different stakeholders in the development of these new technologies.

So why continue if there are more failures than successes? Steel is a multi-billion dollar industry and every success represents huge potential gains for the developers of new technologies. Besides, the steel industry needs further improvements as well as the development of alternatives to answer the demands of modern industry and society.

Numerous published studies by government, industry and independent engineering analysts have consistently concluded that new ironmaking technologies will have to satisfy the following wish list[2, 3]:

- An ability to use iron ore fines directly, without the need to sinter or pelletise. This will solve the environmental issues currently associated with both sinter plants and pellet firing furnaces, especially greenhouse gas emissions.
- Use of coke as a reducing agent to be replaced by the ability to use general grades of coal, waste residues, biomass and other renewable sources of carbon. ▷

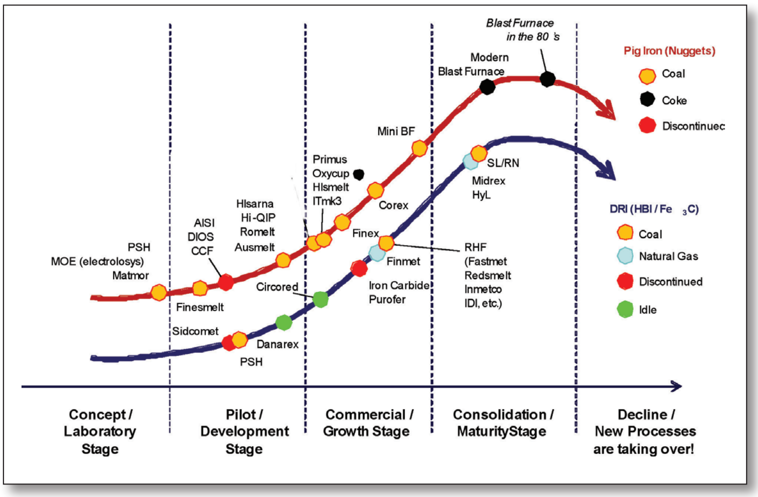


Fig 1 **Maturity of different ironmaking technologies (source: Noldin, adapted from ACARP study)**

	REDUCTANT	
	COAL	NATURAL GAS
Pellets/lump	AISI COREX	
Self-reducing agglomerates	OXICUP ITMK3, Hi-QIP (nuggets)	
Fines	HISMELT, DIOS, ROMELT, AUSIRON FINEX	
Pellets/lump	SL/RN, DRC, ACCAR	HYL MIDREX
Self-reducing agglomerates	FASTMET, MAUMEE IDI, INMETCO, REDSMELT	
Fines	CIRCOFER PRIMUS (*)	CIRCORED, IC (Fe_3C), FINMET

Fig 2 **Example of new ironmaking technologies according to the iron bearing feed and reducing agent**

Environmental concerns related to coke ovens will be answered as a result.

- Find ways to avoid the technical pitfalls and cost penalties inherent in over-mechanised reactors.
- The component process steps should be straightforward and based on proven technology.
- To become more environmentally friendly.
- Carbon consumption rates should be better than or comparable to those of the BF, leading to similar (or lower) carbon dioxide emissions.
- An ability to recycle iron and carbon-bearing wastes generated internally or by third parties.
- To offer minimum scale efficiency and allow implementation in a phased manner.

NEW IRONMAKING TECHNOLOGIES

There are several technologies currently at different stages of maturity, as shown in *Figure 1*[4].

In *Figure 1*, the BF was included in two positions, being close to decline in the early 1980s, before the vast adoption of coal injection (PCI), burden metallisation and top gas recovery turbines, etc. Today, following several improvements, the BF has a long future.

Nevertheless, many industry experts believe that new and emergent ironmaking technologies are likely to update the steel industry in the future, especially in the supply of virgin iron units (primary iron produced from ore) to EAF-based mini-mills and in the process of waste oxides into DRI or hot metal[5]. These new ironmaking technologies can be classified in several ways, depending on the main mechanisms behind the process, type of product, reactor, feed, etc.

As far as the main mechanisms ruling the process are concerned, the following categories can be considered:

- **Bath smelting** The iron oxides, dissolved in the metallic or liquid slag layers, are rapidly reduced, either by the char present in the slag or by the dissolved carbon in the hot metal. Examples are: HIsmelt, HIsarna, Romelt and Ausmelt.

- **Solid state reduction (packed or fluidised beds)** Through the gas-solid reactions taking place inside the reactors, reducing gases (H_2 and CO) promote the reduction of the iron oxides, producing either DRI or hot metal. Examples are: Midrex, Tenova's HyL, Corex and Finex.

- **Self-reduction** The reaction follows a solid-solid model via gaseous intermediates present in the core of the cold bonded self-reducing agglomerates. These agglomerates are chemically sufficient (requiring only heat to be completely reduced) with the constituents in close contact in an inert gases-free environment, resulting in very rapid chemical reactions. Examples are: Oxycup, Hi-QIP, ITmk3 and Fastmet.

As discussed earlier, many categorisations are possible. Another division refers to the type of iron burden and reducing agents used in the process, as shown in *Figure 2*[6].

A short description of the main emergent processes in these categories is given below[6].

Ausiron A variation of the non-ferrous oriented Ausmelt process, it consists of a single-stage process using specially designed submerged lances. The process is based on iron ore fines and coal fines (fuel and reducing agent). The burden material is charged from the top and the iron oxides are dissolved in the slag and reduced by the char present. The energy for the process is supplied by the combustion of coal at the tip of the lance and by the combustion of process CO and coal volatile matter.

DIOS (Direct iron-ore smelting) This discontinued process involves a converter type vessel using a single lance approach to inject oxygen in the interior of the reactor. Although the process can be operated in three configurations, the standard version combines the main vessel with iron ore pre-heating and pre-reduction in a fluidised bed reactor. In the main vessel the reactions take place in the liquid state by the char dissolved in the slag.

AISI The AISI is very similar in concept to the DIOS process (a co-operation agreement existed between the two sides). The fundamental difference is in the use of a DR-based shaft furnace to pre-reduce the pellets before they are charged in the main reduction vessel.

HIsmelt Contrary to most of the bath smelting reduction processes, in HIsmelt, the reduction of the iron oxides and coal gasification takes place in the hot metal bath. The feed materials are charged by lances distributed alongside the reactor instead of at the top. The process uses hot air blast (1,200°C) with oxygen enrichment hot blast (30% O_2) and is based on the direct use of iron ore and coal fines. It operates with a basic slag, rich in FeO, and therefore is able to remove part of the phosphorus dissolved in the hot metal bath. After several problems with the operation of the demonstration plant in Australia the development was interrupted in March 2009.

Corex This is the most developed of the smelting reduction technologies that use coal, and has been in commercial operation since 1989[7]. The process has two stages. First, coal (and occasionally small amounts of coke) are charged in the melter/gasifier where pure oxygen is blown to produce a high temperature/high reducing power top gas. This process gas (95% $CO+H_2$) is then cooled and fed to the reduction reactor to reduce the burden (pellets or lumps) and produce DRI. Melting and residual reduction of the DRI takes place in the melter/gasifier. There are plants in South Africa, India and China, using downstream electrical energy or DRI producing units.

Finex In this process, the reduction stage of the Corex process is replaced by a sequence of fluidised bed reactors. The main advantage compared with Corex is the direct use of iron ore fines instead of pellets/lumps. Following the operation of two pilot plants (15 and 150t/d), a 600kt/y plant was built in South Korea, followed by a 1,500kt/y unit. Construction of a 2,000kt/y plant at Posco's Pohang Works is currently underway[8].

Romelt The process operates a single-stage rectangular furnace at atmospheric pressure. The feed materials are charged from the top and reduction of the iron oxides is by the char dissolved in the slag. Oxygen and oxygen-enriched air are blown in at two different levels by lateral tuyeres to swirl the bath and promote the post-combustion of the gases. The construction of a 200kt/y plant was initiated in Burma, although the project is apparently at a halt.

Circored/Circofer This two-stage fluidised bed (FB) process reduces iron ore fines in a circulating fluidised bed (CFB) up to a metallisation degree of ~70%. This is followed by a bubbling fluidised bed (BFB), where the reduction continues to higher levels (typically 93%). The process operates at low temperatures because of sticking, accretions and re-oxidation problems. The Circored version is natural gas-based while the Circofer is coal-based. A demonstration plant was built in Trinidad & Tobago, although it has been temporarily halted.

Finmet This is a natural gas-based process based on the old FIOR process, but using new fluidised bed concepts. Iron ore fines are reduced in a sequence of four FB reactors, operating at very high pressures (10-12 bar). The DRI produced (92% metallisation) is agglomerated in hot briquetting machines. A 2,200kt/y capacity plant is operating in Venezuela.

Primus This process consists of two stages: a pre-reduction step in a classical multiple hearth furnace to reduce a mixture comprised of fines of iron ore, coal and fluxes with final smelting of the DRI produced in a submerged arc furnace. The final product is hot metal (if the two stages are considered). Material is fed onto the top hearth and cascades down to the discharge in the bottom of the furnace. Transport of the material is by rotating paddles that slowly push the material from one hearth to the next. The energy for the process is supplied by post-combustion of the coal volatiles and upstream CO.

RHF processes Several processes fall into this category such as Redsmelt, Maumee and Fastmet, due to their design similarities. In these processes, self-reducing agglomerates (either pellets or briquettes) are fed into a Rotary Hearth Furnace (RHF) that pre-heats and reduces the burden while the furnace rotates. The energy is supplied by the combustion of process gas and auxiliary fuel promoted by several burners installed in the upper part of the furnace. The height of the layer of material is minimal (a few pellets high) to guarantee that all the ▷

Effect of the gangue content (SiO_2 + Al_2O_3 + CaO + MgO)		
HIsmelt	Medium	• Excess of slag creates disturbances in the process • Chemical characteristic of the slag is important for thermal reasons, therefore, high gangue content will require higher levels of chemical correction.
Finex		• No major problems with primary slag flow • (Al_2O_3) can reach very high levels (~ 18%) • Penalty over the productivity due to higher slag rate.
RHF (includes ITmk3)	Critical	• Solid product, therefore, entrapped gangue may be difficult to remove • High gangue content may difficult the reduction reactions

Table 1 **Effect of gangue content**

Effect of Sulphur content (S)		
Bath-smelting		• Very low S removal due to the thermodynamic conditions • Tends to be higher than other processes due to the above and higher S input (use of high S coal) • Very prone to high SO_x emissions • Sulfur typically split between metal, slag and gas (1/3, 1/3, 1/3)
Finex		• Higher deviation from the equilibrium when compared to a blast-furnace (%S)/[%S] • Tends to be higher than BF hot metal due to higher S input (use of high S coal) • External De-S stations needed (conventional technology) • More prone to high SO_x emissions compared to a blast-furnace (not considering coke-oven and sinter plant)
RHF		• Very critical because S cannot be removed in solid state

Table 2 **Effect of sulphur content**

Effect of Phosphorus content (P)		
Hismelt		• Due to its thermodynamic conditions, roughly 80% of the P input reports to the slag • High (FeO) in the slag (typically 5 to 6%) results in lower metallic yield
Finex		• Due to its reducing atmosphere, all P is reported to the hot metal • Less of problem than RHFs because hot metal in liquid state eases [P] external removal
RHF		• Very critical because P cannot be removed in solid state • P content in the raw material has to be strictly controlled, depending the downstream use of the product

Table 3 **Effect of phosphorus content**

Effect of Zinc and Lead (Zn + Pb)		
Hismelt		• Pilot plant tests reported that Zn/Pb in the raw material left the furnace entrapped in the top dust
Finex		• Due to the operating conditions in the fluidized bed reactors (moderate temperatures and gradual metallization) Zn/Pb accretions may occur and disturb the process.
RHF		• By far the best new ironmaking technology to process high Zn/Pb wastes (several installations worldwide) • High levels of recuperation of these metals

Table 4 **Effect of zinc and lead content**

bed receives a proper amount of energy. The final product is DRI. There are several RHF-based plants in the world, especially for processing waste materials (the process is very effective for EAF dust, for example).

ITmk3 Conceptually similar to the Fastmet process (owned by the same company), the ITmk3 operates at higher temperatures. Therefore, instead of DRI, it produces slag-free iron nuggets due to the melting of the burden in the last zone of the hearth. An industrial plant with a capacity of 500 kt/y was started at Hoyt Lakes, Minnesota, in 2010 and is at ramp-up stage.

Oxycup This process consists of a typical cupola as used in the foundry industry, with a mixture of self-reducing bricks and scrap as burden. The process uses large lumps of coke as fuel (for permeability reasons) and oxygen-enriched air. A 20t/h plant is installed at Thyssen-Krupp Duisburg steelworks.

RAW MATERIAL REQUIREMENTS

One of the main differences promoted by the new ironmaking technologies is the use of lower quality raw materials (low grade ores, Fe and C containing wastes, non-coking coal, etc). Therefore, partially or entirely dismissing use of classical agglomerates (pellets or sinter) and coke, means that raw material costs tend to reduce too, resulting in lower operational costs when compared to the BF route (at least in theory).

Furthermore, if the sinter plant and coke ovens are no longer required, investment costs in new plants tend to be much lower than in a greenfield BF plant. Last, but not least, from an environmental perspective, emissions during the preparation stages virtually disappear, area usage tends to be smaller and lifespan of mineral reserves (iron ore and coal especially) are stretched.

Therefore, contingent on the success of the new ironmaking technologies, this combination of factors may reinvent the steel industry, allowing players with different bottlenecks to revise their strategies in iron production.

The following sections discuss some important characteristics of iron and carbon units for different ironmaking technologies. Other raw materials (binders, fluxes, special agents, etc) are deemed important, but have not been considered in this paper.

IRON UNITS

Tables 1–6 give an overview of the influence of different constituents over some new ironmaking technologies.

CARBON UNITS

HISMELT

- 100% <3mm.

- Use of non-coking coal (some concerns with coking in the tip of the lances in case coking coals are used).
- It is recommended that the coals are dried before use in the smelting vessel.
- Experience with coke breeze (low volatile) and thermal coal (~40% medium volatile), however, the preference is for low to medium volatile coals.
- Direct use of coal fines.
- S content is important, because conditions that are unfavourable for the removal of sulphur result in high S in the hot metal and difficult C solubilisation (wettability of the char is affected). Also, high oxygen potential favours SOx formation.

FINEX
- +20–50mm (coal and coke) and +40–80mm (coal briquettes).
- PCI coal with typical size range (same as in blast furnace).
- Use of non-coking coal in the melter/gasifier.
- 30% of the fuel-rate is PCI.
- Attention must be paid to fines generation in the melter/gasifier (<8mm).
- Coals that produce excess of fines during de-volatilisation due to permeability should be avoided.
- Use of coke (10-20%) to ensure proper permeability (especially in startups and shutdowns).
- Coal briquetting ensures high flexibility as far as size range is concerned.
- Coal briquettes are reported to present higher efficiency, better char bed permeability and higher thermal efficiency.
- High oxygen potential favours SOx formation.
- PCI system allows injection of fines from the de-dusting system, improving environmental performance.

RHF
- Reducing carbon (added in the agglomerate's mixture)
  - 100% <0.15mm (desired) / 100% <1mm (acceptable).
  - Virtually any fine material with over 50% carbon can be used, respecting the existing contaminants (especially ashes and S).
  - Volatile matter is important since it may play a role in the early stages of reduction (upside) but at the same time it can result in higher decrepitation levels (downside).
  - Volatile matter may help protect against re-oxidation of the charge. However, the golden rule is to use high fixed carbon coals.
  - Ash fusion from coal components may create operating problems with the hearth.

	Compression Strength	Decrepitation	RDI	Reducibility
Hismelt	☺	☺	☺	😐
Finex	☺	☺	☺	☹
RHF	☺ (fines) ☹ (agglomerates)	☺ (fines) 😐 (agglomerates)	☺	☺

Table 5 **Overview of metallurgical properties**

	Size range	Comments
Hismelt	100% < 6 mm (acceptable) 100% < 3 mm (desired) 80% < 0,040 mm (tested)	Use of high LOI ores (w/ pre-heating) Use of wastes
Finex	100 % < 8 mm (acceptable) > 5 < 8 mm (desired)	Use of high Al_2O_3 ores Use of high LOI ores Under development for Magnetite ores
RHF	100% < 1 mm (acceptable) 100% < 0.15 mm (desired)	Use of Fe_2O_3 e Fe_3O_4 Use of wastes

Table 6 **Overview of the size range**

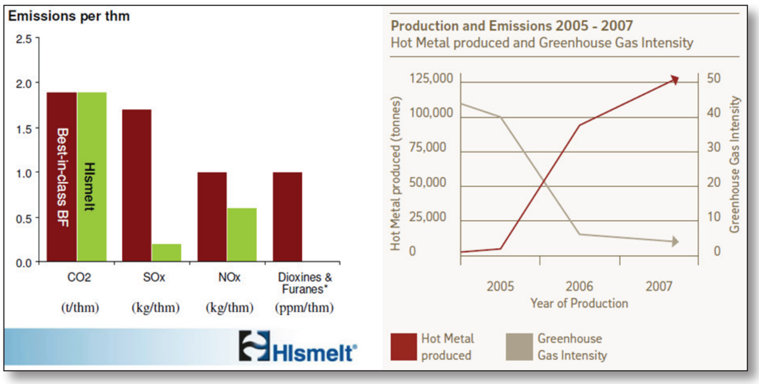


Fig 3 **Emissions from HIsmelt and BF**

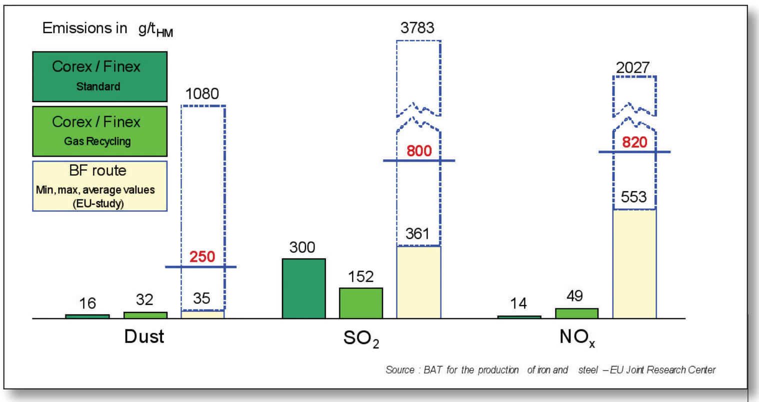
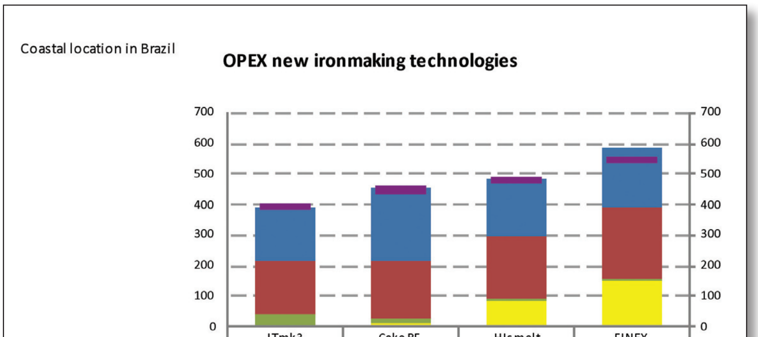


Fig 4 **Emissions from Finex, Corex and BF**



	ITmk3	Coke BF	HIsmelt	FINEX
Iron burden	172	239	191	191
Carbon burden	176	189	200	232
Binders/Fluxes	40	10	10	10
Oxygen	0	15	84	150
Total (after slag/gas credits)	387	441	474	540

Fig 5 **OPEX of ironmaking technologies**

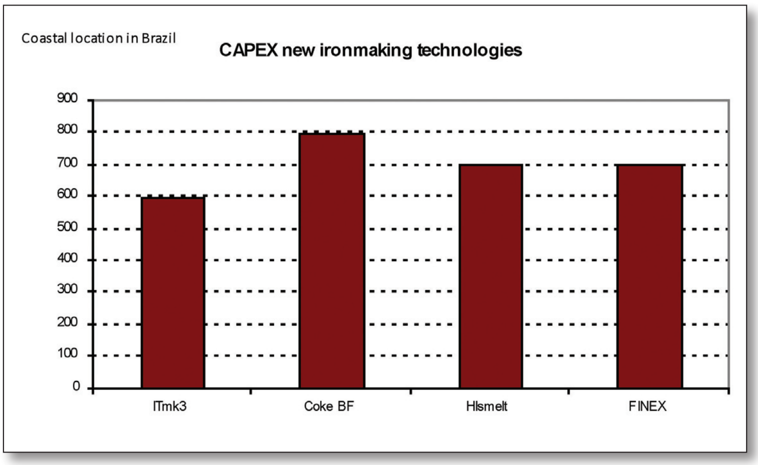


Fig 6 **CAPEX of ironmaking technologies**

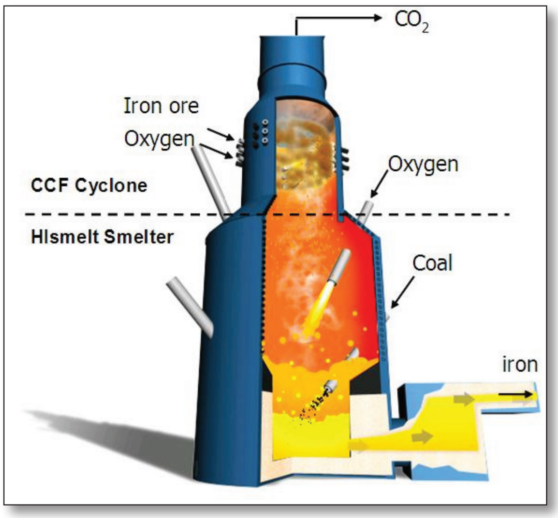


Fig 7 **HIsarna process**

- Process fuel
  - Oil, natural gas, poor calorific gases, among other sources, can be used.

ENVIRONMENTAL PERFORMANCE

Environmental performance of new technologies, with a few exceptions, is based mostly on mathematical exercises rather than trusted references. However, there are a few common points:

- If the sinter plants and coke ovens can be dismissed, the new technologies will produce significantly less gaseous pollutants such as NOx, SOx, VOC, dioxins and furanes.
- Make-up water usage tends to be reduced due to the elimination of process steps and use of more compact reactors.
- They have a smaller footprint – for the reasons above.

As far as specific emissions are concerned, the author preferred to refer to data from the different developers showing the environmentally friendly aspect of some technologies, but stressing that actual plant data are needed for further analysis[4].

ECONOMICS

As with the environmental norms, it is rather difficult to estimate the investment cost of the new ironmaking technologies. Literature data normally reports investment in demonstration plants, but the author does not consider those as good references because a first plant always carries a high amount of revisions, while mistakes are 'normal' in a first project. *Figures 5 and 6* indicate a first OPEX and CAPEX comparison between the main new ironmaking technologies.

FUTURE SCENARIOS

Adoption of new ironmaking technologies by the industry will depend on their actual performance. After initial operation, promoters will pursue operational optimisation, stress the technical possibilities, troubleshoot the systems and seek economic performance. Therefore, no big changes will be introduced in the steel industry over the next 10 years by the adoption of new and emergent ironmaking technologies, despite efforts in different countries.

With regards to likely future scenarios, there may be a growing tendency to combine the best parts of different technologies. There are two very strong examples of this:

- **HIsarna** A combination of the CCF (Cyclone Converter Furnace) and HIsmelt technologies, the development of this process is the responsibility of TATA Steel, within the ULCOS (Ultra-Low CO_2 Steelmaking) framework, a consortium of European steelmakers that has developed a programme to reduce the steel industry's carbon footprint. *Figure 7* shows a schematic of this novel process[9].

- **Circosmelt** A combination of the Circofer pre-reduction step and Ausmelt technologies (see *Figure 8*), this process aims to benefit the smelter (Ausiron) from the pre-reduction stage (Circofer), allowing for larger capacities in the smelter[10].

Another promising opportunity is the development of direct steelmaking, also known as the 'ore-to-steel' processes. This may be the ultimate elimination of process steps between ore mining and steelmaking. Attempts in the past were not successful, but technology keeps evolving and, most importantly, the drivers also change (especially the economic ones), therefore, old efforts may be revisited and new researchers may bring new ideas to the table. The search for better and more efficient processes will never end and, hopefully, evolutionary and – especially – 'revolutionary' technologies will appear on the industry's radar in the future.

CONCLUSIONS

New breakthrough developments in BF technology are becoming increasingly difficult and expensive to achieve, so new processes will be required some time in the future to address specific areas and requirements. Nevertheless, BF ironmaking is likely to maintain its dominance in the upcoming decade since most of the new ironmaking technologies are either at early stages or facing great challenges.

Regardless of the technology and its potential, the development of a new process requires a combination of key success factors such as technical viability, addressing specific market needs, committed partners, financial backing (very often much more than the initial estimates), teamwork, creativeness, patience, prudence and, sometimes the most important, luck. MS

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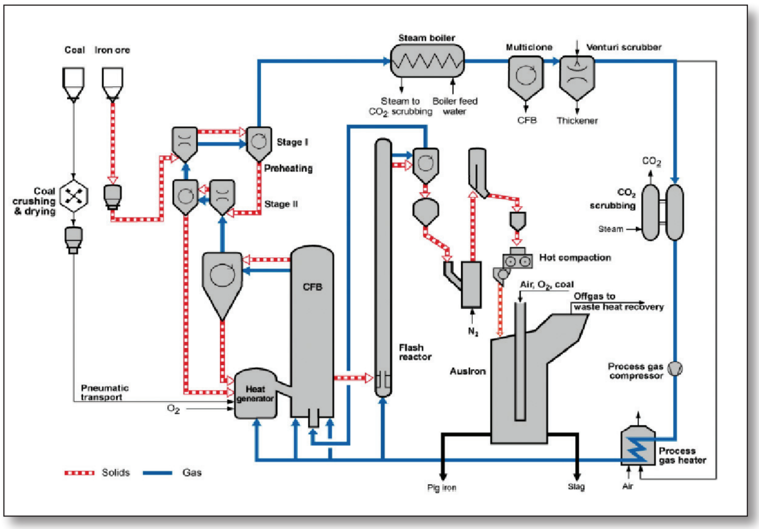

Fig 8 **Circosmelt process**

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