2.0 Ironmaking

Ironmaking involves the separation of iron from iron ore. Ironmaking is not only the first step in steelmaking but also the most capital- and energy-intensive process in the production of steel. There are three basic methods of producing iron: the blast furnace method, direct reduction, and iron smelting.

The blast furnace produced the vast majority of iron in the United States in 2013. Direct-reduction returned to the US with the large Nucor plant St James Parish, Louisiana (HyL plant, 2.5 million tons annual capacity), started up at the end of 2013.

In the next 15 to 20 years there may be a continuing shift away from integrated steelmaking to electric furnace steelmaking, although scrap availability will affect the pace and extent of this shift. The blast furnace will continue to be the major process used to produce iron in the United States, with incremental improvements in terms of fuel rate, fuel source, productivity, and energy efficiency. DRI and smelting technologies may advance.

Gas-based direct reduction will likely grow to include 10 to 15% of the total iron production in the United States. Direct reduction products will be primarily used as a scrap substitute in the EAF, while some forms may be used in the BOF and blast furnace. As indicated by the announced Voestalpine plant at Corpus Christi (2 million tons per annum, operations to start in 2016), direct-reduced iron may become a significant export. This development is directly tied to the availability of low-cost natural gas. Direct smelting processes could also represent a significant portion of production. Recycled iron units such as blast furnace and steelmaking dusts will supply a significant amount of iron, possibly 1 to 2%, through processing via direct reduction or smelting operations.

2.1 Blast Furnace

Currently, the approximately 32 million tons of blast furnace hot metal produced in the United States annually requires about 10 million tons of coke.

Trends and Drivers. It is unlikely that any new blast furnaces will be built in the United States. Iron from scrap, direct reduced iron, and smelter metal will make up the remainder of the required iron units. Coal and natural gas injection will increase, possibly supplying up to 50% of total furnace carbon reductant requirements. Specific productivity in the blast furnace will increase.

The major drivers for technological developments related to the blast furnace are to reduce its reliance on coke and to extend campaign life to reduce capital costs of repairs. These goals will be achieved through increased coal and natural gas injection, and possibly more use of pre-reduced material. The other major concern related to the coke plant/blast furnace method is the high capital cost. However, since few if any will be built, the cost issue must eventually be solved by adapting other processes such as direct smelting.

Technological Challenges. Technical barriers to replacing more coke with injected coal and natural gas are as follow:

- The practical limit and limiting process for coal and natural gas injection are not known precisely, but high rates are possible; the lowest coke rate that has been achieved by coal injection is approximately 260 kg/tonne (520 lbs/ton) at the IJmuiden blast furnace in the Netherlands.

- Since less coke is charged into the furnace, coke might need to be stronger. However, high strength after reaction (CSR) generally implies low coke reactivity; low coke reactivity leads to a higher chemical-reserve temperature and hence lower energy efficiency. Many Japanese operations have been *increasing* coke reactivity; one of the aims of the Japanese Course 50 project is to use additives to obtain both high coke strength and high reactivity. The implication is that it is possible to increase coke reactivity while maintaining adequate strength, and that CSR value does not adequately predict coke performance in blast furnaces. A comprehensive study in the Australian Coal Association Research Program (completed 2008) established reliable relationships between coal blending, coke microstructure, and coke strength. Such a comprehensive study is not available for coals used in North American operations, and would be useful.

- There are limitations for effective uses of process gas because of the structural and physical purposes served by coke.

- Gas turbines for cogeneration of electricity from using blast furnace off-gas have been installed at several plants. Plant-level optimization is required to identify the optimal rates of natural gas (or coal) injection, and optimal oxygen enrichment, if cogeneration is used.

- Shaft injection of reducing gas (using a second row of tuyeres) has been proposed in the context of several blast furnace projects (such as the European ULCOS project, and the Japanese Course 50 project). Detailed flow modeling and study reaction kinetics are required.

New and Emerging Technologies. New and emerging blast furnace technologies include the injection of coal and natural gas to displace coke, improved refractories, and new control technologies. The Japanese have developed a blast furnace model that includes fluid flow and kinetics, and an AISI-sponsored project developed blast furnace flow models, which can be applied to furnaces using high pulverized-coal injection rates, and should be modified for furnaces using high rates of natural-gas injection. AISI is also developing a flash smelting process based on iron ore fines and natural gas as well as the Paired Straight Hearth Furnace which makes high productivity DRI from virgin materials and waste oxides. Both projects are done in cooperation with the Department of Energy and are described later.

2.2 Direct Reduction

For the purposes of this roadmap, direct reduction is defined as a process used to make solid iron products from ore or pellets using natural gas or a coal-based reductant. Table 2-1 summarizes the 2012 production by the main processes. All of these processes have been commercially available for well over a decade. The Midrex and HyL processes produce approximately 75% of direct reduced iron worldwide. Total world production was 74 million tons in 2012; Midrex expects total DRI production to reach 200 million tons per annum between 2025 and 2030. However, these processes use pellets or lump ore, have relatively high capital costs, and require relatively large production units (1 million tons per year) to be economical. Incremental improvements are expected to be made.

Fluid bed, fines based processes are an additional technology, but currently find significant application only as part of the FINEX smelting process.

Rotary Hearth Furnaces and Rotary Kilns offer coal-based options for reduced iron units; given the expected low cost of natural gas, these are not likely to show significant growth in North America in the near future.

***Trends and Drivers*.** There is a pressing need for virgin iron units as North American (N.A.) EAF capacity continues to become a larger share of total N.A. steel production. The lower cost of natural gas (from shale gas developments) will likely spur construction of more gas-based direct-reduction facilities.

Technological Challenges. The gas-based shaft furnace processes are commercially available and further improvements will be incremental. Barriers for fluid-bed processes are primarily related to productivity and equipment, while those for the coal-based processes are related to the undesirable extra gangue and sulfur associated with the coal reductant and the poor physical quality of the reduced iron product. Specific challenges include the following:

- Productivity of fluid-bed processes is not high enough. Better understanding of rate controlling steps and optimization of process variables, including temperature and pressure, are needed. The influence of feed material size consistency on the various processes is not fully defined.

- The products produced by the rotary hearth processes (such as FASTMET, INMETCO and IDI) contain large quantities of gangue and sulfur, which are associated with the coal reductant. The ITmk3 process separates the gangue by melting after reduction. Mesabi Nugget (started up in 2010) is currently the first and only plant of this kind.

- Reduction of composite pellets is inherently strongly endothermic and hence heat-transfer controlled. In rotary-hearth processes, heat transfer control limits productivity, by limiting the bed depth to two or three layers of composite pellets. The Paired Straight Hearth (PSH) process (developed with AISI support) aims to avoid this limitation by operating at a higher freeboard temperature; large-scale demonstration of the process is anticipated.

- The latest version of HyL allows production of direct-reduced iron with up to 5% C, similar to pig iron. The behavior of high-carbon DRI in EAF steelmaking is not known in detail, and the advantages of high-carbon DRI are not clear. Potentially, high-carbon DRI could contribute to low nitrogen levels (in tapped steel) and improved control of slag foaming.

2.3 Paired Straight Hearth Furnace

The Paired Straight Hearth Furnace (PSH) process (US6257879) is an emerging high productivity, direct reduced iron (DRI) technology that may achieve very low fuel rates can operate independently or may be coupled with other melting technologies to produce liquid hot metal that is both similar to blast furnace iron and suitable as a feedstock for basic oxygen and electric furnaces.

The PSH process uses non-metallurgical coal as a reductant to convert iron oxides such as iron ore and steelmaking by-product oxides to direct reduced iron (DRI) pellets. In this process, a multi-layer, nominally 120mm tall bed of composite green balls made from oxide, coal and binder is built up and contained within a translating refractory hearth. The pellet bed absorbs radiant heat energy during exposure to the high temperature interior refractory surfaces of the PSH while generating a strongly reducing gas atmosphere in the bed that yields a highly metalized DRI product.

The PSH will use two linear tunnel hearth furnaces that share a common translating pallet train and which are aligned in parallel and run in opposite directions. Pellets are loaded and unloaded at opposite ends of each furnace and the pallet train moves in a circuit that passes from one furnace to the other in a continuous moving bed process as shown in the figure below (Figure 2-1).

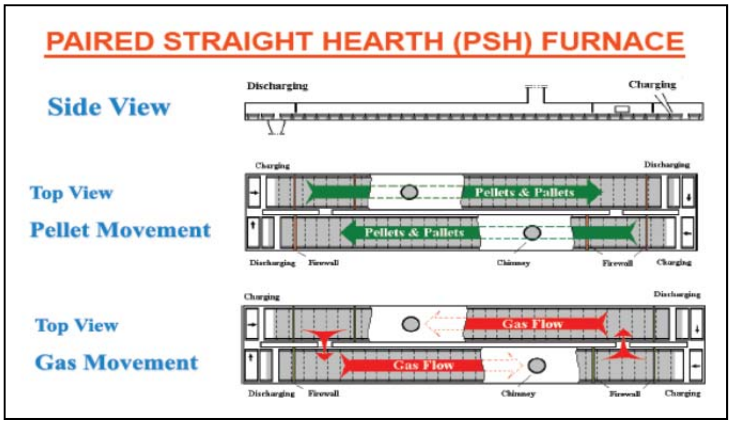

Figure 2-1 – Paired Straight Hearth Moving Bed Process

Table 2-1. Major direct reduction processes

Process	2012 world production (million tons)	Comments
Gas/shaft		
Midrex	44.76	Proven technology
HyL	11.67	Similar to Midrex
Gas/fluid bed	0.53	Only the FINMET process of Orinoco Iron (Venezuela) was operational in 2012
Coal/Rotary Kiln	17.06	Various processes, including SL/RN, Jindal, DRC, Codir, Tisco, SIIL and OSIL.

Source: Midrex Technologies, Inc. 2012 World Direct Reduction Annual Statistics

2.4 Iron Smelting

The objective of iron smelting is to develop processes that produce liquid iron directly from coal and ore fines or concentrate. Liquid iron is preferred to solid iron because there is no gangue and molten iron retains its sensible heat. Coal is the fuel of choice because of its abundance and lower cost. Use of coal directly also would eliminate the need for blast furnace coke, a costly commodity. The ability to use ore fines or concentrate could eliminate agglomeration costs. These new processes should have a high smelting intensity or productivity. High productivity, combined with elimination of cokemaking and ore agglomeration, will significantly reduce the system capital cost.

COREX and FINEX are commercially available, and utilize pre-reduction units (a shaft furnace, and fluidized-bed reactors, respectively) together with a melter-gasifier, producing hot metal that is similar to blast furnace iron. The COREX process does use coal directly, but is still capital-intensive, requiring pellets or lump ore, and some coke, and producing excess energy (off-gas) that must be used for the process to be economical. The FINEX variant of COREX (developed by POSCO) uses fine ore instead. Other processes remain under development. HIsarna is a further development (by Rio Tinto and the European ULCOS program) of Hismelt, using coal and unagglomerated iron ore, a cyclone for preheating, and a smelting reduction vessel; to date, three campaigns have been run on the 8-tonnes-per-hour pilot plant at IJmuiden. Vale has operated a 75,000 ton per annum Tecnored pilot plant (in Brazil) since 2011. The Tecnored process uses self-reducing pellets together with lump reductants; the low height of the furnace allows use of reductants other than coke. Table 2-1 summarizes the characteristics and status of selected direct smelting processes.

2.5 Flash Smelting

The North American steel industry would benefit from the development of a low capital cost process, scalable to large capacities, that can take advantage of the availability of inexpensive iron ore concentrate, and can use fuels that significantly reduce greenhouse gas emissions.

The novel, high-intensity flash ironmaking process is a viable alternative that uses plentiful iron ore concentrates. The process would use inexpensive, abundant natural gas, or hydrogen, to produce hot reducing gas which burns at temperatures above 1300°C. When natural gas is used as the reducing agent, carbon can be added into the molten iron product, lowering its melting point and facilitating direct steelmaking in the same unit to maximize energy savings. Alternatively, the product could also be collected as a solid to be transported to an Electric Arc Furnace for steelmaking. Future system designs could provide up to 5.5% carbon for added benefits such as foamy slags that reduce heat loss, and improved tap-to-tap time.

A major advantage of flash ironmaking over existing ironmaking processes that use shaft or fluidized-bed furnaces is the elimination of sticking and particle fusion at high temperatures. The ability to use ore fines provides an advantage over processes that require ore to be consolidated into pellets for ironmaking. The fine particles also cut the furnace's processing time to seconds. This translates to a smaller system for the same output, potentially reducing both capital costs and operating costs.

Trends and Drivers. The drivers for these new technologies are reduction in capital costs, elimination of cokemaking, reduction in agglomeration requirements, and flexibility in location and economic size. Aside from the already commercial COREX and FINEX processes, the remaining iron smelting processes have only reached the pilot or demonstration stage. Commercialization is still 3 to 10 years away.

Technological Challenges. Before the successful commercialization of any other iron smelting processes can occur, several barriers must be overcome. While limited details have been made public, it can be assumed that extensive pilot-scale testing identified the main operational issues. However, detailed economic analysis is necessary. A Eurofer study (*A steel roadmap for a low carbon Europe 2050*, published 2013) suggests that the capital cost of a steelmaking plant based on smelting reduction would be slightly lower than that of a DRI-EAF plant, with significantly lower operating cost, but the assumptions and uncertainties of these estimates are not stated. Any evaluation of alternative processes needs to include full plant energy and cost evaluation and optimization.

New and Emerging Technologies. Selected processes are listed in Table 2-2.

Table 2-2. Process characteristics and status of some smelting processes

Process	Feed	Status
COREX	Coal, some coke / Pellets and lump ore	Plants operational in Korea, South Africa, India and China
FINEX	Coal / Fine ore	Plant operational in Korea; plant in China (Chongqing) planned
Hismelt / HIsarna	Coal / Fine ore	Pilot tests completed in Australia and the Netherlands
Tecnored	Coal / Self-reducing pellets of fine ore plus reductant	Pilot tests continuing
Flash Smelting	Natural gas/ Fine ore	Pilot tests continuing

2.6 Ironmaking Research and Development Needs and Opportunities

Along with continuing research of the direct smelting technologies listed in Table 2-2, R&D needs have been identified for the blast furnace, direct reduction, and iron smelting as follows:

Blast Furnace

As listed in the text box below, blast furnace R&D needs are primarily based on incremental improvements around current operating practices. One key need for improving this process is the implementation of a comprehensive flow and reaction model of the blast furnace and implementation of low-cost sensors to measure gas composition, temperature and bed permeability.

Another blast furnace need is for improved raw material development. This includes coke and reassessment of coke quality criteria (strength and reactivity).

Process changes such as increased natural gas utilization, pre-reduced feed, and cogeneration of electricity need to be considered in the context of overall plant optimization, with respect to cost, energy efficiency and carbon intensity.

Blast furnace research and development needs and opportunities

- Investigation of factors limiting natural gas and coal injection rates
- Development of furnace flow model to be relevant to high natural gas injection rates
- Alternative ways of utilizing gas, such as shaft injection; detailed flow and reaction kinetic study
- Plant-level optimization with regards to cost, energy efficiency, carbon intensity, and productivity
- Optimization of pre-reduced feed
- Coke alternatives
- Improved coal blending models for by-product and heat-recovery coke ovens
- Fundamental study on coke strength and reactivity requirements, with the aim to operate with more-reactive coke
- Continued decrease in the carbon intensity of blast furnace ironmaking

Direct Reduction

Direct reduction development needs are focused on improving the intensity of carbon-based processes using self-reducing pellets (rate limited by heat transfer), demonstration of the AISI-sponsored Paired Straight Hearth furnace, and quantitatively understanding the effect of DRI quality on process performance (such as carbon input into EAF steelmaking, and the effect of pre-reduced iron on blast furnace productivity, coke rate and carbon intensity).

Direct reduction research and development needs and opportunities

- Increasing the productivity of coal-based processes using self-reducing pellets (heat transfer control)
- Quantifying the benefit of high-carbon DRI in electric furnace steelmaking
- Optimizing use of DRI in blast furnace ironmaking
- Demonstration of the Paired Straight Hearth process
- Plant-level cost, energy and carbon intensity optimization

Iron Smelting

Slag-based reactors, such as HIsarna, inherently require advanced process control, because of the absence of the stabilizing features (the chemical reserve zone, and the coke bed), which are inherent to the blast furnace. Alternative iron smelting processes also need to utilize the off-gas energy, typically within a compact iron smelting unit or pre-reduction unit (unlike the blast furnace, which utilizes sensible heat in the upper shaft and chemical energy in the stoves). The three main processes under development (HIsarna, Tecnored and Flash Smelting) are quite different in this respect. Development and evaluation of these processes should consider how robust the control of the processes is with respect to disturbances such as changes in input materials; detailed process modeling would be required for such evaluation.

Iron smelting research and development needs and opportunities

- Plant-level cost, energy and carbon intensity optimization
- Process modeling and control
- Economic modeling and evaluation
- Continued development of Flash Smelting