Prospects for Hydrogen-based Energy Innovation in the Iron and Steel Industries

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Abstract: The Iron and Steel industry in the United States is one of the major industrial consumers of energy. Hydrogen has been studied as an energy storage and transportation vector from the perspective of a future decarbonized energy economy. In this report, we study the interplay between alternative hydrogen-based steelmaking technologies and a potential scaled-up hydrogen infrastructure.

Introduction

Elemental hydrogen is often considered an "energy vector" as a means to carry energy between the points of generation and points of consumption. In this role, the role of hydrogen is analogous to the role of the nearly ubiquitous energy vector, namely, electricity.[1] Energy in the form of electricity is generated at sources of various kinds, carried over the transmission infrastructure, and delivered to a variety of end users. In contrast, at present hydrogen is primarily produced through a process known as steam-methane reformation, which uses natural gas as the primary energy source, and emits carbon dioxide as a byproduct. However, progress in the use of hydrogen-based energy technology is based on the expectation of increasing production of hydrogen from "clean" processes such as electrolysis of water.[2] End applications of hydrogen include combustion to release heat, or using "fuel cells" that convert hydrogen directly into electricity.

With a view toward a deeply decarbonized energy economy, the US Department of Energy (DOE) has proposed the "H2@Scale" concept which studies the potential for large-scale usage of hydrogen-based energy in various end-use applications.[3] This conceptual framework includes components such as a national hydrogen pipeline delivery system, advances in gas compression technology, standardized delivery infrastructure, and many more. As one estimate of the "Scale" of hydrogen distribution involved in the "H2@Scale" concept, several of these components are viable with a hydrogen consumption of over 1,000 kg (2200 lbs) per day per end-use application. In comparison, the current annual hydrogen production in the United

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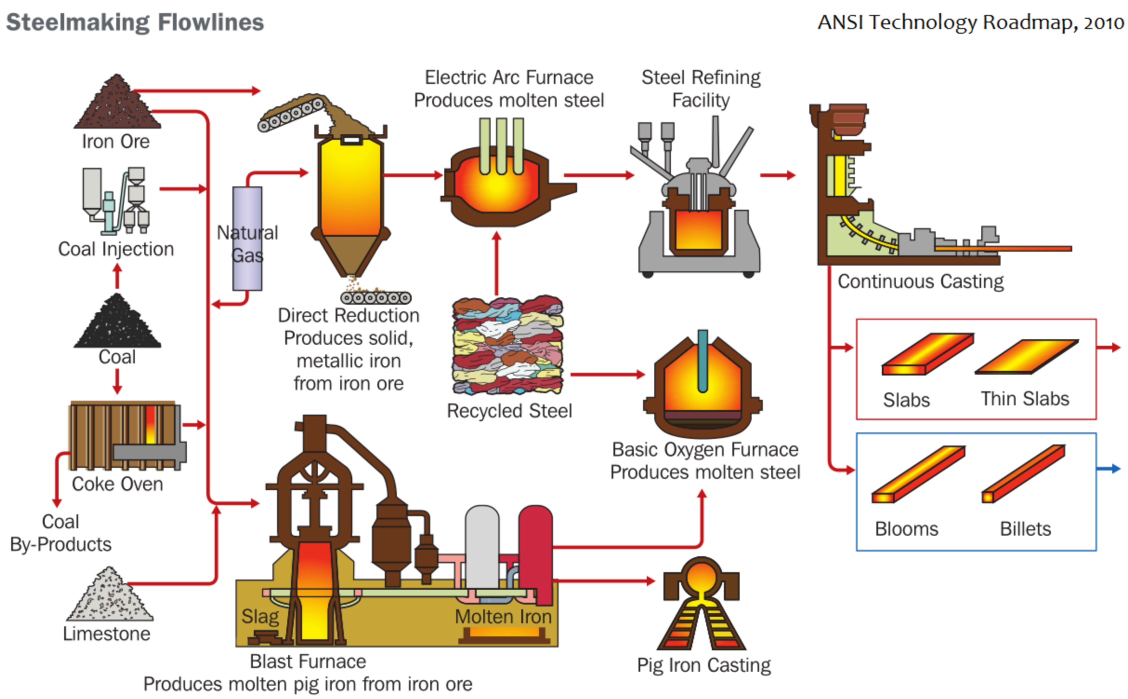
[1] "Questioning hydrogen - ScienceDirect." 9 Jun. 2004, http://www.sciencedirect.com/science/article/pii/S0301421504001193. Accessed 2 May. 2017.

[2] "Technology Roadmap Hydrogen and Fuel Cells - International Energy ...." https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf. Accessed 2 May. 2017.

[3] "H2@Scale Workshop Report. Proceedings from the H2@Scale Workshop Golden, Colorado November 16–17, 2016. NREL." 1 Apr. 2016, http://www.nrel.gov/docs/fy17osti/68244.pdf. Accessed 21 Apr. 2017.

States is approximately 10 million tons.[4] This report assumes the existence of this conceptual framework as a baseline.

Fuel-cell electric vehicles (FCEVs) and grid-scale energy storage are commonly discussed applications of hydrogen-based energy. However, "industries" as a sector of energy consumption account for approximately 32% of all energy consumption in the US,[5] and among major industrial energy usage, the iron and steel industries account for a total usage of 1 quadrillion Btu (1000 trillion Btu), which is approximately 1% of total energy usage in the United States, and approximately 3% of industrial energy usage.[6] In this report, we study the potential impacts of substituting hydrogen as an energy source in the iron and steel industry.



The various energy-consuming processes involved in a steel facility are highlighted in *Figure 1*. In the United States and dominant steel producers such as China, approximately 90% of the steel produced comes from pig iron produced in blast furnaces, although steel production via direct reduction of iron (DRI) is sometimes more common internationally, especially in the

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[4] "DOE Hydrogen and Fuel Cells Program: Program Records."
https://www.hydrogen.energy.gov/program_records.html. Accessed 21 Apr. 2017.
[5] How the United States uses energy
https://www.eia.gov/energyexplained/index.cfm?page=us_energy_use
[6] Preliminary estimates show that U.S. manufacturing energy consumption increased between 2010 and 2014
https://www.eia.gov/consumption/manufacturing/reports/2014/pre_estimates/?src=%E2%80%B9%20Consumption%20%20%20%20%20%20Manufacturing%20Energy%20Consumption%20Survey%20(MECS)-f1

Middle East and Japan.[7] We shall consider two proposals for integrating hydrogen as a fuel source into the aforementioned energy flow which have been explored by the steel industry and DOE: through a greater reliance on DRI, or alternatively, through a new technology based on flash suspension furnaces.

According to the American Iron and Steel Institute, steel facilities in the US range from small-scale units like Carpenter Steel in Latrobe, PA with an annual capacity of 61,000 tons to larger units like ArcelorMittal plant in East Chicago, IN with an annual capacity of 6.1 million tons.[8] For the purpose of this report, we consider the energy requirements of a "typical" steel production plant in the US with an annual steel capacity of 1 million tons.

Incumbent technology: Blast Furnaces

Two main processes currently dominate steel production: (1) Integrated steel mills where iron ore is reduced in blast furnaces and subsequently processed in a primary steel steelmaking plant (BF-BOF) and (2) Mini-mills which rely on melting scrap steel or substitutes in an electric arc furnace (EAF).

Almost 80% of steel is recycled, which *can* be done through electric arc furnaces (EAF) that don't rely on fossil fuel combustion. However, most steel today is still produced from iron ore (approx. 69% worldwide[9]) in blast furnaces (BF), which requires large amounts of coking coal as a reductant. BF are smelting furnaces used to extract iron (in the form of molten pig iron) from iron ore. Thus it fundamentally differs from other methods like direct reduction or flash suspension, which produce solid, pure metallic iron. This ironmaking is the first step in a two-step reduction process, followed by another reduction to produce a final product of steel. This second stage reduction is performed in either a basic oxygen or electric arc furnace, which differs primarily in the amount of scrap/recycled steel used as raw material. It represents the most energy-intensive step in an integrated steelmaking process and also has the highest carbon footprint. Thus many efforts have been made to improve the energy efficiency of blast furnaces, but this is often difficult since it's a highly complex and 100+ year-old process.

Blast furnaces today almost exclusively use coal (in the form of coke) as a reducing agent. The chemical process to convert coal to coke is relatively expensive and consumes large amounts of energy, so research is being done to see if coal can directly be used in the furnace. In addition, coal is also used as the primary fuel (energy input) for the smelting process, while also acting as

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[7] "Steel Statistical Yearbook 2016" World Steel Association. https://www.worldsteel.org/en/dam/jcr:37ad1117-fefc-4df3-b84f-6295478ae460/Steel+Statistical+Yearbook+2016.pdf. The use of EAF (which can only process metallic iron) for steel making implies ironmaking through DRI, while blast furnaces are always followed by basic oxygen furnaces.

[8] "Steel Plants of North America - American Iron and Steel Institute." https://www.steel.org/~/media/Files/AISI/Public%20Policy/Member%20Map/NorthAmerica-Map2013/SteelPlant_NorthAmerica_AISI_version_June252013.pdf. Accessed 20 Apr. 2017.

[9] "Iron and steel CCS tudy (techno-economic integrated steel mills)", International Energy Agency, 2013 http://sacccs.org.za/wp-content/uploads/2013members/2013-04%20Iron%20and%20Steel%20CCS%20Study%20(Techno-Economics%20Integrated%20Steel%20Mill)%20Low%20Res.pdf

a carrier to move bulk material down the column. In total, blast furnaces use around 1000-1400 lbs of coal per ton of hot metal produced[10].

Hydrogen is also a major component (60%) of Coke Oven Gas (COG) burned in the internal energy network of steel mills, with 12.8 Mt (10^6) of H_2 being used for this purpose in the year 2011[11]. These result in a per capita energy use of 19.49 GJ/ton (18.47 million Btu/ton). The extra energy released during the post-combustion of CO to CO_2 can be used to melt more scrap in BOF since scrap requires less than 30% of the energy needed for hot metal. This also raises the productivity in EA, by reducing the electrical energy required for melting by 50-100 kWh per ton of steel[12]. Scientists are also exploring other potential reductants, primarily hydrocarbons such as natural gas, oil, and certain plastics. In addition, there is also the potential to use blast furnaces and coke oven gases for H_2 production in the future[13].

Direct reduction of iron

Direct reduction of iron (DRI) can also be used to produce solid metallic iron. This iron is processed with scrap metal in an Electric Arc Furnace (EAF) to produce molten steel. The iron oxide in either lump, concentrate, or pellet form is reduced at 800-1050 °C (1472-1922 °F) by interaction with reductants (H_2+CO) derived from natural gas or coal. The overall reduction reactions are:[14]

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$
$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

DRI is a rather mature technology. In 2015, 72.57 Mt of direct reduced iron was produced around the world with approximately 25 Mt of new direct reduction capacity under construction.[15] The top DRI-producing nations are India, Iran, Saudi Arabia, Mexico, and Russia, which produced from 5.44 to 17.68 tons of DRI in 2015. In the U.S., the voestalpine Texas MIDREX HBI (Hot-briquetted iron, a compacted form of DRI) plant opened in 2016 and is the world's largest HBI plant.

In 2016, the Department of Energy reported that the U.S. DRI steel industry hydrogen potential is over 64 million tonnes H_2/yr, with the potential benefits in:[16]

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[10] "Economic Impact Analysis of Final Integrated Iron and Steel NESHAP", EPA, 2002 https://www3.epa.gov/ttn/ecas/docs/eia_ip/iron-steel_eia_neshap_final_09-2002.pdf

[11] "Steel and Hydrogen", Birat, Jean-Pierre BIRAT, IEA Hydorgen Raodmap, 2013 https://www.iea.org/media/workshops/2013/hydrogenroadmap/Session1.3BiratETSEPSteelHydrogen.pdf

[12] "Technology roadmap research program for the steel industry", American Iron and Steel Institute https://www.steel.org/~/media/Files/AISI/Making%20Steel/TechReportResearchProgramFINAL.pdf

[13] "An evaluation of hydrogen production from the perspective of using blast furnace gas and coke oven gas as feedstocks" [Source]

[14] MIDREX. Process Brochure.

[15] Midrex. "2015 World Direct Reduction Statistics"

[16] Department of Energy. "H2 at Sale: Enhance the U.S. energy portfolio through sustainable use of domestic resources, improvements in infrastructure, and increase in grid resiliency".November 16, 2016.

- Process intensification
- Reduced capital (replacing capital-intensive coke oven and blast furnace)
- increased energy efficiency
- reduced GHG emissions
- iron ore concentrates processing

Using DRI's basic chemical principle and assuming a 70% conversion efficiency, about 0.077 million tonnes of hydrogen are needed per million ton of iron production. Using the hydrogen price of $1/kg from atmospheric electrolysis, the raw material input cost of hydrogen for a MT iron plant will be approximately $54 million. If natural gas is used to produce the hydrogen needed for such a plant (($Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$), assuming a 70% conversion efficiency, the natural gas cost would be $159 million. It was also reported that the capital cost of a MT iron plant will be $300 - 450 million (inflation-adjusted).[17]

Gas-based DRI is known to be more environmentally friendly than traditional blast furnaces, mainly due to the carbon emissions parity of input fuels: natural gas emits about 50% of the CO_2 per unit of energy as coal does. It was reported that CO_2 emissions for EAF is about ¼ of that for blast furnaces. Whereas pig iron production generates 1.35 tonne CO_2 per tonne iron, DRI only generates 0.70 tonne CO_2.[18]

Flash suspension furnaces

Flash suspension furnaces, also known as flash iron-making technology (FIT) is a new iron-making process under research and development at the University of Utah. The key technical innovation that makes FIT possible is the ability to process finely powdered iron ore down to flakes smaller than 100 microns in size, which gets around the use of energy-intensive processes such as pelletization, sintering, and coke production.[19] Compared with traditional coke-powered blast furnaces, the key advantages of FIT are that it involves lower installation and capital costs and that it can be powered by more diverse sources of fuels, including coal, natural gas, or hydrogen.[20] In comparison with DRI, the end product of FIT as well as traditional blast furnaces, pig iron, is more stable than metallic iron, namely the end product of DRI.

A recent economic feasibility analysis for an FIT-based steelmaking facility was performed by Pinegar et al., which compares establishment and operational costs for FIT facilities that can use either purchased hydrogen, hydrogen produced by reformed natural gas,

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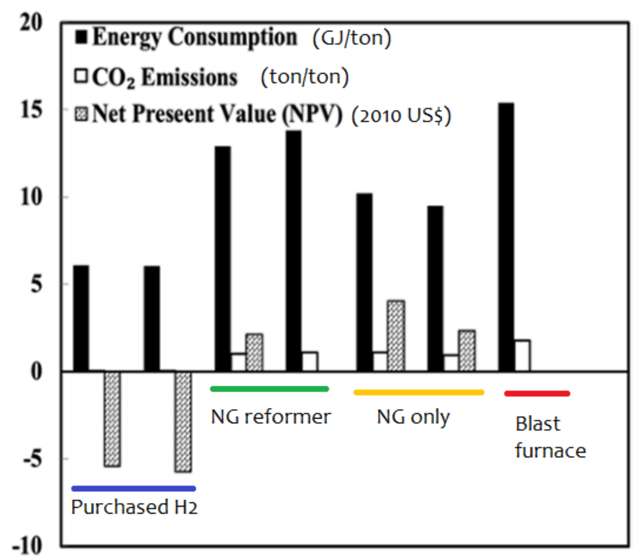
[17] F. Grobler, R.C.A. Minnitt. "The increasing rold of direct reduced iron in global steelmaking", The Journal of the South African Institute of Mining and Metallurgy, 1999.
[18] "2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 3: Industrial Processes and Product Use", 2016.
[19] H Y Sohn, Y Mohassab, "Greenhouse Gas Emissions and Energy Consumption of Ironmaking Processes", Springer, 2016
[20] Pinegar et al., "Flowsheet development, process simulation and economic feasibility analysis for novel suspension ironmaking technology based on natural gas: Part 3 – Economic feasibility analysis" http://www.tandfonline.com/doi/pdf/10.1179/030192312X13345671456897?needAccess=true

“reformerless” natural gas, with a conventional blast furnace facility. (see figure) According to this analysis, FIT facilities have lower total energy consumption and lower net CO_2 emissions than a blast furnace capacity in all cases and have a lower cost of operation in all cases except for the one using purchased hydrogen (at 2010 prices). It has been noted (Sohn et al.) that an FIT facility using purchased hydrogen would be cost-competitive with a blast furnace in the presence of a carbon tax policy that imposes a tax of $50/ton of CO_2 emission (at 2016 prices).



According to the Pinegar et al. analysis, a steel plant with a flash suspension furnace would have a natural gas consumption of 0.4 (ton of natural gas)/(ton of hot metal produced). To provide an equivalent amount of energy via combustion, this would correspond to 0.165 (ton of hydrogen)/(ton of hot metal produced). If we consider our model steel-making facility with an annual capacity of 1 MTon of steel, the total demand for hydrogen from this facility would be 165,000 ton of hydrogen per year. At 2016 prices, this corresponds to the total cost of hydrogen of approximately $165 million per year. To provide context, the total estimated operational cost for this FIT plant is $400 million per year, while the total estimated capital cost of establishment is $500 million (Pinegar et al.).

Projections with Different Hydrogen Costs

The cost of Hydrogen as a feedstock product was close to $1/kg in 2016.[21] Since the price of natural gas has historically been a key variable in determining the market price of hydrogen, this price is subject to variations of up to a factor of 6 more than its current value.[22] However, as discussed previously, an important element of the H2@Scale concept is the increased efficiency

[21] "Current Hydrogen Cost - (DOE) Hydrogen and Fuel Cells Program." https://www.hydrogen.energy.gov/pdfs/htac_oct13_10_bonner.pdf. Accessed 2 May. 2017.
[22] "Natural Gas Prices - Historical Chart | MacroTrends." http://www.macrotrends.net/2478/natural-gas-prices-historical-chart. Accessed 2 May. 2017.

of energy into hydrogen through improvements in techniques such as electrolysis. Some variations of electrolyzers are expected to increase efficiency by up to 40% when operating at scale, which motivates studying the impact of steelmaking technologies at various different hydrogen price points.[23]

To compare the costs of the above technologies, several hydrogen prices are assumed in this section to capture the potential impacts this has on the iron and steel industry. The assumed prices are $0.50, $1.0, $2.0, and $4.0 per kilogram of hydrogen.

Table 1. Comparison of total fuel cost (million $) with different hydrogen costs

Hydrogen Prices ($/kg)	**BF + BOF**	**DRI + EAF****	**Flash Furnace (+ BOF)**
0.50	N/A	38.4 - 159	82
1.00	N/A	76.7-159	165
2.00	N/A	159	330
4.00	N/A	318	660

Conclusions

Although alternative steel manufacturing technologies are more expensive than existing methods given the current state of the energy market and input prices, they offer greater scope for efficiency improvements and climate change mitigation by controlling emissions and reducing the carbon footprint of steel. Moreover, there is the possibility for these to become more cost-competitive in the future due to economies of scale, experiential learning, and policy incentives (e.g. DOE's H_2 @ scale).

Since the Iron & Steel industry used 1060 trillion Btu in 2006 and has contributed to about 7% of global CO_2 emissions (approx. 1.2 $GtCO_2$ /year)[24], there is great potential for this industry to reduce its emissions intensity via various alternative technological improvements. The numerical summary of the three technologies analyzed above is summarized in Table 1. Although the initial capital investments for both DRI and flash furnace technologies are much higher than that of blast furnaces, the cost may decrease due to economies of scale. Moreover, both of these technologies have lower greenhouse gas emissions than blast furnaces. In fact, it

[23] "Current Hydrogen Cost - (DOE) Hydrogen and Fuel Cells Program." https://www.hydrogen.energy.gov/pdfs/htac_oct13_10_bonner.pdf. Accessed 2 May. 2017.
[24] "Iron and steel CCS study (techno-economic integrated steel mills)", International Energy Agency, 2013 http://sacccs.org.za/wp-content/uploads/2013members/2013-04%20Iron%20and%20Steel%20CCS%20Study%20(Techno-Economics%20Integrated%20Steel%20Mill)%20Low%20Res.pdf

was suggested that a tax of $50/ton of CO_2 emissions would make flash furnaces competitive with blast furnaces. In addition, such technologies do away with the need for additional, expensive carbon capture and sequestration facilities onsite at steel plants.

Table 2. Comparison of the cost of the three technologies analyzed at a typical 1 Mt steel plant[25]

<table>
<tr><th></th><th>BF (Ironmaking)</th><th>BOF (Basic Oxygen Furnace for steelmaking)</th><th>DRI + EAF</th><th>Flash Furnace + BOF</th></tr>
<tr><td>Capital Investment (million $)</td><td>211</td><td>100</td><td>225</td><td>500</td></tr>
<tr><td>Raw material inputs (scrap & electricity) (million $/year)</td><td colspan="2">92 million (for BF + BOF combination)</td><td>--</td><td>400</td></tr>
<tr><td>Fuel cost (million $/year)</td><td colspan="2"></td><td>76.7-159*</td><td>165</td></tr>
</table>

*Back-of-the-envelope calculation based on a natural gas price of $3/MMBtu and a 70% conversion efficiency of natural gas to hydrogen.

From the perspective of a future scaled-up hydrogen economy, our analysis shows that individual hydrogen-powered steel plants would account for the demand of several hundred thousand tons of hydrogen, depending on the exact technology and scale. The size of the demand would make steel plants major industrial consumers of hydrogen, comparable to the projected consumption of hydrogen from FCEVs in major state or regional markets. Hydrogen-powered steel plants, like current blast furnace establishments, would also be eligible to sell excess energy by converting it into electricity via a cogeneration mechanism, however, the benefits of cogeneration or CHP are not considered in this report.

The interest in using alternative energy for steel manufacturing extends beyond stakeholders in the steel industry and hydrogen producers. Local and state jurisdictions within the US that have environmental sustainability and energy efficiency objectives, along with the US federal government, may choose to use various policy tools to stimulate the use of hydrogen based steel manufacturing technologies. In addition to the carbon tax policy mentioned earlier, governments may consider legislation such as the proposed California state bill AB 262 (2017), which indirectly incentivizes the use of alternative fuels in manufacturing, by allowing state agencies to consider environmental impacts in procurement decisions. As an example, AB 262,

[25] Technology Brief I02, IEA ETSAP, 2010
https://iea-etsap.org/E-TechDS/PDF/I02-Iron&Steel-GS-AD-gct.pdf

if passed, would allow state and local agencies to prioritize "green steel" for infrastructure projects that would otherwise be using high-carbon footprint, and possibly imported steel.

A more complete analysis of the impact of hydrogen on the iron & steel industry would include additional elements. More technologies in this industry need to be considered to make a fair comparison and to identify the most prominent one, such as Smelting Reduction Iron. The present lack of a viable hydrogen distribution system requires further cost estimations for establishing such infrastructure or a substitute, such as converting natural gas to hydrogen onsite. Moreover, the numbers we present above do not come from a homogeneous source and therefore call for close scrutiny. Also, it may be valuable to study and borrow other countries' iron and steel industry practices, such as building DRI plants. Additionally, different regions may have different resource availability and policy incentives for utilizing hydrogen. Finally, a single industry's success responds directly to overall market signals and other industries' strategies; for example, if hydrogen becomes widely adopted across various markets, the prospect of hydrogen in the iron and steel industry will be more promising.

Further Reading

- Cavaliere, P. (Ed.). (2016). *Ironmaking and Steelmaking Processes: Greenhouse Emissions, Control, and Reduction*. Springer.
- Pivovar, Bryan. *H2@ Scale Workshop Report*. No. NREL/BK-5900-68244. NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)), 2017.

Appendix

Source	Reported Quantity	Value	Units	Plant capacity	Assumptions
EPA - Lankford et al., 1985	Mass of coke required per ton of pig iron produced from **BF**	450-650	kg	1Mt/y	N/A
Grobler, 1999	Capital cost for DRI	300-450	$/t	N/A	N/A
IEA ETSAP, 2010	Investment cost for DRI	142-145	$/t-yr	N/A	Economic lifetime is around 20 years
IEA ETSAP, 2010	O&M cost for DRI	13	$/t-yr	N/A	Not including pellets, fuel (natural gas), and electricity costs.
IEA ETSAP, 2010	Investment cost for EAF	80	$/t-yr	N/A	N/A

IEA ETSAP, 2010	O&M cost for EAF	32	$/t-yr	N/A	Not including steel scrap, lime, O_2 gas, natural gas, and electrical power.

http://ietd.iipnetwork.org/content/blast-furnace-system
http://ietd.iipnetwork.org/content/direct-reduced-iron
http://ietd.iipnetwork.org/content/smelting-reduction