Cost Effectiveness Analysis of HYL and Midrex DRI Technologies for the Iron and Steel-Making Industry

By

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Executive Summary

Climate change and reducing carbon dioxide (CO_2) emissions is an immense challenge for this world. Lowering CO_2 emissions is essential to the goal of limiting the global average temperature increase to below 2°C from pre-industrial levels. Power generation, followed by transportation and industrial sectors are the three largest sources of CO_2 in the United States. The energy-intensive iron and steel industry accounts for the largest industrial contributor of CO_2. This paper focuses on the cost-effectiveness of installing new technology at an existing steel mill that uses blast furnace technology in an effort to reduce direct CO_2 emissions.

The first section of this report describes the steel making process and related carbon dioxide emissions. It reviews the two primary methods in which steel is produced: blast furnace/basic oxygen furnace and the electric arc furnace, and lists the CO_2 emissions per ton of steel from both methods.

The next section discusses two specific production technologies: Midrex and HYL. It relays how they reduce emissions relative to the current standard technology (blast furnace/basic oxygen furnace), and how they differ from one another.

The third section explains the cost analysis methodology used for data analysis. It also explains how the data was collected for the study, and assumptions that were made to complete the analysis. The objective of the report is to determine potential cost savings if Midrex or HYL technology is installed in lieu of the current business as usual (BAU) case of the blast furnace.

The following three sections present the results of the analysis based on three scenarios: business as usual, Midrex, and HYL. Using the cost analysis method, the costs of the blast furnace/basic oxygen furnace, Midrex, and HYL were calculated over a period of 25 years. The costs take into account capital expenses, operations & maintenance, and key energy inputs. Then the costing method was applied to the Midrex and HYL scenarios to determine which had the most cost savings potential over BAU. A sensitivity analysis was also included in each individual section. The results show that not only does the HYL/EAF combination yields the most cost savings over the business as usual scenario, but it also results in the most reduction of CO_2.

The last section discusses the relevance of the results, specifically discussing why HYL technology has not been deployed in the past. Lastly, a recommendation is made to companies looking to install this technology to conduct a more detailed engineering analysis to determine the feasibility for their specific mills.

Contents

Introduction

According to the 2014 Intergovernmental Panel on Climate Change (IPCC) assessment report, carbon dioxide atmospheric concentrations “increased by 40% since pre-industrial times primarily from fossil fuel emissions” (Stocker et al, 2013). Carbon dioxide (CO_2) is the primary greenhouse gas which is emitted through anthropogenic activities. The IPCC report further stated that it is “extremely likely” that global surface temperature increase was caused by the increase in greenhouse gas concentrations. Anthropogenic CO_2 emissions are primarily generated through the combustion of fossil fuels. The main sources are electricity generation, transportation, and industry (EPA, "Carbon Dioxide Emissions", 2015). The energy-intensive iron and steel industry is the largest industrial contributor of CO_2. According to the International Energy Agency, the steel industry accounts for approximately 6.7% of the world’s CO_2 emissions (“Steel’s Contribution to…”, 2014). The U.S. EPA estimated that in 2010, the iron and steel industry accounted for 117 million tons of CO_2 in the United States alone (“Available and Emerging...”, 2012) or 1.6% (EPA, 2016). For every ton of steel produced, the industry emits 1.8 tons of CO_2. It is the primary greenhouse gas emitted by the industry (“Available and Emerging…”, 2012).

Steel is a vital component in today’s world. Its presence can be found all around us in the everyday items we use, such as automobiles and buildings. It accounts for the second largest industry (by revenue) in the world after oil and gas with an estimated global turnover of 900 billion USD (Worldsteel “Facts”, 2016). In 2014, the world steel industry produced over 1.6 billion tons of steel. The United States alone generated 88.2 million tons (World Steel in Figures, 2015).

Because the steel industry releases a substantial amount of CO_2 emissions and faces increased pressure to reduce these emissions, steps are continually taken to reduce the industry’s carbon footprint. This paper will explore the costs of installing new technology at an existing steel mill that can reduce direct CO_2 emissions.

Steel Making Process and CO_2 Emissions

Steel is primarily made by one of two processes: the blast - basic oxygen furnace (BF-BOF), and the electric arc furnace (EAF). The BF-BOF is a two-step process. First, in the blast furnace, mined iron ore is combined with limestone and coke to form molten iron. The purpose of a blast furnace is to chemically reduce and physically convert iron oxides into liquid iron called "hot metal" (Blast Furnace, 2016). Integrated steel mills that utilize this process also have auxiliary operations in the form of coke and sinter/pellet plants. According to the American Iron and Steel Institute, coke is the most important raw material fed into the blast furnace (Valia, 2015). It is used to reduce iron ore to iron. High quality coal is heated in an oxygen-free atmosphere to carbonize the coal resulting in coke. In contrast, sinter and pellet plants help to agglomerate fine iron ore dust in conjunction with other material (typically limestone) to form a product that can be added to the blast furnace.

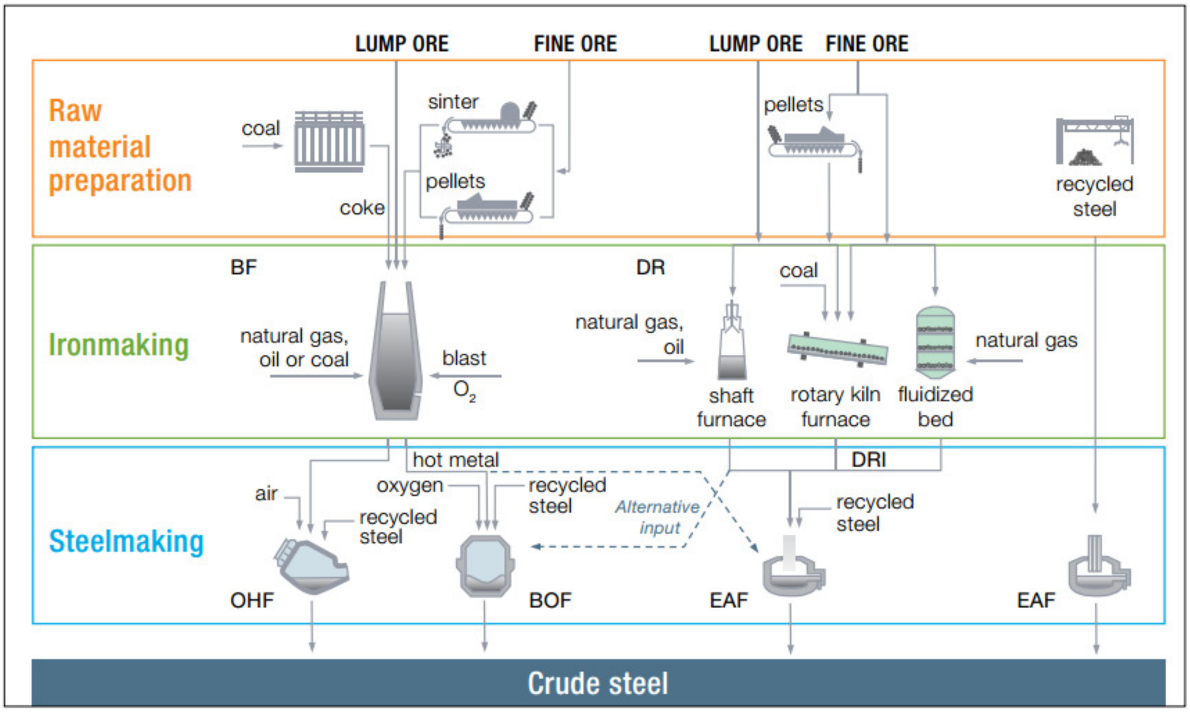
Another alternative to hot molten iron making is the direct reduction method. In this method, iron is reduced in its solid state using either coal or natural gas as a fuel. One advantage of this method is that iron can be added as lumps, pellets, or fines, and if coal is used, it does not need to be coked. Therefore, a sinter/pellet and a coke plant is not needed for this operation. The end product is called direct reduced iron or DRI.

After the hot metal is formed, the basic oxygen furnace then utilizes it as the principal raw material. It is mixed with varied quantities of steel scrap to make different grades of steel. Oxygen is blown into the furnace at high velocities to oxidize carbon and silicon contained in the hot metal releasing tremendous amounts of heat which melt the scrap producing crude steel (Stubbles, 2015). In 2014, 73.9% of crude steel production was through the BF-BOF method (World Steel in Figures, 2015).

The secondary way steel is made is through an electric arc furnace. An electric arc furnace, steel is melted by electric arcs between a cathode and one direct current anode or three alternating anodes (Worrell, 2010). The main charge is recycled steel scrap. Limestone and oxygen are also added to create slag formation and promote metallurgical reactions. Electric arc furnaces offer flexibility to the end user by allowing for hot metal to be used completely or partially in lieu of the scrap metal or vice-versa. The hot metal can be obtained through the blast furnace or DRI, although the direct reduction method is more common.

These diagram below outlines these processes:

Figure 1: Overview of the steel-making



Source: World Steel Association

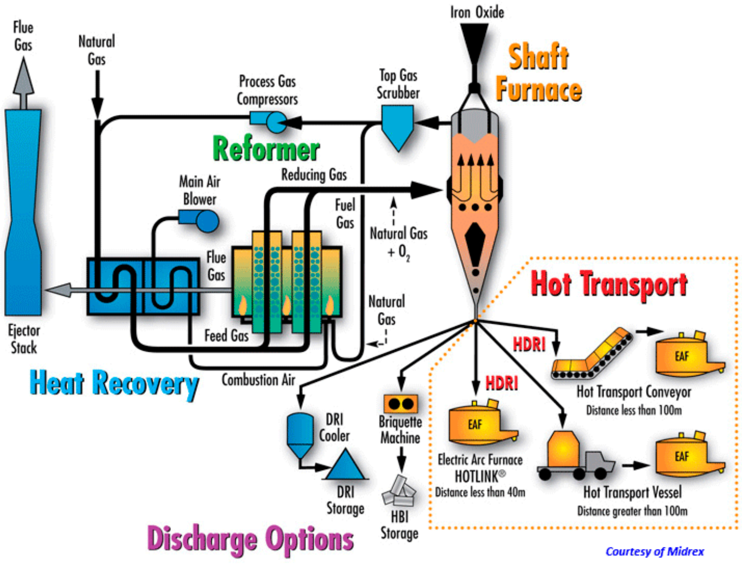
Both processes are very energy intensive through the direct burning of fossil fuels such as coal and natural gas, or indirectly through the use of electricity. Global steel production is heavily dependent upon the use of coal via the BF-BOF process. In 2013, over 70% of total global steel production relied directly upon coal. Over 1.2 billion tons of coal were used in 2014 in global steel production which equated to 15% of the total global coal consumption (World Coal Association, 2015). CO_2 emissions from BF-BOF combinations account for 1.7-1.8 tons of CO2 per ton of crude steel, and 0.4 tons of CO2 are emitted per ton of crude steel for the scrap-based electric arc furnaces (Carpenter, 2012). In the last 50 years, the industry has taken huge strides and reduced its energy consumption per ton by 60% (World Steel Association, 2014). Due to this substantial improvement in energy efficiency, new steps must be taken to maintain the current level of CO_2 emissions or reduce them further.

Alternative Technologies

Midrex

Midrex is a process by which iron ore pellets, lump iron ore or a combination of both is reduced in a vertical shaft/reduction furnace. The reduced material then flows through catalyst tubes where it is chemically converted into a gas containing hydrogen and carbon monoxide. As the iron ore moves down the furnace through gravity flow, the gas rises through the material column and removes oxygen from the iron carriers. This forms the direct reduced iron (DRI) which is typically composed of 90 to 94% iron. After the DRI exits the shaft furnace, it can be cooled and compressed to briquetted iron for safe storage and transportation. The hot metal can also be taken directly to the electric arc furnace for immediate use. This technology eliminates the need for a coking or sintering plant. (Industrial Technology Database, 2012). A process flow diagram of the Midrex technology can be found in Figure 2.

Figure 2: Midrex process

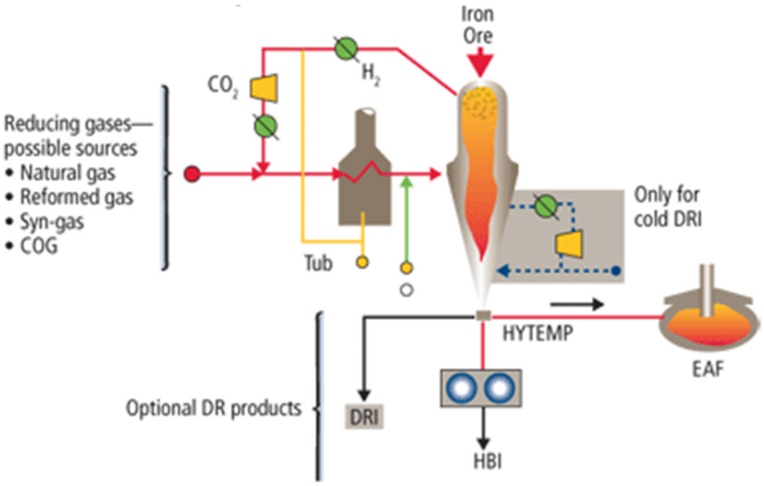


Source: Midrex

HYL

HYL, also known as Energiron, technology efficiently reduces iron ore pellets into highly metallized hot or cold iron. Utilizing high operating pressure, the process uses reducing gases within a moving bed shaft furnace reactor to remove oxygen from iron ore pellets and lump ore. The process is independent of any external gas reforming unit, so it can be designed to use any available reducing gas source including natural gas, reformed natural gas, syngas from coal gasification units, and coke oven gas. For purposes of this analysis, only the HYL natural gas technology is considered. The process can also handle a wide range of iron ores, including high sulfur ores, in both pellet and lump form or combinations of both. (HYL Technologies, 2007). A process flow diagram of the HYL technology can be found in Figure 3.

Figure 3: HYL process



Source: Industrial Efficiency Technology Database

It is important to note that while both these technologies can be used to produce hot metal for the basic oxygen furnace, for the purposes of this report an electric arc furnace will be constructed in lieu of the basic oxygen furnace to produce the crude steel. Electric arc furnaces are more flexible because they can utilize either scrap, hot metal, or a combination of both.

Analysis Objectives

The objectives of this analysis are as follows:

1. Determine costs for each of the three scenarios (BAU, Midrex, HYL), including any capital and raw material/energy inputs, and the associated CO_2 emissions.
2. Calculate the present value of costs of each scenario, and compare the Midrex and HYL costs and emissions to BAU (blast furnace).
3. Provide recommendations to potential stakeholders in the steel industry based on the difference in costs and emissions.

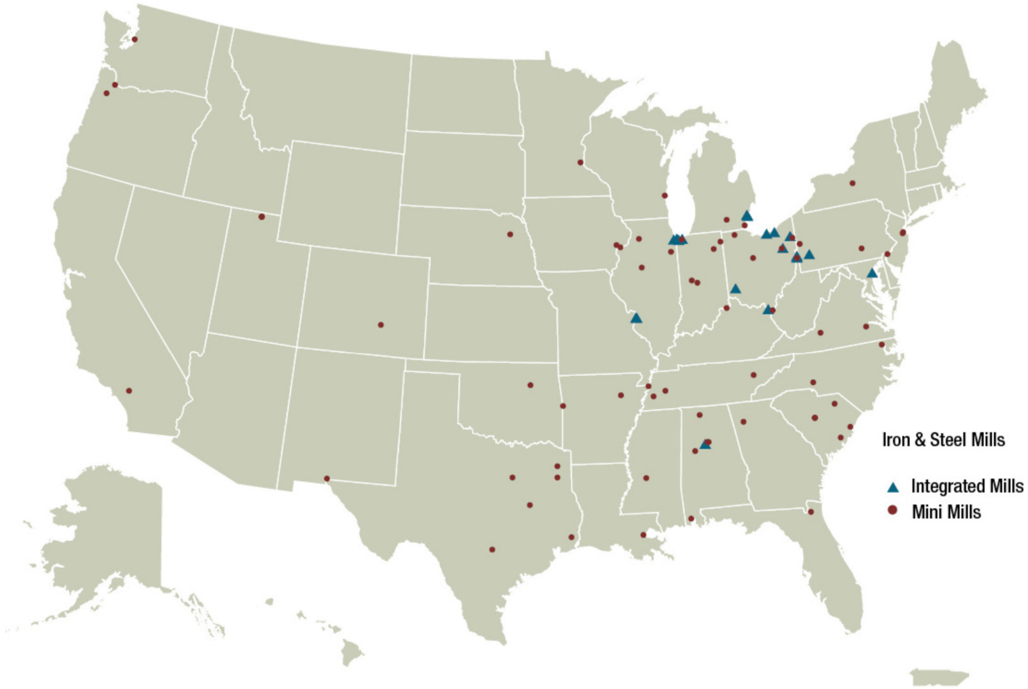
Methodology

The methodology of this study involved two main steps: data collection and cost analysis, including a sensitivity assessment. First, data on the economic costs of these three technologies were determined.

Data on costs and emissions

1. Representative mill (BAU) – The mill was chosen on based on representative integrated steel mill emissions in the northeastern United States. On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases (GHG) from sources that emit 25,000 metric tons or more of CO_2 equivalent per year in the United States (GHG Reporting Program, 2013). Using the EPA's Greenhouse Gas Data Flight Tool, 2014 emissions were extracted for four states in the iron and steel sector: Ohio, Illinois, Indiana, and Pennsylvania. Historically, this area accounts for a large number of steel mills as evidenced in the Figure 4.

Figure 4: Iron and Steel Mills in the United States



Those mills that had reported more than one million tons of CO_2 emissions in 2014 were further evaluated based on raw iron and steel making capabilities. Those mills are represented in Table 1.

Table 1: NE United States Integrated Steel Mills

Representative Mills	State	# of Blast Furnaces	Iron Capacity (Mtpy)	# of Basic Oxygen Furnaces	Raw Steel Capacity (Mtpy)
Arcelor Mittal Burns Harbor	Indiana	2	4,626,642	3	4,535,924
Arcelor Mittal Indiana Harbor	Indiana	5	8,708,974	6	9,117,207
US Steel Gary Works	Indiana	4	6,658,736	6	7,919,723
Arcelor Mittal Cleveland	Ohio	2	2,812,273	2	2,630,836
US Steel Granite City	Illinois	2	2,177,243	2	2,721,554
US Steel Mon Valley Works - Edgar Thomson Plant	Pennsylvania	2	2,086,525	2	2,682,545

Source: Available and Emerging, 2012 and arcelormittal.com

For the purposes of this report, the Arcelor Burns Harbor mill was chosen as the representative sample. This mill represents a true integrated mill because it has a blast furnace, basic oxygen furnace, and both coking & sinter facilities onsite. A literature review was then conducted to determine operating costs per metric ton for a blast furnace, basic oxygen furnace, coking plant, and sinter facility. Those costs were converted to 2015 dollars using the Bureau of Labor Statistic's Inflation calculator. The costs were then multiplied by the capacity of the mill. Potential CO_2 emissions were also estimated for this mill using the capacities and published emission factors. Please see Appendix A for a detailed breakdown of cost per ton, emissions, and literature sources.

2. Midrex and HYL technology – A literature review was conducted to determine operating costs per metric ton. Those costs were then multiplied by the capacity of the representative mill. Since Midrex and HYL are both DRI-based technologies, the capacity of the blast furnace from the integrated mill was used to estimate the costs for ironmaking, and the capacity of the basic oxygen furnaces was used to

estimate the costs for steel making with the electric arc furnace. Please see Appendix A for a detailed breakdown of these costs, associated emissions and data sources.

Cost Analysis

Second, an analysis was carried out to determine the present value of costs over the lifetime of the equipment for each technology:

- Business as Usual – Blast Furnace/Basic Oxygen Furnace
- Midrex in combination with an Electric Arc Furnace
- HYL in combination with an Electric Arc Furnace

A Microsoft Excel spreadsheet was created to estimate costs for each scenario. All key costs including capital, raw materials, and energy inputs were included. Present value (PV) of the costs was calculated by the following formula:

$$PV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$

C_t = costs during the period
r = rate of return (10%)
t = number of periods (25)

Then a net present value (NPV) of cost differences from BAU was calculated for the Midrex and HYL scenarios using the following formula:

NPV(Midrex) = PV(BAU) - PV(Midrex)

NPV(HYL) = PV(BAU) - PV(HYL)

The NPV represents the cost difference from switching from the current business as usual technology to the aforementioned Midrex and HYL technologies. Lastly, a sensitivity analysis was also applied to determine how the NPV varied when any of the inputs were changed.

Cost Parameters and other Assumptions

The present value cost analysis was conducted by assuming a 10% discount rate, and equipment lifetime of 25 years. Operating and maintenance costs, including labor to operate those units, were also considered. Costs of other equipment needed in order to create the final steel product (coil, slab, billet, and/or pipe) were not included. This equipment is independent of the main iron and steelmaking processes which are the focus of this study. Only capital costs, operating and maintenance costs, major raw material inputs, and energy consumption were considered in this analysis. Annual sales were based on the average 2015 national price of hot-rolled coil which comprised the majority of product manufactured by this plant. Construction of the Midrex/HYL – EAF combinations was assumed to have taken 12 months, which did not produce any revenue for the plant during this time period. The loss in revenue was included as an additional cost during the first year. CO_2 emissions resulting from the direct operation of this equipment were calculated. Indirect emissions, such as those from power generation, were not considered.

Results

Scenario 1 – Cost and Emissions Analysis of Business as Usual

The representative mill (Arcelor Mittal – Burns Harbor facility) is capable of producing 4.63 million metric tons of iron and 4.54 million metric tons of raw steel each year. In addition, the facility has a coke making facility and sinter plant with respective capacities of 1.75 metric tons per year and 5,897 metric tons/day (Arcelor Mittal, 2014). The coke facility is used to carbonize the coal, and the sinter plant agglomerates iron ore fines into a product that can be utilized by the blast furnace. It was assumed that the sinter facility operated five days out of the week for a total of 50 weeks per year to produce a total of 1,474,250 metric tons per year.

Since all operational units were in production, the only capital costs that were captured were the costs to re-line the blast furnace. According to the American Iron and Steel institute, the relining is the process of replacing the refractory lining of the blast furnace (Steel Glossary, 2015). This lining is composed of bricks that are exposed to molten metal and wear out over time. Relining a blast furnace can be a very costly effort, and can vary from "$100 up to $300 million" USD (Hunter, 2012). For purposes of this study, it was estimated that the furnaces would need to be relined at year 0 and year 15, and the relining would take approximately three months (Steel Glossary, 2015) and cost $200 million per furnace each time.

It should also be noted that during year 0 and 15, loss of profit from having to shut down operations for relining was also included as an additional cost. This measure was calculated by subtracting the cost of production for three months from the sales revenue for three months. The Arcelor Mittal Burns Harbor mill mainly produces hot-rolled coil. Sales revenue was based on the average North American price of hot rolled coil in 2015 from MEPS International, a leading independent supplier of steel market information (North American Carbon Steel Prices, 2015). Table 2 below shows the breakdown of material, costs, and direct CO_2 emissions in order to make one metric ton of crude steel via the BF-BOF method of steel-making.

Table 2: BF-BOF Costs

	Blast Furnace	Basic Oxygen Furnace	Coke Plant	Sinter Plant	Units	Price (2015 USD)	Total
Costs							
Capital	Cost to reline 2 blast furnaces in year 0 and 15 @ $200 M each						$800,000,000
*O&M**	$16.62/mt						$76,950,600
Inputs							
*Iron Ore (assuming pellet and sinter) **	1.4	--	--	--	mt/mt	$55.21/mt	$357,871,220
*Coke**	800	--	--	--	kg/mt	--	--
*Coal**	--	--	1.6	--	mt/mt	$159.74/mt	$447,272,000
*Limestone**	.3	--	--	--	mt/mt	$99.57/mt	$138,302,730
*Scrap Metal**	--	.12	--	--	mt/mt	$243.84/long ton	$130,718,527
*Oxygen**	--	55	--	--	m^3/mt	$0.07/$m^3$	$17,479,000
*Electricity**	--	23	36	26	kwh/mt	$0.0693/kwh	$14,258,510
*Natural Gas**	--	0.8	2.8	1.4	MMBtu/mt	$2.62/MMBtu	$27,761,389
*O&M**	$16.62/mt						$76,950,600
Total Annual Costs							**$1,210,613,976**
CO2 Emissions	1.5	0.11	0.56	0.2	mt/mt	N/A	8,719,250

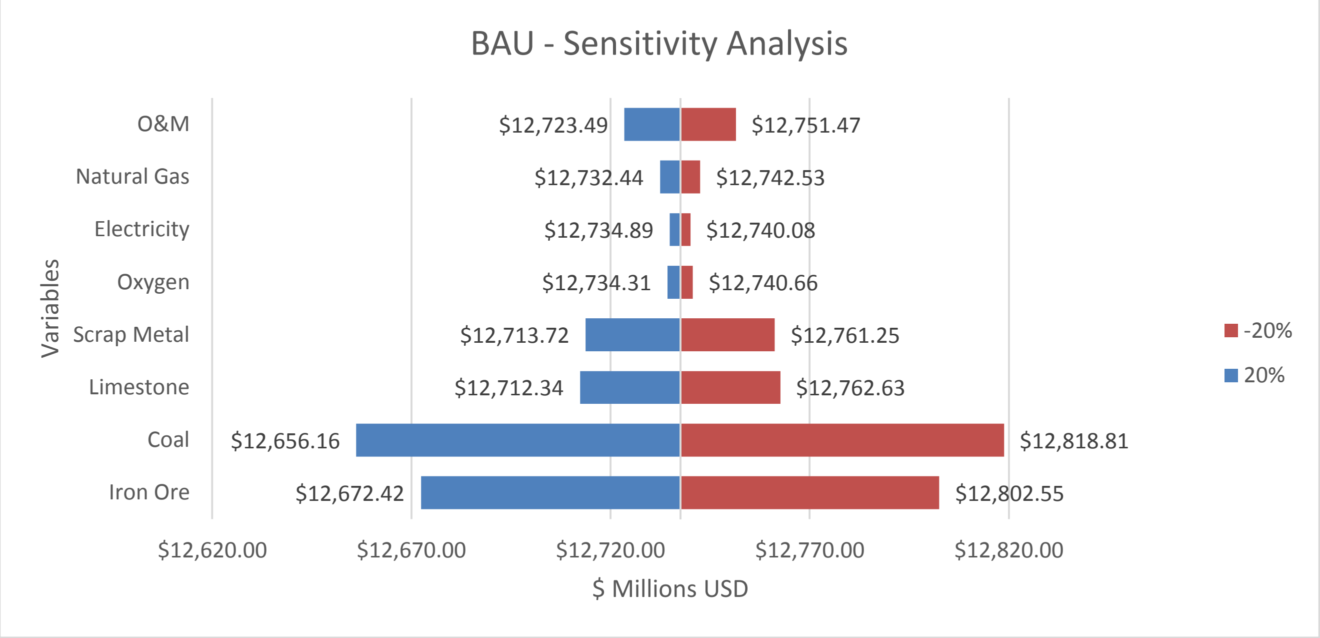
**Total annual costs are only those costs identified with an asterisk.*

Operating & maintenance costs were derived from the International Energy Agency's Energy Technology Systems Analysis Programme for Iron and Steel (Iron and Steel, 2010). According to the World Steel Association, it takes 1.4 metric tons of iron ore, 800 kg of coke, and 300 kg of limestone to make one metric ton of steel. Worrell's Energy Star Guide for the steel industry identifies the remainder of inputs (oxygen, electricity, and natural gas). A complete breakdown of inputs and costs for all three scenarios is available in Appendix A. Based on these inputs, the total annual cost to operate these units is an estimated $1.21 billion dollars. Over the period of 25 years, this yields a present value of costs of $12.74 billion USD. CO_2

emissions were estimated at 8.72 million metric tons, and were based on the production capacity of the mill.

A sensitivity analysis was also conducted where each parameter was varied plus or minus 20%. The results are shown in Figure 5. The business as usual scenario is most sensitive to fluctuations in coal prices followed by iron ore prices. For example, if coal prices increased by 20%, then it was expected that the present value of costs would also increase as evidenced in the figure below. These variances could alter the NPV by millions of dollars.

Figure 5: BAU Sensitivity Analysis



Scenario 2 – Cost and Emissions Analysis of Installation of Midrex technology

This scenario analyzes the installation of Midrex DRI technology in lieu of the blast furnace, and an electric arc furnace in place of the basic oxygen furnace. It was estimated that it would take one year to construct the new units. Therefore, year zero includes a loss of annual profits in addition to the one-time capital cost of $1.43 billion (Iron and Steel, 2010). The loss of profits was calculated in the same manner as for the blast furnace: the annual costs of production were subtracted from annual sales revenue. A cost estimate of demolishing the blast furnace was also included in this scenario. This was based on Tata Steel's demolishing of a blast furnace at their Margram facility in 2013 which cost 550,000 Euros (Walters-UK, 2013). That furnace had a capacity of 2 million metric tons which is comparable to the blast furnaces at the Burns Harbor mill. That cost was then converted to 2015 USD and multiplied to account for two blast furnaces. Midrex technology does not need an on-site coking or sinter facility. Therefore, the costs of those processes enter the calculation as avoided costs (a cost-reducer for Midrex). The costs were calculated by estimating the energy inputs of each plant from the blast furnace scenario above. Table 3 shows the key inputs and costs for the Midrex/EAF route:

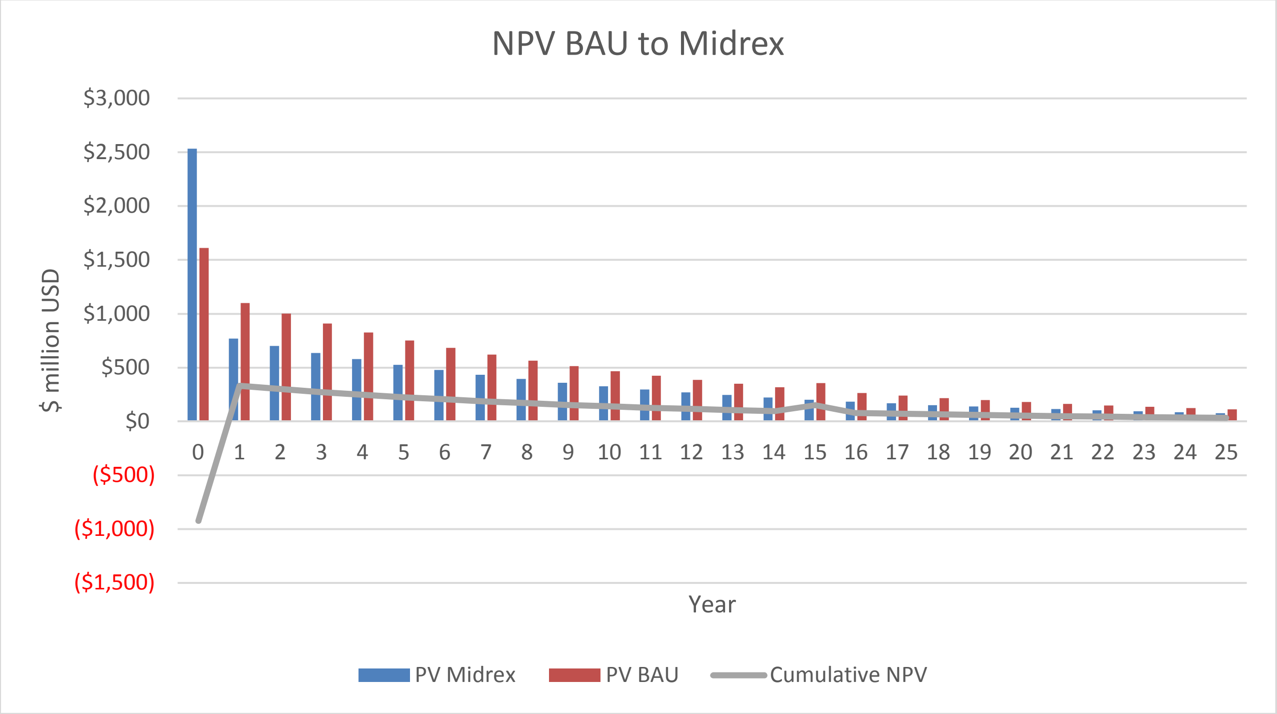
Table 3: Midrex-EAF Costs

	Midrex	Electric Arc Furnace	Units	Price (2015 USD)	Total Costs
Benefits					
No Coke Plant	Derived from BAU				$464,475,900
No Sinter Plant	Derived from BAU				$8,063,853
Costs					
Capital Investment	$199.90	$111.43	$USD/mt		$1,431,429,200
*Iron Ore (assuming pellet and sinter) **	1.7	--	mt/mt	$55.21/mt	$434,557,910
*Limestone**	--	0.064	mt/mt	$99.57/mt	$28,931,059
*Scrap Metal**	--	.264	mt/mt	$243.84/long ton	$287,580,760
*Oxygen**	--	10.43	m^3/mt	\$0.07/m^3	$3,134,654
*Electricity**	135.4	401	kwh/mt	$0.0693/kwh	$169,607,731
*Natural Gas**	9.11	0.4	MMBtu/mt	$2.62/MMBtu	$115,279,817
*O&M**	$12.93	$80.96	$USD/mt		$280,993,600
Demo of Blast Furnace					$1,570,122
Total Annual Costs					$1,321,835,653
CO2 Emissions	0.65	0.08	mt/mt	N/A	3,372,700

**Total annual costs are only those costs identified with an asterisk.*

The remainder of the inputs were gathered from the World Steel Association, International Energy Agency, and the Energy Star Guide for the Iron and Steel Sector. Please refer to Appendix A for a complete breakdown of inputs, costs, and sources. The total annual cost to operate the Midrex/EAF units is an estimated $1.32 billion dollars. It is important to note that the annual costs for year zero are more because they do include capital costs and demolition of the blast furnaces. Over a period of 25 years, this yields a present value cost of $10.23 billion USD. The present value does factor in the annual cost reductions for not operating a coke and sinter plant. The costs of converting from BAU to Midrex are conveyed in Figure 6 below.

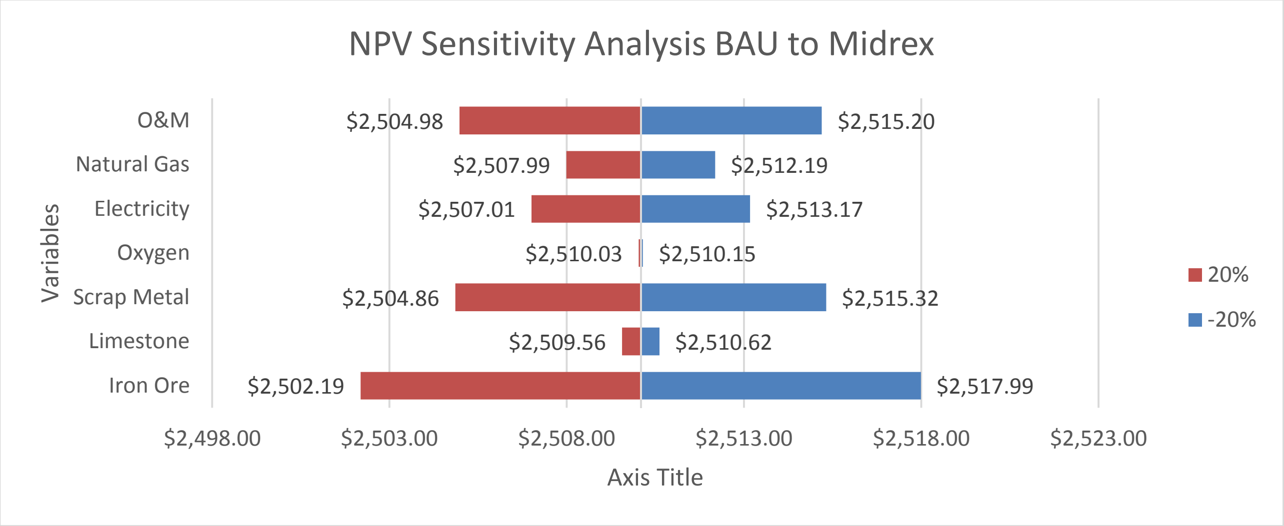
Figure 6: NPV BAU to Midrex



Initially, in year zero, Midrex does have higher capital costs. However, over time the annual costs of Midrex are lower than BAU. The NPV over 25 years is calculated at $2.5 billion USD, which means $2.5 billion USD will be saved over the course of 25 years by switching to Midrex. However, this does not take into account the costs to demolish the coke and sinter facilities. This could possibly make the costs higher, and reduce any cost savings.

Further evaluating this scenario with a sensitivity analysis, the Midrex/EAF is most sensitive to iron ore. In addition, it is also sensitive to fluctuations scrap metal pricing and operations & maintenance costs. If O&M increased by 20%, the total cost savings (NPV) would decrease. Consequently, if O&M decreased by 20%, the total cost savings would increase over BAU. The sensitivity analysis is plotted in Figure 7 below for all key parameters.

Figure 7: NPV Sensitivity Analysis BAU to Midrex



Flexibility is another advantage of Midrex. For example, if iron ore prices increase, more scrap metal can be added and vice-versa. These variations in price can lead to a significant change in the NPV that could vary by millions of dollars. However, even the most drastic change in the NPV, would still yield a cost savings over the BF-BOF scenario.

Direct CO_2 emissions also substantially lower in this scenario at 3.37 million tons, which represents a 61% reduction from BAU. The reduction is attributed to the use of natural gas and electric power as opposed to coal usage.

The discount rate was also analyzed for sensitivity. In Table 4 below, the discount rate was changed from 10% to 5%, and then it was varied from 10% to 15%. The discount rate is the required rate of return to determine the present value of future cash flows. In this study, 10% was chosen as the standard discount rate because the company could have used monies set aside for capital expenditures, and invested them instead in the market. This analysis shows that the higher the discount rate, the smaller the cost savings (NPV). Using an even more conservative, and realistic, discount rate of 5% yields an even higher cost savings because the stream of cost savings in the future has a higher present value.

Table 4: Midrex NPV when discount rate is varied

Discount Rate	5%	10%	15%
NPV (Millions USD)	$4,470	$2,510	$1,494

Scenario 3 – Cost and Emissions Analysis of HYL Installation

This scenario analyzes the installation of the HYL DRI technology in lieu of the blast furnace, and an electric arc furnace in place of the basic oxygen furnace. As with Midrex, HYL technology also does not need an on-site coking or sinter facility. The benefits of not having sinter/coke facilities were obtained from the energy inputs from the blast furnace scenario. Capital costs (Iron and Steel, 2010) were calculated to be an additional $1.41 billion USD. As with the Midrex scenario, year zero accounted for a loss of profits due to one-year downtime for construction and additional cost for the demolition of the blast furnaces. Table 5 contains the key inputs and costs for the HYL-EAF installation:

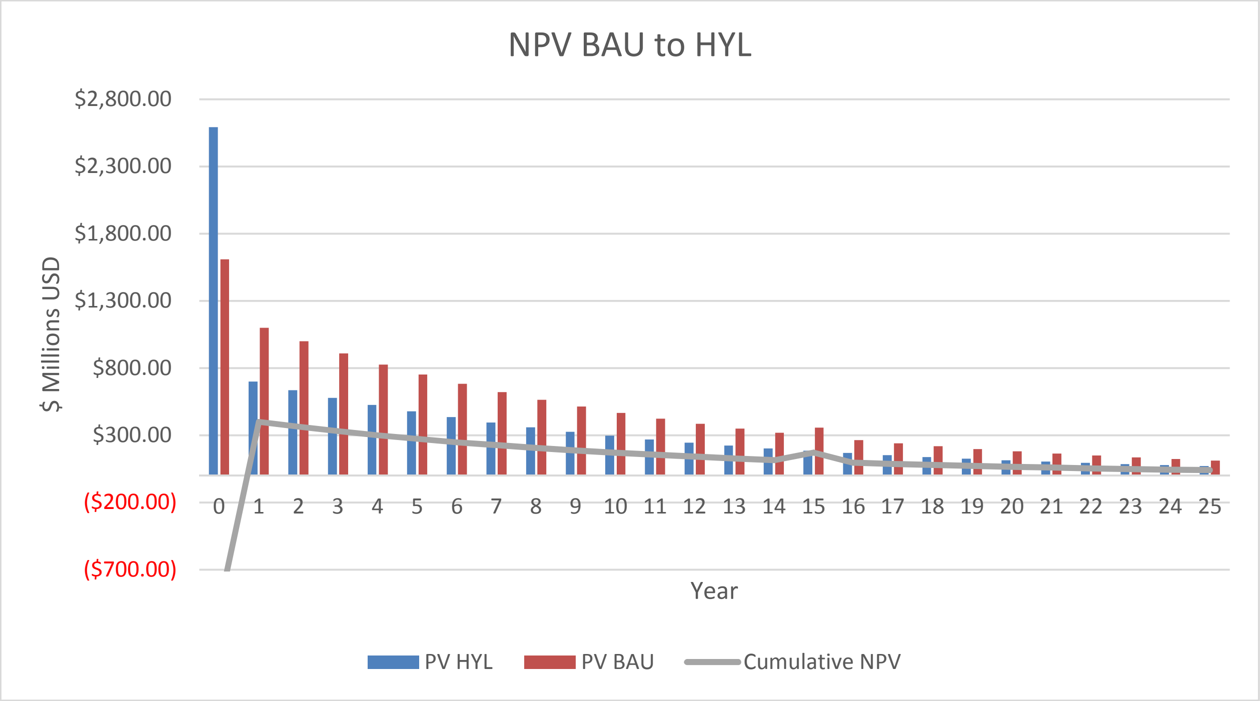
Table 5: HYL-EAF Costs

	HYL	Electric Arc Furnace	Units	Price (2015 USD)	Total Costs
Benefits					
No Coke Plant	Derived from BAU				$464,475,900
No Sinter Plant	Derived from BAU				$8,063,853
Costs					
Capital Investment	$196.33	$111.43	$USD/mt		$1,414,900,100
*Iron Ore (assuming pellet and sinter) **	1.4	--	mt/mt	$55.21/mt	$357,871,220
*Limestone**	--	0.064	mt/mt	$99.57/mt	$28,931,059
*Scrap Metal**	--	.264	mt/mt	$243.84/long ton	$287,580,760
*Oxygen**	--	10.43	m^3/mt	$0.07/m^3	$3,134,654
*Electricity**	104.2	401	kwh/mt	$0.0693/kwh	$159,596,930
*Natural Gas**	9.84	0.4	MMBtu/ mt	$2.62/MMBtu	$124,183,677
*O&M**	$12.93	$80.96	$USD/mt		$280,993,600
Demo of Blast Furnaces					$1,570,122
Total Annual Costs					$1,242,471,901
CO2 Emissions	0.53	0.08	mt/mt	N/A	2,817,100

**Total annual costs are only those costs identified with an asterisk.*

Inputs were obtained from International Energy Agency, HYL website, and the industrial technology database. Based on these inputs, the total annual cost (excluding year zero) to operate these units is an estimated $1.24 billion dollars. The present value of costs over a 25-year period yields $9.58 billion USD. Figure 8 below shows the cost savings of converting to HYL/EAF technology from BAU:

Figure 8: NPV BAU to HYL

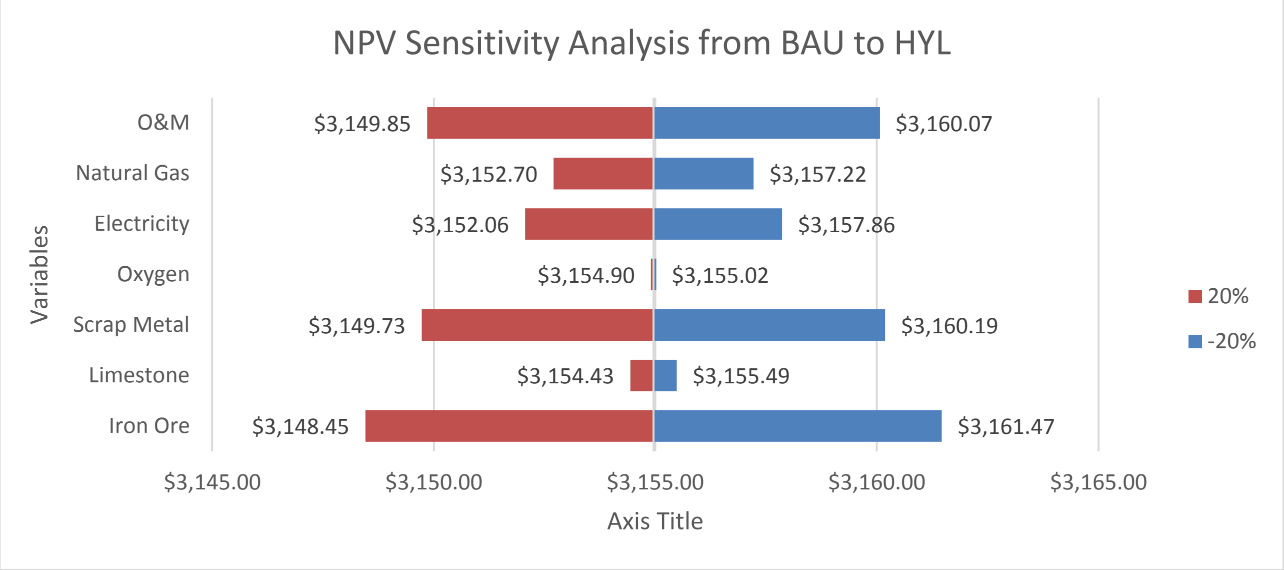


As with Midrex, HYL does have higher capital costs in year zero. However, over time the annual costs of HYL are lower than BAU. The NPV over 25 years is calculated at $3.1 billion USD, which means the end user will save $3.1 billion USD over the course of 25 years by switching to HYL. This is a greater costs savings from the Midrex scenario. Again, this does not take into account the costs to demolish the coke and sinter facilities. This could possibly make the costs higher, and reduce any cost savings.

HYL direct CO_2 emissions were also significantly lower in this scenario at 2.82 million tons, or 68% reduction from BAU. The reduction is also attributed to the use of natural gas and electric power as opposed to coal usage.

HYL-EAF, like the previous scenario, remains most sensitive to variations in iron ore price followed by the price of scrap metal and O&M costs. It operates very similar to the Midrex-EAF option in that it can accept varying amounts of either scrap metal or iron ore. Figure 9 below shows how the NPV changes if any one of the variables fluctuate more or less by 20%.

Figure 9: NPV Sensitivity Analysis BAU to HYL



The discount rate for the HYL scenario was also analyzed for sensitivity. As with the Midrex scenario, the table below also shows that the higher the discount rate, the smaller the cost savings (NPV). The conservative discount rate of 5% yielded the largest cost savings.

Table 6: HYL NPV when discount rate is varied

Discount Rate	**5%**	**10%**	**15%**
NPV (Millions USD)	$5,506	$3,155	$1,936

Discussion and Conclusion

The analysis shows that these alternative technologies not only save costs but also reduce emissions. Table 7 below summarizes all three scenarios. HYL-EAF option yields the highest cost savings, even after analyzing all the parameters for sensitivity.

Table 7: Summary Table

	Option 1 BAU (BF-BOF)	Option 2 Midrex-EAF	Option 3 HYL-EAF
Appraisal period (years)	25	25	25
Capital Costs	\$800,000,000	\$1,431,429,200	\$1,414,900,100
Sum of Undiscounted Costs	\$32,453,869,420	\$23,725,698,246	\$21,842,122,022
Cost-effectiveness analysis of monetary costs at a 10% Discount Rate			
Present Value of Costs	\$12,737,483,872	\$10,227,394,604	\$9,582,523,240
PV Cost difference from BAU	\$0	\$2,510,089,268	\$3,154,960,632
Carbon Dioxide Emissions (mt)	8,719,250	3,372,700	2,817,100
CO_2 Reductions	--	5,346,550 (61%)	5,902,150 (68%)

It is clear that HYL DRI technology not only provides the most cost savings, but it also reduces the most CO_2 emissions. So why has this option not been deployed already? Until recently, DRI technology could not handle the large tonnage that blast furnaces typically output. HYL DRI technology has made many improvements in the last 40 years, specifically in regards to its expanding ability to handle a higher tonnage of material inputs. Voestalpine and Nucor Steel have both recently installed (or will install) DRI technology at their new respective mills in Texas and Louisiana. The DRI technology at the Voestalpine mill will be able to generate 2.2 million metric tons of iron per year (Voestalpine, 2013). This is similar to the size of the blast furnaces at the Burns Harbor Mill.

Another reason why DRI technology was not as prevalent as the blast furnace method was due to the high cost of natural gas. In the past, it was more economical to use coal rather than natural gas. Now thanks to the shale revolution in the United States, natural gas has become a reliable and more cost-efficient option.

DRI technology is primarily utilized in the Middle East/North Africa (44%) followed by Asia (25%) and Latin America (17%). In contrast, the North American market only accounted for 4% of world production in 2014 (World Direct Reduction Statistics, 2015). DRI technology is still relatively new for the United States where there is an abundance of scrap metal. Many manufacturers have chosen to forgo the ironmaking process altogether, and only install electric arc furnaces to meet their steel demand. However, scrap steel prices can be very volatile. Installation of DRI can complement the process by substituting DRI hot metal for scrap metal. In the case of integrated mills, DRI is a more cost-effective choice albeit with very high initial capital costs.

The HYL-EAF route also eliminates approximately 5.9 million tons of direct CO2 emissions. That is a 68% reduction from the current blast furnace-basic oxygen route. The HYL/EAF method does use considerably more electricity than the BF-BOF method, so indirect CO2 emissions created from the generation of power may be higher. HYL can also be modified with a carbon capture system that is capable of reducing emissions another 25 to 30% (IEA, 2013).

For a facility as large as the Arcelor Mittal Burns Harbor location, it would be recommended to use this analysis as a basis for deciding a preliminary budget. Then a full engineering analysis would have to be conducted to ensure this project is indeed financially viable. One barrier to installation would be the very high upfront capital costs of DRI technology. An existing mill not only has to look at installation costs, but also the loss in profit from construction downtime. This can be overcome by installing the technology in phases rather than at one time.

Reductions in CO2 emissions could also prove to be a benefit if the area ever enacts legislation aimed at reducing those levels. The United States has committed to cutting greenhouse gases by 26 to 28% from 2005 levels by 2025 through the Paris Agreement. Reductions in the steel sector will play a part in achieving this goal. Carbon could be priced in the future via a cap and trade program or a carbon tax, and this would provide steel companies with a strong incentive to reduce emissions rather than cost savings alone.

Appendix A

	BF-BOF Method	Coke	Sinter	Electric Arc Furnace	Midrex	HYL	Costs (2015 $)
Iron Ore (assuming pellet and sinter)	1400kg [1]			--	1700kg [4]	1400 kg [7]	$55.21/mt [9]
Coal (as coke)		1600 kg [16]		16kg [1]	--	--	$159.74/mt [10]
Limestone	300kg [1]			64kg [1]	--	--	$99.57/ mt [11]
Scrap	120kg [1]			880kg [1]	--	--	$243.84/long ton [12]
Oxygen	55 NM^3 [2]			10.4 NM^3 [4]	--	--	$0.07/$m^3$ [13]
Electricity	23 kwh [2]	36 kwh [2]	26 kwh [2]	401 kwh [2]	135.4 kwh [4]	104.2 kwh [4]	$0.0693/kwh [14]
Natural Gas	0.8 MMBtu [2]	2.8 MMBtu [2]	1.4 MMBtu [2]	0.4 MMBtu [2]	9.62 GJ [6]	10.4 GJ [8]	$2.62/MMBtu [15]
CO2 Emissions	1.61 mt [2,3]	0.56 mt [5]	0.2 mt [5]	0.08 mt [5]	0.65 mt [4]	0.53 mt [4]	--

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