Primer on
Bringing Mature Technology Pieces Together
for Zero Carbon Dioxide Emissions
Iron Ore Reduction

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Iron ore reduction is the removal of oxygen from iron oxides (the key parts of iron ores) to produce iron. The iron ore reduction done in blast furnaces is more often called iron ore smelting.

This primer describes a combination of three mature technologies that can be used together to achieve large-scale iron ore reduction in which no (zero) carbon dioxide (CO_2) is emitted at all. One of these three mature technologies is called a (direct reduction) shaft furnace.

Shaft furnaces are currently used in some iron ore reduction plants. The scale of individual, state-of-the-art shaft furnaces is similar to state-of-the-art blast furnaces. They have production of 1–2 million metric tonnes of iron per year per furnace (Midrex A). An image of a newer shaft furnace can be seen at http://www.jindalsteelpower.com/businesses/angul.html (it is part of the scaffold-like tower in the left foreground of the main view of the Angul plant).

In 2015 worldwide iron production from plant using shaft furnaces was 58.6 million metric tonnes; in comparison, the 2015 iron production from blast furnaces was 1,154.4 million tonnes (World Steel Association). The three main reasons for the much larger blast furnace production are: (i) that shaft furnaces are a relatively newer technology (small demonstration plants were first built in 1969) (Midrex A); (ii) the decades long lives of iron ore reduction plants; and (iii) the availability of cheap coal in major iron producing countries. The blast furnace/coal burners include China, which output 60% of all blast furnace iron production in 2015 (World Steel Association). Shaft furnaces have been widely and preferentially adopted in countries with access to cheap natural gas, such as Iran, Saudia Arabia and Mexico (World Steel Association). The newest iron ore reduction plant in the USA (started up in Texas, in 2015) uses a large shaft furnace and is powered using natural gas (Midrex A; Voestalpine).

Shaft furnaces do *not* have to be driven by a fossil fuel like natural gas.

To explain this point this primer starts by considering the inputs and outputs from a shaft furnace. The inputs are (i) iron ore (*i.e.* iron oxides, some other transition metal oxides plus impurities), (ii) gaseous reducing agent and (iii) heat. The basic outputs are (a) hot iron mixed with some other transition metals plus the impurities and (b) oxidized gaseous reducing agent. The impurities are taken out in post-processing. The only things most readers will probably not understand right away are the gaseous reducing agent and the oxidized gaseous reducing agent.

There are just two relevant gaseous reducing agents, molecular hydrogen and carbon monoxide. Shaft furnaces can use either hydrogen, carbon monoxide or a mixture of both. In current practice shaft furnaces generally use a mixture (Midrex B). Blast furnaces use only carbon monoxide, which is produced inside blast furnaces by the partial combustion of carbon in coke (coke is 85–90% carbon). Remembering that iron oxide reduction is the removal of oxygen from iron oxide to produce iron, it is the individual molecules of hydrogen or carbon monoxide that pull the oxygen from the iron oxide and grab onto the oxygen, and they themselves turn into, respectively, water molecules and CO_2 molecules. So, the oxidized gaseous reducing agent is simply gaseous water, CO_2, or a mixture of these.

What can be done so that shaft furnaces do *not* have to be driven by fossil fuels? The most mature technologies that can do the job, and that do not burn fossil fuels, are (a) water splitting electrolysis and (b) renewable energy electricity plant (such as wind turbines). Water electrolysis splits water molecules into molecular hydrogen and oxygen, and each of these comes out in separate streams of (almost) pure hydrogen and pure oxygen. The oxygen can be stored and sold off to produce a secondary revenue stream. The hydrogen can be sent straight into a shaft furnace to reduce iron ore. With this option the gaseous reducing agent is just hydrogen, no carbon monoxide is used at all, so no CO_2 gets made in the shaft furnace at all, and so there are no CO_2 emissions from shaft furnaces using straight hydrogen reducing agent. Water electrolysis plant is driven by electricity. So, as long as the electricity used by the electrolysis plant is produced with zero CO_2 emissions (such as electricity from wind turbines), hydrogen production, hence also iron ore reduction, can be done with zero CO_2 emissions.

It is worth emphasizing that water splitting electrolysis is a mature technology (it was rapidly optimized in the 1950's for US Navy submarine operations), it is the state-of-the-art technology for producing highly pure hydrogen gas, and large-scale electrolysis plant is widely deployed. Wind turbine technology has been greatly improved over the last 40 years, has now become widely and cost competitively deployed.

This outlined zero CO_2 emission iron ore reduction process is so simple, the question then arises why has it not already been looked at? In fact, roughly ten years ago it *was* being looked at, although only briefly.

In 2004 a 75 million euro/year research program was started called ULCOS (an acronym for Ultra Low Carbon Dioxide Steel-making) which was 60% funded by the large European steel-makers (led by Arcelor, now merged to become ArcelorMittal) and 40% funded by the European Commission. The program ended in 2012 when ArcelorMittal pulled out (ULCOS wiki). A website for ULCOS is still running, and the information there indicates that the program's main research efforts to lower CO2 emissions from steel-making were (a) to modify blast furnace methods and (b) to attempt molten metal oxide electrolysis (ULCOS website). (This type of electrolysis is significantly different from, and much more difficult than, water electrolysis.) In addition, a relatively obscure 2006 symposium paper by Wagner *et al.,* funded through ULCOS, reported results on narrow basic chemistry aspects of direct shaft furnace iron ore reduction using pure hydrogen. The introduction to Wagner *et al.* indicates that the ULCOS program was giving some consideration to just the iron ore reduction technology outlined above in this primer. The funding for the research of Wagner *et al.* was terminated by ULCOS. The obvious reason for this termination was, that back in 2006, the European steel-makers considered the outlined process an economic non-starter.

The situation going into 2017 is not the same as in 2006. For one thing, wind turbine electricity energy costs have been greatly reduced, especially for the US Great Lakes and Great Plains regions. More importantly, each year of the past decade has produced more alarming evidence of global warming. Increased concern from many individuals over climate change means that there is considerable marketing value in making products using steel made with zero CO_2 emissions from steel-making methods verses steel made using blast furnace iron ore reduction.

In Two Planet Steel's own 2016 cost analysis, for selling to many retail customers, the marketing benefits of using new clean-steel in a large array of products (including cars, domestic furniture, fixtures and appliances) massively out-weigh any cost advantage for blast furnace based steel that the ULCOS effort may have found in 2006, even without legislation to alter market costs to favor new methods of steel-making with zero CO_2 emissions. The Two Planet Steel analysis found that, if the value of the pure oxygen by-product of the new ore reduction was set to nil (this is unrealistic as the pure oxygen by-product does have some significant value), and if there is no CO_2 penalty put on blast furnace produced iron (this also will become increasingly unrealistic), these two “ifs” provide the best possible conditions for blast furnace iron in a comparison with the new clean iron, then blast furnace produce produced iron will come out $0.00 to $0.08 per kilogram cheaper than new clean iron (this cost difference range depends on the cost of coal). By the commodity pricing standards of the iron and steel industry a difference of $0.08 per kilogram is actually a large difference. However, commodity pricing comparisons are not relevant to an end customer of a domestic steel water faucet. An 8 cent iron cost difference on a one kilogram domestic steel water faucet is simply dwarfed by the marketing added-value to the end faucet price (probably $1 to $5) of being able to say that the faucet was made with zero CO_2 emissions steel (and other important value factors such as aesthetic design, fabrication quality, product presentation and more).

It is also possible to draft legislation (that *both* Donald Trump and Al Gore would back) that simultaneously favors national domestic steel production, steel jobs and zero CO_2 emissions steel-making (over traditional blast furnace based methods) to the point that clean-steel is the best cost option for all retail and business customers across all end product markets that use steel, including construction projects. Such legislation might be written in different ways. It might include the following: (i) a ban on all imports of products containing steel produced from iron that was reduced in plants that emit CO_2 from the reduction process; (ii) direct or indirect methods to encourage investment in new, zero CO_2 emissions iron ore reduction plant ; (iii) a carbon tax on iron made in the national market using CO_2 emitting reduction furnaces; (iv) a program to foster new economic activities to coal-mining in traditional coal-mining regions; (v) a sensible timeline for carrying out the other parts. Given such legislation from the US Congress, areas around the Great Lakes are likely to especially benefit from the jobs and wealth created by a new, clean US steel industry. Such legislation would directly cause the USA to cease being a net importer of steel products for some extended period, also a strong, clean-steel brand will be attractive to many consumers around the world which will likely usher in a period of net exports of finished products made with clean-steel. Such US legislation and newly successful US industries of clean-steel and clean-steel finished products will put pressure on other steel-makers around the world to transition to clean-steel-making, and other legislatures are likely to consider the benefits of adopting similar clean-steel legislation, or adopt it before the US Congress.

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