INSIGHT BRIEF

THE DISRUPTIVE POTENTIAL OF GREEN STEEL

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INSIGHT SUMMARY

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- Because the steel industry is one of the largest emitters of CO_2, contributing 6%–7% of global greenhouse gas emissions, it is imperative to find a low-carbon process for primary steelmaking in order to adhere to a 1.5°C pathway.
- Several non-coal-based technologies for primary steelmaking are currently being piloted, with hydrogen-based direct reduction being the furthest developed.
- Using today's global average grid power, primary steel production with hydrogen has the same CO_2 footprint as the highest-performing installations of the prevailing blast furnace method.
- In the United States and European Union, switching to hydrogen-based steel production represents an immediate CO_2 emissions reduction opportunity for new assets of 20% and 40% respectively.
- Given that prices of electricity and coking coal are not coupled, the 20% cost premium of hydrogen-based steel production is eliminated at electricity prices of $15–$20/MWh or lower, a cost level achieved already today by renewable power plants across several geographies (e.g., Brazil, Mexico, Saudi Arabia, Portugal and the United States).
- While this sounds promising, adding up all of the steel mills from all of the companies currently investing in or committing to zero-carbon technology only represent 8% of global steel production. A 100-fold step-change in the pace of transition is required to adhere to a 1.5°C pathway, which will require a concert of market, regulatory, and finance interventions to accelerate deployment of low-carbon technologies.

THE CLIMATE IMPERATIVE FOR GREEN STEEL

Despite efforts to increase recycling, the remaining production of primary steel (i.e., steel made from iron ore) emits more CO_2 than we can accept to keep global warming below 1.5°C There is a critical need to find new, low-carbon solutions for iron ore reduction. Hydrogen-based direct reduction is one of several promising options.

Steelmaking is one of the sectors contributing the most to global greenhouse gas emissions, with a global footprint of 2.9 $GtCO_2$ per year, and is on track to consume 50% of the total remaining 1.5°C carbon budget by 2050. The process of making steel and shaping it into useful geometries requires high temperature and intensive energy consumption, which usually comes in the form of fossil fuels. On top of that, the steelmaking process requires breaking the chemical bond in iron ore to get access to pure iron, a reaction that requires a reagent to bind with oxygen. Broadly speaking, in the last 2,000 years of steelmaking, that reagent has been coal, which generates CO_2 as a by-product.[1]

[1] Iron ore comes in two forms, either hematite (FE_2O_3) or magnetite (FE_3O_4), which both produce pig iron (Fe) and carbon dioxide (CO_2) using coal.

Simply speaking, steelmaking can be broken down into three process steps:
1. reduction
2. transformation
3. forming

In the first step, the oxygen in the iron ore is separated from the iron to produce pig iron. In the second step, pig iron is alloyed with other minerals such as nickel, chromium, manganese, or molybdenum, to create a crude steel material with the physical properties required in the final application. Finally, the steel is formed through a series of hot and cold processing steps into the final shape that the customer will use. And while all these steps are energy intensive, since the metal needs to be heated up to be malleable, the bulk of the CO_2 emissions originate from the iron ore reduction.

To understand the challenge of decarbonizing the steel industry, it is important to distinguish between these three process steps and their objectives, despite the common practice of co-locating and integrating them. The integration improves energy efficiency since, for example, it is not necessary to cool an ingot of pig iron down for transport and then reheat it for transformation.

An often-highlighted carbon emissions reduction strategy is to shift from blast furnace (BF) production to electric arc furnace (EAF) production, but the two processes are not direct substitutes. The EAF process, which is basically a way of using electricity to heat up metal to a point where it can be transformed and shaped, needs an already-reduced input material; in other words, it cannot produce steel from iron ore. A BF plant, on the other hand, is usually integrated with the transformation step, and often hot forming as well, so its output goes directly to cold rolling mills or extrusion plants. An increased use of the EAF process requires an increase in the supply of recycled scrap steel back into the system to enable the shorter and less carbon-intensive process.

In almost all steel production outlooks, however, there will not be sufficient scrap available to provide all the steel that the global economy will consume. This is partly an effect of stock and flow balances in a growing economy, and partly because there are accumulating quality issues with recycled steel that disqualify it for high-grade applications. The bottom-line implication, however, is that despite efforts to increase recycling, the remaining production of primary steel (i.e., steel made from iron ore) emits more CO_2 than we can accept to keep global warming below 1.5°C or even 2°C.

To curb climate change, the process of reducing iron ore to a product that is equivalent to pig iron is imperative. After decades of research, several technologies are beginning to approach commercial readiness. In addition to carbon capture and storage (CCS), which in theory can be applied to a blast furnace just as well as to a power plant, the two most promising low-carbon technologies are molten oxide electrolysis (MOE) and hydrogen direct reduction (HDR). Currently, neither of these options are commercially available at scale. This insight brief explores what the implications might be of large-scale hydrogen-based steelmaking.

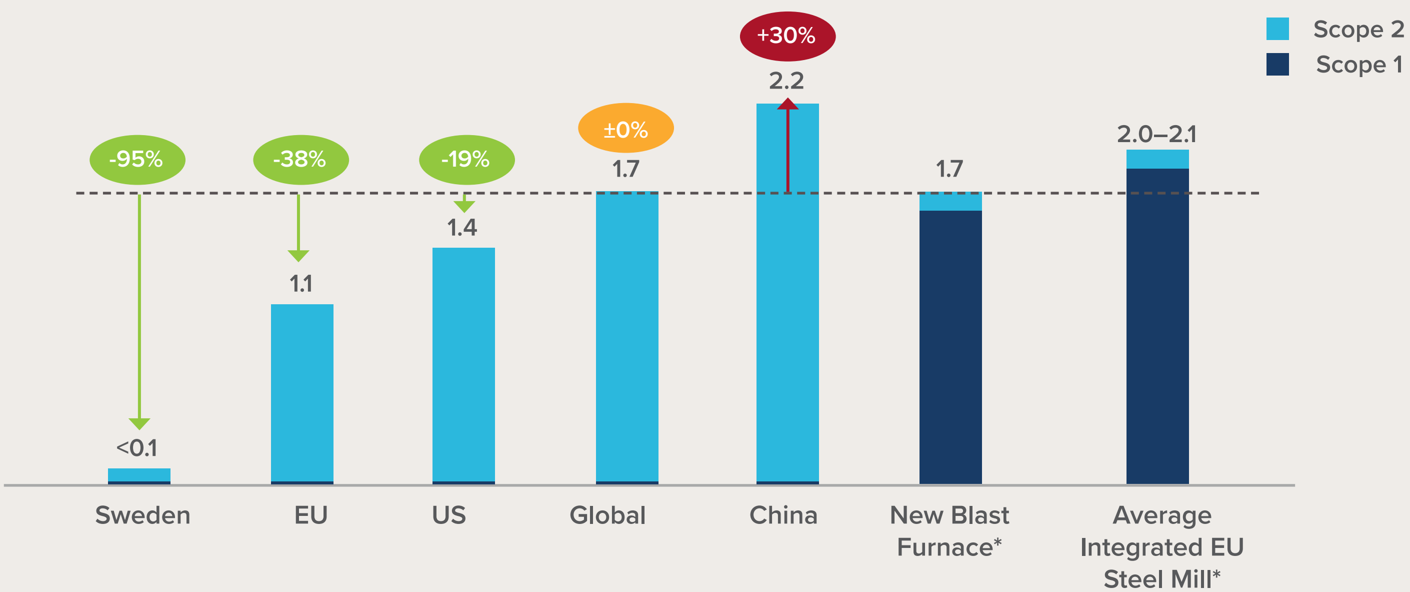
THE CO_2 EMISSIONS FROM HYDROGEN DIRECT REDUCTION

There is no need to wait for 100% renewable hydrogen production to decarbonize steelmaking, since the current global average grid power is sufficiently low carbon to break even with conventional blast furnace processes.

Hydrogen-based direct reduction uses hydrogen instead of coal as a reagent to reduce iron ore to pig iron, eliminating the CO_2 emissions from the equivalent process in a traditional blast furnace. However, direct reduction requires an EAF to heat up the reduced iron for the consecutive process steps and the production of hydrogen itself requires a significant amount of electricity, which in turn might emit CO_2 depending on the structure of the grid supplying the electricity.

For one ton of crude steel produced from iron ore, the hydrogen generation requires 2,633 kWh of power, and in addition, the direct reduction and EAF plants consume 816 kWh. Assuming global average CO_2 intensity of 0.48 tCO_2/MWh for the power, each ton of crude steel generates emissions of 1,713 $kgCO_2$. This should be compared with a blast furnace, which emits a total of 1,714 $kgCO_2$ for each ton of crude steel. Clearly, the global power system has reached an inflection point where decarbonization of steelmaking is possible without further deployment of renewable power assets.

Exhibit 1: CO_2 emissions from steelmaking (tCO_2/ton crude steel)



* 1,7 $tC0_2$ per crude ton of steel represents best available technology (BAT) performance, an average European integrated blast furnace emits 2.0–2.1 tCO_2 per crude ton. Source: HYBRIT **http://www.hybritdevelopment.com/**

Exhibit 1 illustrates how the CO_2 intensity of grid power in different regions impacts the greenhouse gas emissions from hydrogen-based steelmaking. Sweden, which is where a first commercial pilot of the process is being built, would reduce emissions by more than 95%, while the United States and Europe would reduce emissions by 20% and 40% respectively. And because the power generation portfolio in China is so dominated by coal power plants, the emissions would actually increase from switching to hydrogen-based steelmaking.

Basically, this means that there is no need to wait for the steel industry to decarbonize until there is a reliable supply chain of hydrogen generated by 100% renewables, referred to as Green Hydrogen or *Solar Gas*. Significant abatement can be achieved using existing grid power, and as more renewables come online on the grid, the impact of the transition will gradually increase. This provides an opportunity for immediate investments to begin the asset transitions in a gradual shift toward low-carbon steel, rather than waiting for Green Hydrogen to be available at competitive prices followed by an investment rally to shift the whole industry to low-carbon production in a much more accelerated transition.

COMPETITIVENESS AND COST DRIVERS

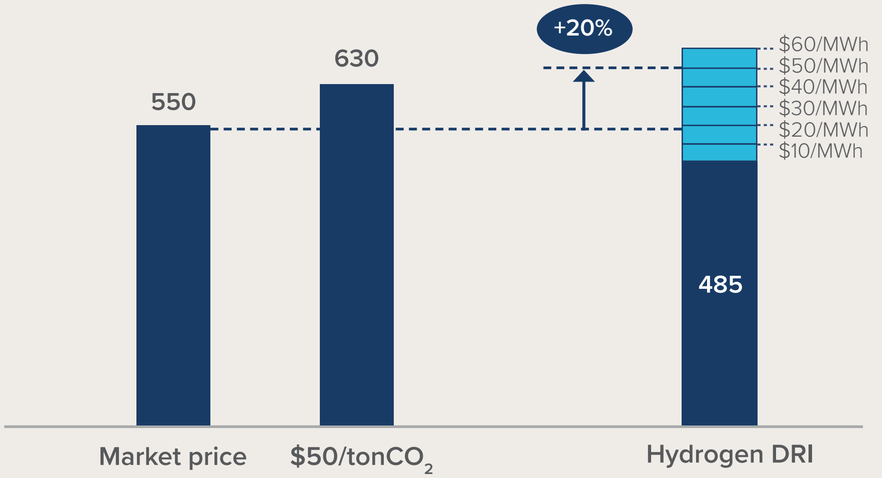
Both hydrogen direct reduction and molten oxygen electrolysis use electricity instead of coking coal as the main energy input, which means that the cost structure is exposed to completely different energy markets. Both technologies are indicatively competitive with prevailing blast furnace reduction—without a carbon tax—at electricity prices of $15–$30/MWh, which is a cost level at which renewable power assets are already performing.

While steel market prices fluctuate, the market typically clears around $550 per ton. Early assessments of production price of full-scale hydrogen-based direct reduction indicates a 20%–30% higher cost compared with conventional steel production. This higher cost corresponds to a carbon price of around $70–$100/tCO_2. Some of the cost drivers will be quite similar in the two production routes, such as iron ore price and labor cost. But given that the two technologies are using completely different energy inputs, they have cost structures exposed to different energy markets. This means that the market prices of these energy inputs are as important or more than a hypothetical carbon tax in deciding which technology can produce the lowest-cost steel.

For example, this calculation of additional cost is based on using grid power supply for industry in northern Europe, which represents a fully loaded power price of close to $50/MWh. While the details of the cost structure are not published, the power consumption for the process is, so the underlying non-energy cost can be estimated to be around $485 per ton. Exhibit 2 illustrates the additional cost contribution for electricity used in the direct reduction and hydrogen production in increments of $10/MWh. Knowing that the analysis is rough and not based on a fully transparent cost structure, it still indicates a break-even competitiveness—without any carbon tax—for electricity prices just below $20/MWh. If a hypothetical $50/t$CO_2$ carbon price is introduced, the hydrogen-based process is competitive with power prices already at $40/MWh.

Similarly, molten oxide electrolysis, a competitive zero-carbon technology that allows iron ore reduction using electricity instead of coal, is expected to be cost competitive with conventional steel at electricity prices in the range of $15–$30/MWh.

Exhibit 2: Production cost benchmark for hydrogen direct reduction at different electricity prices



These are price levels that are regionally within reach. Last year, DOE research showed that the average wind power price in the central United States has dropped below $20/MWh. Solar PV is reaching these cost levels in some parts of the world as well, with record power purchase agreements cleared below $20/MWh in the Middle East, Mexico, Brazil, Portugal and Los Angeles. As cost for renewable power continues to plummet, and the cost of the direct reduction and hydrogen installations also start to come down, the relative competitive landscape for steelmaking regions could be significantly impacted, with new emerging production hubs and mounting pressure on incumbent producers.

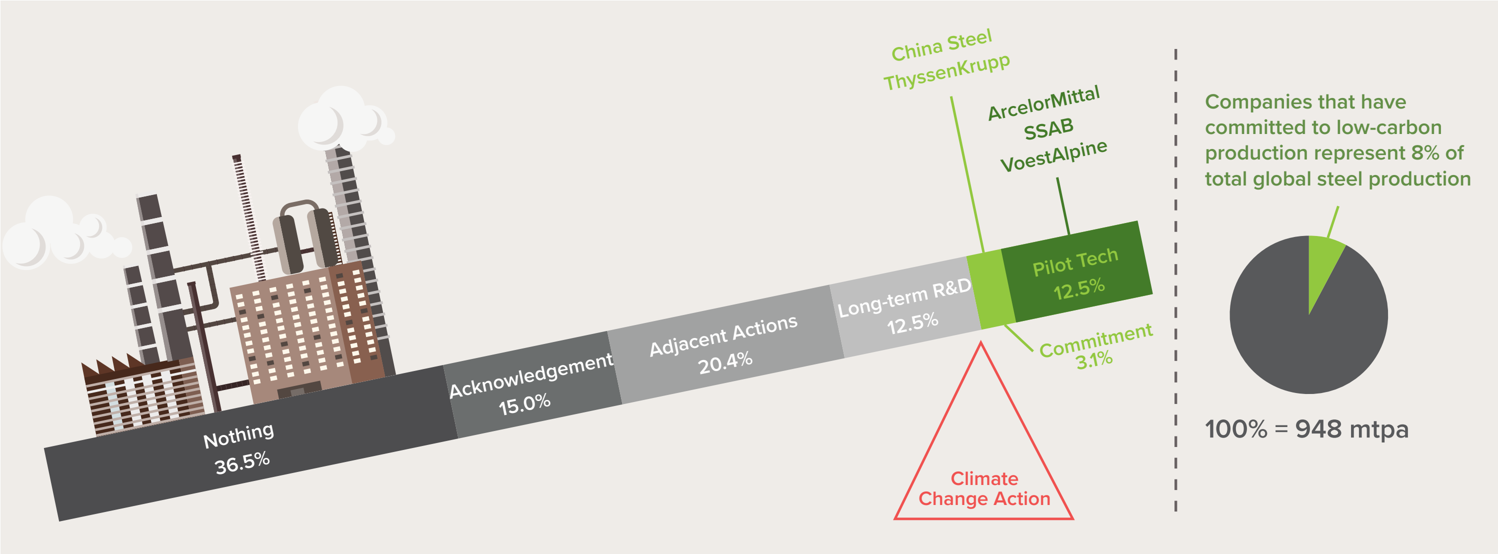
OPPORTUNITIES TO ACCELERATE THE STEEL TRANSITION

The steel mills of progressive companies that currently invest in and commit to low-carbon production only represent 8% of global steel production. A 100-fold step-change in the pace of transition is needed for the steel industry to adhere to a 1.5°C pathway. This will require a concert of interventions to accelerate deployment of low-carbon primary steelmaking technology.

In a global environment of continued cost reduction for renewable power, tightening regulations on carbon emissions, and new, promising technologies entering the commercial pilot stage at only 20%–30% higher cost, low-carbon processes are starting to make economic sense. However, the scale of change is daunting. Today, the global economy consumes around 1,700 million tons of steel per year, a demand level that is expected to grow slowly toward 2,150 million tons in 2050. Today, almost 1 billion tons are supplied with primary steel, but as scrap supply increases over time, all of that demand growth is expected to be met with recycled steel. Thus, the need for iron ore reduction capacity is forecasted to remain roughly stable in the same time period. Even in scenarios that leverage demand reduction to achieve carbon abatement, there is a residual annual demand of 550–750 million tons of primary steel in 2050.

Blast furnaces come in different sizes, but a typical facility has the capacity to produce 3 million tons per year, which means that we will have the equivalent of 250–350 blast furnaces operating in 2050. To switch these assets over to zero-carbon technology by 2050, to adhere to a 1.5°C pathway which requires net-zero emissions by 2050, translates to avoiding the construction of or closing down about ten blast furnace steel mills per year. Currently, one of the leading developers of zero-carbon steel technology, HYBRIT, a Swedish joint venture between an iron ore producer, a steel manufacturer, and a power utility, is on a timeline to replace one blast furnace by 2030. And while several other companies, such as Thyssenkrupp, Arcelor Mittal, and China Steel, are making long-term commitments and investing in research and development, there are no other announcements of actual production. As Exhibit 3 illustrates, even if the most progressive steel companies were to switch over to zero-carbon steel processes, it would only represent 15% of the production of the 40 largest steel producers, which corresponds to only 8% of the total global steel market.

Exhibit 3: Climate change momentum of 40 largest steel companies



The 100-fold step-change, going from converting one blast furnace every 10 years to converting ten blast furnaces every year, will require a concert of interventions, pulling every available lever to accelerate technology deployment. Specifically, we at RMI see multiple coordinated efforts that would mutually reinforce each other:

1. **Market intervention**
   - A differentiated low-carbon steel product to enable the supply-demand dynamic to create a price premium for a higher-performing supplier
   - Asset portfolio differentiation to reduce risk exposure to medium-to-long-term market development toward a low-carbon future
   - New vehicles to scale IP beyond single entities

2. **Policy intervention**
   - Industry self-regulation and decarbonization commitments of critical scale
   - Carbon taxes or equivalent mechanisms to reduce the cost advantage of high-carbon manufacturing
   - Import tariffs based on carbon content to protect the local market from carbon leakage (i.e., competition from high-carbon import)
   - Carbon performance requirements in government and/or private procurement

3. **Finance intervention**
   - Government or voluntary support to lock in value premium for low-carbon steel production to reduce uncertainty for investors in emerging technology
   - Late stage R&D support for commercialization of technologies currently in pilot stage
   - Investor pressure on steel companies to disclose and improve their carbon performance
   - Securitization programs or other financial tools to manage the potential write-down of value of high-carbon production assets

ABOUT ROCKY MOUNTAIN INSTITUTE
Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.