Columbia Business School
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Steel Workshop Report

Climate Knowledge Initiative
Max de Boer, Rapporteur
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Foreword

The Climate Knowledge Initiative (CKI) was set up by Columbia Business School in 2023 with the aim of providing business leaders with the curated, actionable knowledge needed to pick investable and scalable green technologies, while unapologetically flagging areas where business and public interests diverge. To accomplish this task, CKI takes both an industry-sector and solution view of the climate problem. CKI plans to address the industry sectors that contribute the most carbon emissions (e.g., steel, transportation) as well as the most promising solutions (e.g., solar, hydrogen).

The first topic CKI tackled was decarbonization of the steel industry. CKI last fall invited a group of business leaders and academic experts with extensive experience in the steel industry to a workshop at CBS's campus. Participants contributed brief presentations on their topic of expertise, which were followed by open discussion and debate. Climate economist and CBS professor **Gernot Wagner** moderated the discussion. The workshop participants were:

- **Chris Bataille** – Adjunct research fellow at the Center on Global Energy Policy at Columbia SIPA
- **Åsa Ekdahl** – Head of environment and climate change at the World Steel Association
- **Marie Jaroni** – Senior vice president for decarbonization and ESG at Thyssenkrupp Steel
- **Kyung-sik Kim** – Head of South Korea's Steel Scrap Center and former senior vice president at Hyundai Steel
- **Heather Lee** – Steel team lead at Solutions for Our Climate
- **Sandeep Nijhawan** – CEO and co-founder of Electra
- **Maria Persson Gulda** – Chief technology officer at H2 Green Steel
- **Dierk Raabe** – Director of the Max Planck Institute for Iron Research
- **Dan Steingart** – Professor of chemical metallurgy and chemical engineering at the Columbia School of Engineering

The full CKI steel content is available via leading.business.columbia.edu/climate/steel. This report is an attempt at representing ideas and information discussed during the workshop. It has been issued under the auspices of the Climate Knowledge Initiative at Columbia Business School; workshop participants are not responsible for its contents.

Setting the Scene for Steel

In 2021, global steel production reached a global record of about 2 billion tonnes. This steel finds its way into a large range of products — from vehicles, buildings, and infrastructure to the cans we use to store food. If one were to look around right now, chances are they would see something that contains steel. Because steel is an essential material in modern societies, it is likely both steel demand and steel production will continue to increase for the foreseeable future. Countries like India, Nigeria, and Indonesia are steadily climbing their way up the Human Development Index, which has been shown to correlate with steel demand.

Unfortunately, the production of steel causes enormous emissions of greenhouse gasses. On average, the production of 1 tonne of steel results in the emission of 1.91 tonnes of CO_2. All combined, the industry is responsible for about 10% of global annual CO_2 emissions. Given the Paris Agreement provision that all industrial sectors must reach net zero emissions by 2050, the steel industry faces a monumental task. With only 27 years left to reach this target, which is about the average lifespan of a steel plant, industry leaders must make important decisions today instead of tomorrow.

So, why wait?

The Challenge Ahead

There are many reasons why steel is difficult to decarbonize. It’s not just that it uses large amounts of electricity generated from fossil fuels or requires transport that runs on fossil fuels. Actually, carbon is a component of the final product — it is the less than 1% of carbon added to iron that turns it into steel. Aside from this fact, three additional decarbonization challenges were identified during the workshop: the ubiquity of the blast furnace, the economic importance of the steel industry, and the lack of people and progress in the field of metallurgy.

This discussion starts with an inconvenient truth: The blast furnace is an amazing piece of technology—one that has been fine-tuned and perfected over the past 100 years—and humans simply have not reached the same level of understanding and sophistication when it comes to other steelmaking technologies. The blast furnace can handle a range of different qualities of ore, while some other technologies can take only those ores of a certain quality. Moreover, it is easy to deal with ore impurities in a blast furnace: When the ore is melted, the impurities simply float to the top of the blast furnace, where they can be easily sloughed off.

Maybe the most important aspect of the blast furnace is the chemistry at work inside it. The key process is the reduction of iron ore, which comes down to ripping away oxygen atoms from iron oxides to turn them into pure iron. Multiple chemical elements are used to do this. Hydrogen, an element that will be revisited later, is one of them, but by far the most effective element is carbon. The only downside of this highly efficient process is that the carbon is transformed into CO_2 during the process.

It is because of this ease of use and low cost that India plans to expand its steelmaking capacity over the next 10 years largely through the addition of new blast furnaces. Blast furnaces may not make sense from a decarbonization perspective, but they do from a cost perspective. Thus, we face a dilemma: Should investment and research on improving blast furnaces continue? Yes, blast furnaces will likely never be able to produce zero-emissions steel. But if countries keep building them, should they at least try to make them less CO_2 intensive?

A second point to consider is the economic importance of the steel industry. In an ideal world, steel production could simply be located closer to iron mines or where electricity is both cheap and green. In the current situation, however, iron is often produced in places that meet neither of these considerations.

Unfortunately, many countries are reluctant to see their steel production capacity move abroad because they consider steel to be a material of critical importance to their domestic economy. To be dependent on another country for steel supply means to be dependent on another country for production of weapons and infrastructure. This dependency extends beyond just the production of steel itself. If a country switches to a new, foreign production method for steel, it may mean that it will become dependent on another country for crucial spare parts or the know-how to build new plants. These forces combine to push countries to keep their own steel industry alive and may make them more reluctant to switch to new, less polluting steelmaking technologies.

Third, the steel industry will need many bright minds to get through a challenging and difficult transition, but many of these bright minds are not keen on working in the industry. Top engineers are attracted to flashier industries like artificial intelligence (AI) and battery technology. For that reason, there is a severe shortage of skilled people, like metallurgists, who can design and operate the new green steel plants needed to drive the transition.

This problem is already visible across universities. Where a search for scientific papers on the topic of *climate change* resulted in over 50,000 publications in 2022, a search for *sustainable metallurgy* resulted in only 110 publications that year. Meanwhile, a noticeable shift has occurred in terms of those who do study metallurgy: At European universities, there are often more Indian and Chinese students in these classes than domestic students. This trend may not be a problem in and of itself, but it does indicate that sustainable steelmaking knowledge is shifting from the West to the East. More and more intellectual property on green steelmaking is coming from China, leaving some concerned about national security. Meanwhile, in Europe, material science faculties must fight the threat of closure due to a lack of student interest. Nowadays, retiring professors are not replaced.

A heavy industry like steel must deal with more traditional recruitment problems as well. Production is more often located in rural areas or near small industrial towns, away from the big cities young people often prefer to live in. Money also plays a role. Newer and trendier industries like AI and battery technology have enough financing behind them to pay engineering graduates high salaries. In a commodity industry, such salaries straight out of school can be hard to come by. The same is true for research, where very little funding is spent in the West on sustainable metallurgy.

This lack of expertise extends even further, to areas like permitting. Permitting authorities need people with deep expertise to evaluate permitting applications of steel companies wishing to build new green plants. If they do not have the right people to evaluate these applications, permits are not granted, resulting in the delay of projects.

These problems are not unique to the steel industry. Besides people who design and build new green steel plants, there is also a need for people that, for example, will be able to figure out how to recycle batteries and build hydrogen pipelines. The hard reality is this: The world’s CO_2 problem is not going to be solved if not enough people study physics, chemistry, and engineering.

Public perception may also be a large part of the equation. Studies have shown that while people have become more aware of the existence of the steel industry in recent years, they also view it less favorably. There is a similar trend in the media: Media coverage of the steel industry has increased, but it has also become less favorable. This has been largely due to climate change, and the role of the steel industry as a polluter, becoming a more prominent topic. Incumbent steelmakers have felt this change in perception most acutely. The public now tends to see them as a part of the problem rather than part of the solution.

The Technology Transition

One thing is clear in the steel industry: Steelmaking methods must change. What is not yet clear, however, is which technology is going to help producers do so. Notably, no one knows how to replace the blast furnace.

One candidate often cited is green hydrogen DRI-EAF, which stands for direct reduced iron-electric arc furnaces. In this production process, hydrogen is used instead of carbon as the reductor that rips the oxygen molecules away from iron oxides to create pure iron. The iron is then melted in an electric arc furnace, after which it is ready for downstream processing. It is also during this final phase where some carbon is added to transform the iron into steel.

Green hydrogen DRI-EAF has some clear advantages compared with traditional steelmaking. The big one is that if the hydrogen is made using green electricity and the electric arc furnace is powered by green electricity, the process is close to being carbon free. Another advantage is that the iron coming out of the DRI reactor is not extremely hot, meaning it can be easily compressed into briquetted iron and then easily shipped and traded.

Green hydrogen DRI-EAF also comes with some drawbacks. One is that the electric arc furnace can deal with only high-grade ores, meaning that ores from low-grade mines cannot be used. But perhaps more important is the fact that from an energy consumption perspective, producing iron with hydrogen is inefficient. When using electricity to produce hydrogen, 40% of the energy inputted is lost. That means there has to be an abundance of green electricity available for hydrogen DRI-EAF production for this option to make sense.

Another new steelmaking technology being developed is electrolysis. In this production method, electrical energy is used to rip away the oxygen from iron oxides instead of a chemical element like carbon or hydrogen. A major advantage of this process is that it is the most efficient from an energy perspective.

One production method that falls in the electrolysis category is electrowinning. In the first step of this process, iron ore is dissolved into an acid to create an iron solution. The iron solution is then placed into a reactor that contains anodes and cathodes, which are used to run an electric current through the iron solution. This current causes pure iron to form at the electrodes placed in the solution, and the iron is then melted in an electric arc furnace, after which it is ready for downstream processing.

Electrowinning has a couple advantages over traditional steelmaking. One is that it handles low-grade ores well. In traditional steelmaking, iron ore containing water can be an issue. But with electrowinning, it is not, as the ore is dissolved in acid before iron production. This also makes it easier to deal with a range of impurities commonly found in iron ore. For instance, silica—a common iron ore impurity—does not dissolve in acid, meaning it stays behind in solid form and can easily be filtered out.

Another advantage is that the electrowinning process can be set up at a much smaller scale than is common in blast furnace plants. This means production can be more decentralized, which can be an important factor for developing economies where transportation infrastructure is still under development.

Electrowinning does have some disadvantages compared with traditional steelmaking. A major one is that production happens in batches rather than being continuous, as is the case with blast furnace steelmaking. Workers must actually go into the reactor to break off the iron that was formed from the electrodes. Compare this to the blast furnace process, where new iron ore can be constantly added to the top of the blast furnace and hot, liquid iron can be tapped from the bottom. A second concern is that electrowinning has not yet been proven at scale for iron production. It is used to produce aluminum, but global aluminum production is only 1/20th of the global steel production. That means it has yet to be seen if electrowinning can work at the scale required.

If electrowinning could work at scale, it could come with a beneficial side effect. As noted, electrowinning works by consuming electricity to rip off oxygen from iron oxide. Basic thermodynamics states that if this reaction is reversed, it releases electrical energy. In theory, electrowinning reactors could therefore be used as giant batteries. As such, the result could be enormous: Imagine a world where iron and steelmakers consume massive amounts of electricity during times when renewable electricity generation is at its peak and then, later in the day, give some electricity back to the grid if demand exceeds supply. Not only could green steel be produced this way, but steel production could also be used to store green energy. Two birds, one stone.

Besides electrowinning, another form of iron production using electrolysis is under development: molten ore electrolysis (MOE). During this process, solid iron ore is added to a reactor that contains a liquid electrolyte. Electrodes are then lowered into the mixture and used to send a strong electrical current through it. The result is pure iron in a molten state, which can be tapped from the bottom of the reactor. This process offers the advantage of continuous production.

Unfortunately, this solution should be viewed with cautious optimism, as the method is still under development. A challenge here is to develop electrodes that can survive being dipped into liquid molten iron. It is also likely that MOE can only process iron ore that has impurities within certain bounds, because those impurities will function as part of the electrolyte. Again, it remains to be seen if this production method can be applied at a commercial scale.

Carbon capture, utilization, and storage (CCUS) must also be discussed, given that it is frequently cited as a viable solution. Some view CCUS as a silver bullet for decarbonizing the steel industry, but there is one problem: Right now, it does not work.

At present, there are no blast furnaces with a working CCUS installation. This lack of CCUS is due to two technical reasons. First, blast furnaces have many different points at which CO_2 can escape, making capture difficult. A second issue is that the gas emitted from a blast furnace contains many other pollutants and that its composition can vary widely over time. Therefore, any captured gas is unfit to use, meaning storage is the only option. And while CCUS can work on DRI installations that use natural gas instead of hydrogen, DRI currently makes up only a small portion of globally installed steelmaking capacity.

Industry leaders could take the gamble and try to make CCUS work for blast furnaces. However, this would not be an insignificant bet. According to some estimates, it would take an investment of between $10 billion and $20 billion and five to 10 years to get CCUS for blast furnaces to work. Right now, that investment level is nowhere near being reached.

If CCUS has yet to work for blast furnaces, and getting there would take considerable time and money, why do people so often talk about it like it works? Large policy and economical models often include a CCUS component in their steel industry projections. Often, the costs are as low as \$50 per tonne for capture and \$30 per tonne for storage, which is the barest of bare minimums. Instead, it would be more honest to call this component "unknown," as in, "We do not know how we are going to solve this, but we know we have to." The language point may seem pedantic, but it does matter. Investors in the steel industry now often ask why investments in new and risky steelmaking technologies are required. They ask, "Why not just use carbon capture and storage?"

There needs to be better education for investors and the broader public on the limits of carbon capture for steelmaking. It does not work yet, and without the right level of investment, it likely never will. Now the industry could make the choice to gamble and do the research and investment required to make it work. Some even see CCUS as a potential solution for all the blast furnace capacity India will add over the coming years. But to do so will require both people and money.

Besides the aforementioned technologies, there is a range of other steelmaking technologies that could deliver (some) decarbonization processes. Right now, however, these other technologies look less promising than the ones discussed, or they are expected to prevail only in certain niche applications. One of these less promising technologies is the injection of hydrogen into existing blast furnaces. While it reduces CO_2 emissions, there is a certain limit it can approach without having to change equipment, which means coal cannot be fully replaced.

Another halfway solution is smelting reduction. With this production method, the coking process for coal can be eliminated, which does result in some CO_2 emissions reduction. Another benefit is that the CO_2 that is still released during production is concentrated and easy to capture, which makes CCUS a viable option. The big disadvantage of smelting reduction, however, is that it requires a complete replacement of production equipment. If a producer is spending the capital expense to replace its equipment anyway, why not go for a zero or near-zero emissions option? An alternative is to conduct smelting reduction of ores with a hydrogen plasma in electric arc furnaces, a promising method that builds on existing technology (EAF plus injection systems) and is scalable.

One example of a niche application is to replace the coal in blast furnaces with biomass. This is a carbon-neutral process because the biomass previously absorbed carbon from the atmosphere. At the moment, some steel plants in Brazil, where plenty of biowaste from farming activities is available, successfully use this technique. The issue is that there is not enough sustainable biomass (think biological waste products) to allow the whole world to switch to this production method. Cutting down forests to produce steel is just replacing one problem with another.

One final thought to conclude this section on technology: It is clear that the transition to clean steelmaking is going to be a difficult process. There is not one new steelmaking technology that is a clear winner for the whole world to adopt. Based on factors such as the availability of resources and geopolitical concerns, countries will likely adopt different technologies and do so at different paces. There is not going to be a perfect transition; rather, we must accept that we will likely end up in a kind of messy middle. It is neither pretty nor ideal, but it is most likely.

Seeking Solutions

Now that the difficulties of making green steel have been discussed above, it's time to start thinking about solutions. What can be done to accelerate the steel transition?

The simplest way to think about solutions is to look at the classic waste management hierarchy: reduce, reuse, recycle. Starting with reduce, how can we design things in a smarter way so we have to use less steel? Designing buildings and cars more efficiently alone could reduce the amount of steel required by up to 40%. When it comes to reuse, buildings could be designed in such a way that girders can be reused after the building is torn down.

Fortunately, the next step, recycling, already works well when it comes to commodity steel, usually long products for construction. It is the most circular metal on the planet. Around the world, scrap steel is collected and then recycled using electric arc furnaces. The limiting factor right now is the availability of scrap steel: There is a lot of it to go around in advanced economies, but many developing economies have limited availability. The good news is that scrap steel availability in developing economies is expected to increase over time. In fact, there may be a point around the year 2100 when there is enough steel in global circulation that we no longer need to produce virgin steel. Unfortunately, the world's CO_2 problem must be solved way before then.

Therefore, more difficult, technological changes will also need to happen. As discussed earlier, it is important that we accept that this transition is going to look differently across the world and that different countries will move at different speeds.

If there is a willingness to go through radical technological transitions to reduce CO_2 emissions, then the full steel value chain must also be considered. Right now, iron ore is mined and then shipped to a steel plant. There, the iron ore is reduced and made into steel. Does this model still make sense when a large part of the steel industry switches to new production methods? In the old model, reliable and cheap access to coal and natural gas may have decided the location of steel plants. But when steel is produced using green hydrogen DRI or electrolysis, access to cheap and green hydrogen or electricity matters most.

One could imagine a future in which iron ore is reduced at a few large, central locations across the world where there is abundant and cheap access to renewable energy or hydrogen. The iron produced could then be shipped from these locations to a number of decentralized locations that have electric arc furnaces, as these can be used for both virgin steelmaking as well as recycling locally collected scrap.

This is only just one example — many other configurations are possible. If electrolysis takes off, for example, perhaps iron ore mines could shift to dissolving their iron ore in acid on-site and ship the solution instead of the ore. It is not yet known what setup will be most efficient, but what is clear is that the industry should not just blindly copy the old setup for a new world.

Another consideration may seem like a simple question: What exactly is green steel? Right now, there is no global definition, meaning every steel player is making up its own. Conflicting definitions are confusing to customers and could lead to greenwashing. A global definition is needed to eliminate this confusion.

The issue is that as soon as one starts to think about defining green steel, all kinds of difficult questions come up, starting with the definition of *green*. Should this include only embedded CO_2 emissions or other externalities such as the release of air pollution? For those who agree with this point, *clean steel* might be a better term than *green steel*.

But assuming the focus is on only CO_2 emissions, the question is where to draw the line. A gut reaction may be to put it at zero emissions per tonne, but is that realistic? Even very clean production methods like hydrogen DRI still produce some direct CO_2 emissions. But if the bar is put above zero emissions per tonne, where exactly *should* it be?

Another issue is the mixing of scrap and virgin steel. Scrap steel has a low emissions footprint because it only needs to be melted again. A poor definition of green steel could lead to steel producers mixing high amounts of scrap steel into their production to offset the high emissions of virgin steel production. This pitfall could discourage companies from doing the hard work to switch to new, cleaner production methods.

The last point on this incomplete list: How should indirect emissions be dealt with? Producing steel with 100% electricity may seem like a great solution at first, but it could in fact be bad for the environment if the electricity used comes from a grid running mostly on coal. However, what if the steelmaker in question used a power purchasing agreement for solar energy for part of the production?

What becomes clear is that a green steel definition means that many complicated questions will need answers. All these questions cannot begin to be answered here, but some first thoughts came out of the workshop's discussions. It may be tempting to classify green steel based on production method. Simply put, this would mean, for example, that steel produced by electrolysis would be green but blast furnace steel would not. This classification would be misguided, restricting investment and innovation only to production methods that fall under the green steel definition while overlooking other promising alternatives. Making the definition production-method agnostic may be more likely to increase innovation.

When it comes to scrap steel, a green steel definition should strike a fine balance between not discouraging the use of scrap steel and not discouraging innovation in clean production methods. One way to do this could be to make any definition of green steel dependent on how much scrap steel is used — that is, the more scrap steel is used, the lower the emissions of the virgin steel would need to be to meet the green steel definition.

Finally, instead of looking at green steel, should the question be about green iron? It may be much easier to define green iron given that this would eliminate the question of how much scrap steel is used. To be decided.

Unfortunately, none of these suggestions will ever matter if the steel industry can no longer attract the people needed to implement them. Steelmaking needs to become hot again, for which there are a couple of suggestions.

But first, why is talk focused on lithium but not iron? Recent government and media attention has made the public very aware of how critical the role of lithium is in the energy transition. Could the same not be said about iron and steel? New electric vehicles and wind turbine blades cannot be made without steel. So, to make steel sexy again, governments around the world could designate iron a critical material just like many have done with lithium. Doing so could raise awareness among the public that to transition to zero emissions, steel is needed too.

Steel industry incumbents have it tough when it comes to recruiting, as students have a hard time believing they are actually part of the solution. Green startups, on the other hand, have recent graduates coming to them in droves. One thing steel companies could do to benefit from this interest is create separate divisions within their organizations that encompass their green activities. This distinction could help convince graduates that they can make the world more sustainable even if they work for steelmakers.

Finally, universities also have a role to play here. Students have become less interested in material sciences over time, which shrinks the pipeline of engineers for the steel industry. One way to revive interest is to offer material sciences in combination with topics students now gravitate toward, such as AI and sustainability. This idea does not have to be a marketing gimmick, as there are ways these topics can be seamlessly combined with material sciences to be beneficial to both students and future employers.

Next, we move to an examination of the role policy will play in accelerating the steel transition.

First, governments should focus on reducing friction in the steel transition. On the demand side, this could be done through green steel requirements in procurement for government projects. On the supply side, this could mean accelerating the permitting processes for new steel plants. European Union countries showed they could get permitting done for new LNG terminals at light speed after the invasion of Ukraine. This crisis mindset should be applied to green steel projects as well.

As a next step, governments could consider implementing green premiums, which would be the most effective way to make low-emissions steel competitive with regular blast furnace steel. One way could be to introduce a green iron production tax credit, similar to what the United States did for hydrogen in 2022. An iron tax credit would mean that for every tonne of iron produced, the manufacturer gets to deduct a certain amount from its taxes. As previously mentioned in the discussion of green steel and green iron definitions, the tax credit should be technology neutral to encourage innovation. Another way could be to introduce carbon pricing in combination with a carbon border adjustment mechanism to prevent carbon leakage, just like the EU has done for carbon-intensive products like fertilizer, cement, and of course, steel.

Finally, governments could help by reducing the risks of investments in new steelmaking technologies, which in turn would help companies reduce their cost of capital. Investments in new steel ventures tend to have high risk because of the combination of high capital requirements and fluctuating prices. In an industry that operates on three-month spot prices, risk can be reduced considerably if prices are guaranteed for a longer period of time.

One way to do this is through contracts for difference, backed by a supportive government. With a contract for difference, a steelmaker is guaranteed a certain price per tonne of steel. The counterparty in the contract for difference — in this case, a government — chips in if the market price drops below the guaranteed price. However, if the market price rises above the guaranteed price, the government pockets the difference. With this guaranteed price, steelmaking companies pioneering emissions-free technologies could have a better chance to raise financing.

Electricity for All

The steel challenge may seem daunting, especially when considering all the other industries that also need to transition to hit net zero by 2050. Besides producing near-zero emissions steel, there is a need for windmills, heat pumps, electric vehicles, and much more. Where should the industry start?

There may be a good case to start with steel, and not just because it is responsible for 10% of global CO_2 emissions. No matter which transition path the world ends up following, one point is sure: The steel industry is going to need a lot of electricity, either directly or indirectly through the consumption of hydrogen. Given how important many countries consider their steel industry to be, governments may listen when the steel industry expresses a need for more electricity.

The steel industry could, therefore, be an important catalyst to drive global electrification. It has a couple advantages over other sectors that will require a lot of electricity. First, the steel industry is highly concentrated, which means it can make its needs heard with governments. Second, the industry has no choice but to consume massive amounts of electricity if it wants to decarbonize. Products like EVs and heat pumps are still relatively new, and there are still many efficiency gains to be made to reduce electricity demand. Steel, on the other hand, quickly runs into the cold, hard boundaries of thermodynamics: If there is not enough electricity, there is no steel transition.

As this discussion makes clear, steel decarbonization has no easy, blanket solution. In developed economies, existing steelmaking infrastructure needs to be replaced and new supporting infrastructure needs to be created within the time span of one average plant life. In developing economies, there needs to be a balance between decarbonization and growth targets, giving countries a chance to develop their economies. We must discover which steelmaking technology offers the most effective and cost-efficient transition in every country with a steel industry. And we need to get it all done in the next 30 years.