Emerging Technology Concepts to Fully Decarbonize Ironmaking

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ABSTRACT

The most energy- and carbon-intensive step in today's steelmaking value chain is blast furnace ironmaking, wherein coke reduces iron ore to iron. The global steel industry is developing ironmaking decarbonization strategies, but significant challenges remain, particularly developing solutions at a cost that would incentivize blast furnace retrofit or replacement.

We analyze new technology concepts that could completely decarbonize ironmaking if demonstrated and scaled. First, we present the energy-emissions-cost tradespace of existing and pilot-scale ironmaking technologies and identify whitespace opportunities. Then, we propose three requirements for any candidate technology to decarbonize ironmaking at scale: levelized cost of steel, GHG intensity, and the future scalability of all inputs. Next, we evaluate several early clean ironmaking technology categories that could meet these criteria: (1) hydrogen plasma ironmaking, (2) high- and low-temperature direct electrolysis of ores to iron, (3) biomass-based ironmaking, and (4) emerging thermochemical ironmaking technologies, including sustainable syngas. Finally, we identify the specific challenges each category faces and discuss potential goals that would enable technology concepts to succeed.

We find several themes to be common across the technology categories. The cross-cutting R&D needs for ironmaking processes are: (a) process intensification and new reactor designs to best utilize sustainable energy carriers and (b) modular reactors to ease technology de-risking, scale-up and commercialization. We also find that integration of zero-emissions ironmaking technologies into the existing value chain must be considered, including synchronization and integration with steelmaking processes and testing to meet iron specifications for iron insertion into steelmaking furnaces.

Introduction

Global Steel Production

Globally, iron and steel production emit the most CO_2 of all manufacturing sectors. About 1800 megatonnes (Mt) of crude steel are produced annually each year (World Steel Association 2018), of which approximately one-third was recycled from scrap steel (Cullen, Allwood, and Bambach 2012). This enormous amount of steel is used in all sectors, e.g., for the construction of buildings and other infrastructure, cars and other transportation modes, mechanical and electrical equipment, and consumer goods, appliances, and packaging. Despite their many benefits, these many steel products come with hefty energy and emissions outcomes: ~7% of global energy use (over 38 EJ; (Allwood and Cullen 2015)) and ~7% of global greenhouse gas (GHG) emissions (3.5 Gt CO_2e; (Bloomberg New Energy Finance 2020)). These high emissions are the price of improved living conditions; as one stakeholder summarized, referring to a plateau of steel stock once nations have largely developed: "Happiness is ten tons steel per capita." Annual steel production is expected to almost double by 2050, reaching ~2500

Mt steel per year, as communities in developing nations begin to enjoy higher qualities of life (International Energy Agency 2020).

Domestic Steel Production

The domestic production of steel today accounts for about 4% of U.S. emissions and 2% of U.S. energy use. An industrialized nation which is no longer growing rapidly, the United States experiences a relatively consistent annual steel demand of about 120 Mt/yr (about 8% of global demand) (World Steel Association 2018). As shown in Figure 1, about 2/3 of this steel is produced domestically (80 Mt in 2013) and 1/3 is net imported either as semifinished steel (29 Mt) or as steel inside goods (14 Mt). As shown in Figure 1, domestically, steel is produced via two routes: (1) the blast furnace – basic oxygen furnace (BF-BOF) route, and (2) scrap combined with natural gas-based direct reduced iron (NG-DRI) ironmaking – electric arc furnace recycling (EAF) route. In 2010, about 31 Mt steel was made via the BF-BOF route and about 49 Mt was made via the EAF route.

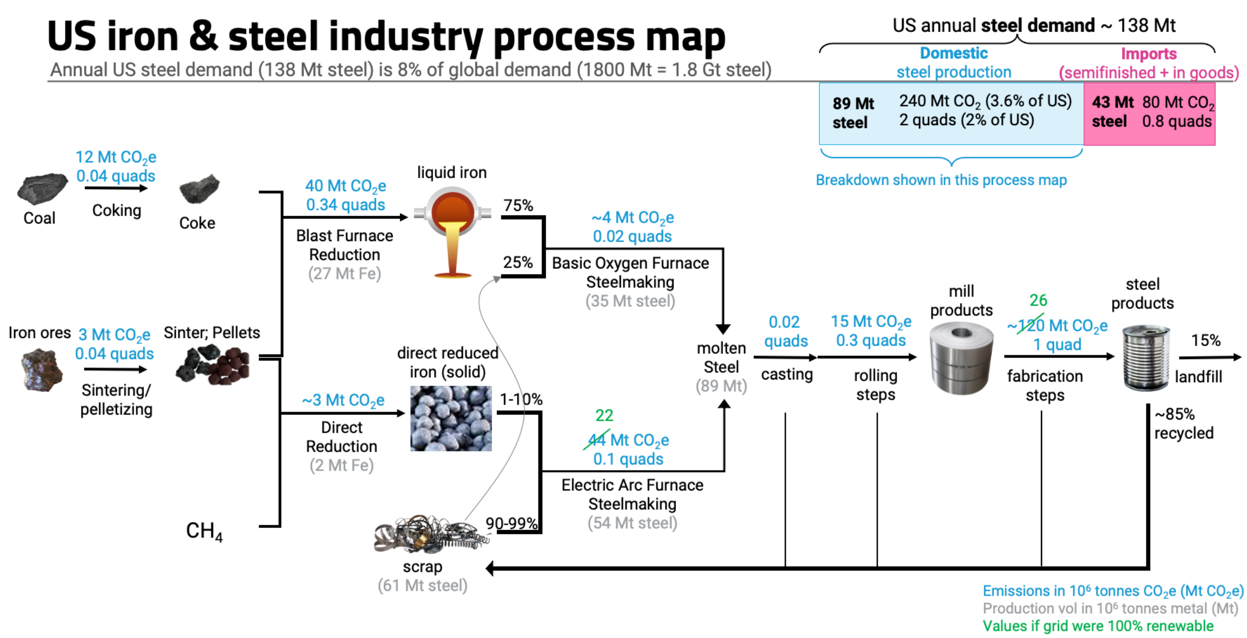

Figure 1. Process map of the United States iron and steel industry annotated with energy use, GHG emissions, and production volumes. These approximate values correspond to the year 2010. *Sources*: World Steel Association 2018; Allwood and Cullen 2015; "Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing,"; Fruehan et al. 2000; United States Environmental Protection Agency 2012.

The availability of steel products worldwide is crucial to sustainable development goals, but steel's embodied emissions must be abated to avoid the most serious effects of climate change (Committee on Accelerating Decarbonization in the United States et al. 2021). Ore pre-processing emissions (e.g., sintering/pelletizing, shown in Figure 1) are common to all commercialized ironmaking routes today. Technologies to decarbonize or eliminate these agglomeration steps, while important, are outside the scope of the present study. As shown in Figure 1, the most emissions-intensive process stages are blast furnace ironmaking, and fabrication, each of which emits 1.5 t CO_2e / t metal produced at that stage (Chang and Fang 2021). However, emissions are evolving with the nation's electricity mix. A future scenario with

100% green electricity has been envisioned, in line with President Biden's goal of a net-zero economy by 2050 (Volcovici et al. 2021). The emissions in this scenario are shown in green in Figure 1 when different from the baseline scenario. Emissions from EAFs and fabrication will decrease substantially with a green grid. In contrast, the other stages are largely fossil fuel driven, and the greening grid will thus have a negligible impact on their emissions. This future scenario highlights that the BF ironmaking process is the largest emissions source in the steel value chain for which there is no existing emissions-reduction technology solution today.

In the present work, we highlight the R&D breakthroughs needed for zero-emissions ironmaking processes with a credible future path toward enabling zero-emissions steelmaking at global scale (~2 Gt steel/yr).

Evaluation of Commercial and Pilot-Scale Ironmaking Technologies

In this section, we evaluate the main two commercial ironmaking technologies (BF-BOF and NG-DRI) and the main two piloted lower emissions ironmaking strategies (CCUS and H_2 DRI). Our evaluation metrics are: cost, emissions, and energy, with all quantities normalized per tonne of crude steel.

1. Commercial Fossil Fuel-Fired Ironmaking

Fossil-based ironmaking represents the vast majority of global ironmaking installments,[1] because of widespread fossil fuel availability, low cost, and, in many cases, already-recovered capital investments. Globally, steel is produced via four fossil-based routes, as shown in Table 1:

Table 1. Global steel production routes

Route	% of global steelmaking
BF-BOF	71%
scrap recycling in EAFs	24%
NG-DRI	4%
coal DRI	1%

Source: Fan and Friedmann 2021.

Herein, we discuss only the BF-BOF route and the NG-DRI route. We refer the reader to the literature regarding scrap recycling – whose emissions are ~0.2 t CO_2e/t crude steel, thus about 10% of that of the BF-BOF route (International Energy Agency 2020; Pauliuk et al. 2013) – and the coal-based DRI route (Fan and Friedmann 2021), which we do not analyze in this work, though we underscore its growing prominence especially in India.

Representative BF-BOF and NG-DRI emissions and levelized crude steel production costs are shown in Figure 2, and their specific energy use per tonne steel are shown in Figure 3. Taken together, these data indicate that primary steel production is a large greenhouse gas source and that substantial opportunities may exist to improve energy efficiency.

[1] Biomass-based ironmaking in Brazil is the only major commercially deployed alternative to fossil-based ironmaking today, to the best of our knowledge.

2. Carbon Capture, Use and Storage (CCUS) Pilots

A dominant medium-term strategy toward zero-emissions steelmaking is to implement carbon capture, use and storage (CCUS). CCU refers CO_2 capture and subsequent conversion into saleable products like fuels, chemicals, and materials. CCU is expected to play a transitional role but does not constitute a zero-emissions solution, since the CO_2 is typically emitted after the product is burned or used. Conversely, CCS refers CO_2 capture and permanent storage, for example in geological repositories. These CCUS capabilities may be retrofitted onto fossil fuel-based ironmaking reactors like BFs and DRI systems, or even designed into greenfield ironmaking installations. Adding CCUS is expected to increase the levelized cost of crude steel by about 15-29% (Gates 2020), as shown in Figure 2, and is expected to increase energy use by at least 0.2 GJ/t crude steel, as shown in Figure 3 (Fan and Friedmann 2021). Several R&D efforts and pilot projects aim to demonstrate these technologies and decrease their costs, including: HIsarna (van der Stel et al. 2013), Al Reyadah (Sakaria 2017), Carbon2Chem (Wich et al. 2020), Steelanol (Van der Stricht et al., n.d.), and COURSE 50, among others.

Unfortunately, even with CCUS, the fossil-based routes' emissions are nontrivially high, at 1.0 t CO_2e and 0.3 t CO_2e per t crude steel produced, respectively, for the representative BF-BOF-CCS retrofit and NG-DRI-CCS retrofit routes assessed by Fan and Friedmann (2021) (Figure 2). These residual emissions stem primarily from incomplete CO_2 capture from flue stream and, for the BF-BOF route, also from uncaptured emissions from the coking process. Ultimately, while CCUS is a helpful near-term partially decarbonized transitional technology, fully zero-emissions long-term strategies are also important for future net-zero climate goals.

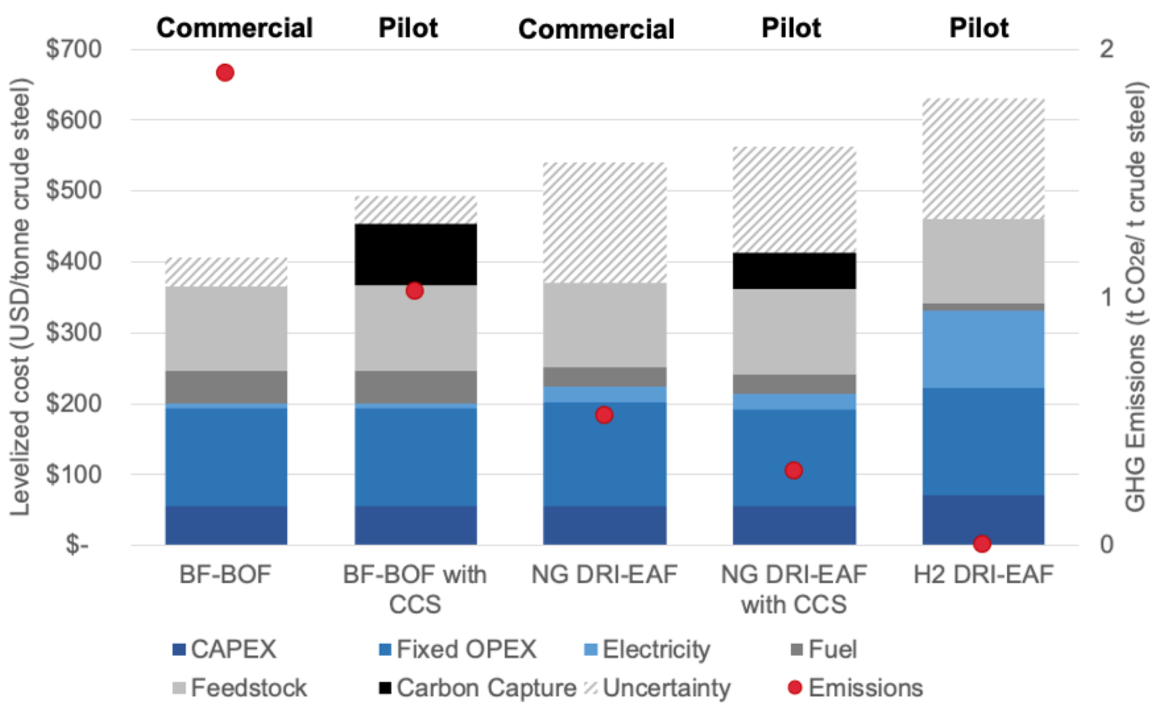

Figure 2. Levelized cost of steel for commercial and pilot routes as greenfield deployments with 3 c/kWh zero-carbon electricity. Emissions include Scope 1, Scope 2, and upstream coking process (Scope 3). *Source*: Own assumptions, based largely on IEA (2019) and Fan and Friedmann (2021). IEA (2019) The Future of Hydrogen, https://www.iea.org/reports/the-future-of-hydrogen.

3. Hydrogen-Based Direct Reduced Ironmaking (H_2 DRI) Pilots

A dominant long-term strategy for many global steel companies is to first produce net zero-emissions hydrogen, then use the hydrogen in direct reduced ironmaking, H_2 DRI, and finally insert the DRI into a steelmaking furnace ("The Use of Hydrogen in the Iron and Steel Industry," n.d.; Sortwell et al. 2018; Koch Blank, n.d.; Hasanbeigi, Arens, and Price 2014). We briefly discuss the R&D thrusts for these processes.

Hydrogen Production. Several technology routes are being envisioned for net-zero emissions hydrogen production, including "green" hydrogen production from water via electrolysis using renewable electricity and "blue" hydrogen production from steam methane reforming and subsequent CCS of the co-produced CO_2. Today, zero-emission routes to H_2 are at least 50% more expensive than their fossil-based counterparts (IEA 2019). Moreover, as shown in Figure 2, the levelized cost of steel via H_2 DRI is projected to remain higher than the CCS and fossil routes (IEA 2019) The R&D, implementation, and policy challenges to lower the cost and increase the availability of various zero-emission hydrogen production methods are reviewed elsewhere (IEA 2019). Department of Energy Secretary Granholm's recent announcement of an initiative to produce \$1/kg H_2 in one decade (United States Department of Energy 2021) is one example of several efforts to reduce hydrogen production cost.

Hydrogen Direct Reduced Ironmaking. After hydrogen production and possibly hydrogen storage and transportation, the hydrogen gas may be used as a reductant for ironmaking. Several pilots and R&D efforts are underway to de-risk technology options, including: the H2Future project by voestalpine (Buergler and Prammer 2019), the Hybrit project by SSAB, LKAB and Vattenfall (Pei et al. 2020), MIDREX (2018), GrInHy and SALCOS by Salzgitter (Dorndorf 2020; Juchmann and Redenius 2021), and the H2morrow project led by thyssenkrupp (Reuters Staff 2021), among others. An energy use of just over 12 GJ/t crude steel is projected by the IEA for a representative H_2 DRI technology, making it potentially less energy-intensive than BF ironmaking (Figure 3). Challenges and opportunities for H_2 DRI are reviewed elsewhere (International Energy Agency 2020).

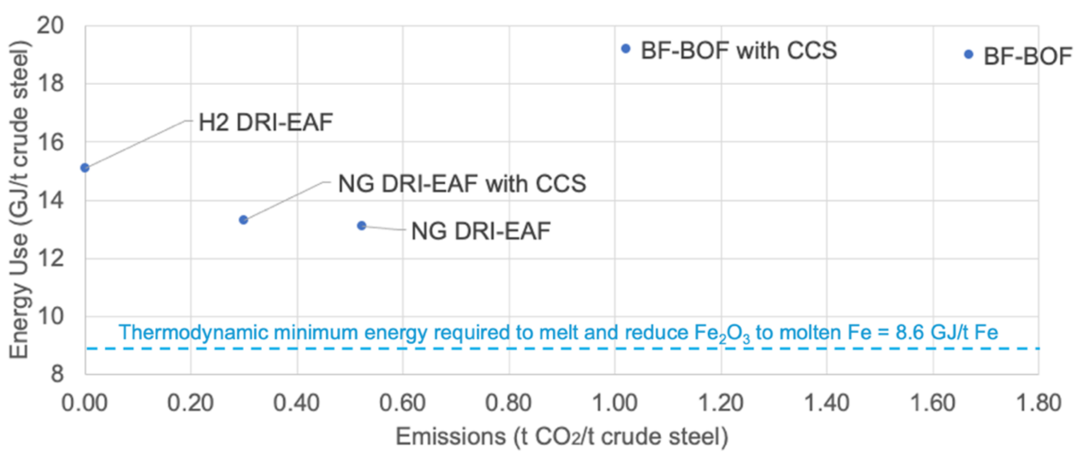

Figure 3. Energy-emissions tradespace for representative commercial and pilot ironmaking routes. *Source*: Own calculations, with assumptions based on values from IEA (2019) and Fan and Friedmann (2021). Thermodynamic minimum energy to produce molten iron is from Fruehan et al. (2000) and is roughly the energy needed to produce molten steel.

The Whitespace for Future Zero-Emissions Ironmaking Technologies

Unfortunately, the currently explored pilot technologies – CCUS and H_2 DRI – have drawbacks. CCUS still emits a substantial amount of GHG, so either bioenergy with CCS (BECCS) or direct air capture (DAC) are needed for net-zero steel production, significantly adding to cost. H_2 DRI has several risks, including uncertainty surrounding the availability of cheap zero-emissions hydrogen. Accordingly, new clean ironmaking technologies with lower cost than currently explored options are an important target.

In addition to being zero-emissions and reaching cost parity with the incumbent options, new ironmaking technologies should also provide a credible technology pathway to steelmaking at global scale, in order to potentially substantially decarbonize the sector. Thus, the global availability of process inputs must be considered, as summarized in Table 2.

Table 2. Metrics for future ironmaking technologies

Criterion	Potential target value	Incumbent value
GHG emissions from ironmaking process	0 t CO_2e/t Fe	1.4-3 t CO_2e/t Fe (Fan and Friedmann 2021)
Annual scalability of inputs needed for process (tons/yr)	Enough to enable ~2Gt/yr steel production	Gigatons of iron ore, coking coal, slag, and process water
Could produce a pig-iron replacement at cost parity with CCS and H_2 DRI routes	>= 95 wt.% pure Fe at ~\$500/ton	95 wt.% pure Fe at ~\$400/ton

Next, we evaluate several emerging ironmaking concepts that could meet these criteria.

Zero-Emissions Ironmaking Technology Concepts

Several promising technology routes could meet these three criteria. Acknowledging that this list is not exhaustive and underscoring that further innovative ideas not shown here are important to consider as well, we evaluate the following four representative examples:

(1) Hydrogen plasma ironmaking
(2) Electrolytic ironmaking
(3) Biomass-based ironmaking
(4) Emerging thermochemical ironmaking routes

1. Hydrogen Plasma Ironmaking

Route overview and benefits. In this technology category, hydrogen plasma (HP) is used as a reducing agent instead of H_2 gas. The main problem this technique is solving is that the H_2 iron ore reduction reaction is endothermic, but many current DRI furnaces are not set up to provide heat to the reaction. Rather, they rely on the exothermic CO and iron ore reaction to provide heat in-situ. However, HP contains more energy than H_2, as it comprises vibrationally excited molecular, atomic, and ionic states of hydrogen (mix of H, H^+, H_2^+, H_3^+ and/or H_2^*). Thus, the HP iron ore reduction reaction is exothermic. Moreover, the reaction rate of HP with ore is fast and reactant collisions are productive with high efficiency. These features imply that the number of gas recycling cycles needed can be low, and the temperature needed to activate the reaction is less than for H_2 gas.

Prior art and current work. Many methods have been investigated and pre-piloted which are reviewed elsewhere (Behera et al. 2019) but there is no current full pilot-scale work. The most advanced current pre-pilot demonstration to the best of our knowledge is within voestalpine's work in collaboration with the University of Leoben (Plaul, Krieger, and Bäck 2005).

R&D breakthroughs needed. As opposed to other ironmaking routes discussed herein, which may find appropriate application in different niches than H_2 DRI, HP ironmaking may be considered to be directly competitive with H_2 DRI because it requires the same inputs. Hydrogen plasma (HP) ironmaking shares many of the same challenges as H_2 DRI, in that both technologies first rely on the upstream production of zero-emissions H_2. Moreover, a successful HP reactor design would do well to benefit from the specific efficiency and productivity gains of HP without overrunning levelized cost of steel above the cost parity metric set above. Challenges and R&D needs specific to HP ironmaking are shown in Table 3.

Table 3. Hydrogen plasma ironmaking key challenges and R&D needs

Benefits	Key challenges	R&D needs
• Greater thermodynamic driving force and faster kinetics • Reduced reaction temperatures • Solves issue of endothermicity (heating requirement) of H_2 DRI	• Plasma generation and control (e.g. arc stability) • Energy efficiency, including heat management/cooling • Reactant efficiency, i.e., plasma utilization rate • Continuous production • Plasma impact on refractory lining	• Reactor designs for continuous Fe production that achieve low energy/electricity use per tonne iron produced • Study and minimization of plasma degradation of refractory lining

2. Electrolytic Ironmaking

Route overview and benefits. Electrowinning – also known as electrolysis – to produce iron from ores typically follows this redox reaction:

$$FeO_x \rightarrow Fe + x/2\ O_2$$

No additional reducing agent is needed, since the overall reaction is a disproportionation of the iron ore, wherein Fe^{n+} cations are reduced and O^{2-} anions are oxidized.[2] The reaction is powered by electricity and takes place in an electrochemical cell, wherein Fe is produced at a cathode and oxygen gas (O_2) is produced at an anode. A central potential benefit of electrolytic ironmaking from ores is the possibility of high energy efficiency due to the direct pathway from clean electricity to ironmaking, without employing any chemical (fuel) intermediate.

[2] We have seen electrons being described as 'the reducing agent' in several published works, but this concept is not accurate. Rather, reducing agents are species that provide electrons to other species. In ore electrolysis, the oxide anions in the ore act as the reducing agent.

R&D breakthroughs needed. The temperature-independent challenges and opportunities for electrolytic ironmaking are summarized in Table 4. The largest technical challenges for electrolytic ironmaking are annual production volume, i.e., throughput, and, relatedly, physical scale. These are both bottlenecks because the Fe production rate limitation is current delivered from the surface area of the electrodes (often measured in A/cm^2 of electrode surface). An example class of solution to this challenge would be strategies that make electrochemical ironmaking scale by volume instead of by area.

Another challenge common to all electrowinning approach styles is presence of impurities in the ore. If these impurities have similar densities and solubility characteristics to Fe, they may be incorporated into the final metal product, a phenomenon that may be either beneficial or detrimental depending on the element and the desired metal or alloy ferrous product. Accordingly, zero-emission techniques to either: (1) beneficiate the ore in advance of their introduction into the electrolytic cell or (2) separate impurities while in the electrolytic cell or assembly, would be broadly enabling.

Table 4. Electrolytic ironmaking key challenges and R&D needs (all temperatures)

Benefits	Key challenges	R&D needs
• Possibility of high efficiency from renewable electricity, without intermediate fuel	• Annual production volume (throughput) • Scale • Ore impurities	• Modular reactors • Electrodes and chemistries that enable very high (~1A/cm^2) current density • Cheap impurity removal technologies, e.g., ore beneficiation

We next separate out electrolysis routes into two categories: high-temperature electrolysis (> ~1500 °C), and low-temperature electrolysis (< ~110 °C), as the technoeconomic drivers are different for the two temperature regimes. We have not included intermediate-temperature ironmaking because it is considered technoeconomically suboptimal (Stinn and Allanore 2020).

2a. High-Temperature Electrolysis for Molten Fe Production

Route overview and benefits. In this process, which takes place above 1500 °C, a molten electrolyte dissolves the iron ore, and liquid iron metal is produced at the cathode. A main benefit of a high-temperature process is faster kinetics, potentially implying faster throughput.

Prior art and current work. The main concepts in this category have used molten oxides as the electrolyte. Arcelor-Mittal and others explored the MIDEIO ULCOS process from 2004-2012 (Wiencke et al. 2018). Boston Metal has commercialized work from MIT (Allanore, Yin, and Sadoway 2013) and is currently funding a pilot project the United States (Boston Metal n.d.).

R&D breakthroughs needed. One main challenge for these techniques is high upfront cost (capital expenditure) associated with several issues: (a) refractory materials are needed to contain the melt and must withstand high temperatures and potentially corrosive environments, (b) a large amount of current may run through the cell, to resistively heat to > 1500 °C, so the buswork needed to handle these large currents is nontrivial, and (c) inert, non-corrosive anodes may become expensive depending on what material is used.

Another challenge for high-temperature electrolysis is that the large amount of electricity used (including for heating) may imply high cost of electricity to run the plant. Furthermore, it is possible that these plants must operate as baseload electricity users, in order to keep the melt hot, delivering continuous operation.

The challenges for this technology are summarized in Table 5. To solve these challenges, research to make cheaper refractories and low-cost, energy-efficient buswork would be broadly enabling. Modular reactors may be key to helping to solve the issues with upfront capital investment. Inert anodes must be developed which have lifecycle costs low enough to meet levelized crude steel cost targets.

Table 5. High-temperature electrolytic ironmaking key challenges and R&D needs

Benefits	Key challenges	R&D needs
• Faster reaction kinetics	• High upfront cost • Baseload electricity requirement	• Inert anodes • Low-cost refractories/insulation • Low-cost, efficient buswork and rectification

2b. Low-Temperature Electrowinning for Solid Fe Production

Route overview and benefits. The ore electrolysis redox reaction run at low temperature may have the benefits of lower energy use – since a solid as opposed to molten product is formed – and lower cost of equipment, as no refractories are needed. Moreover, it may enable flexible production, benefitting from low electricity prices at peak production times.

Prior art and current work. The SIDERWIN demonstration project pioneered by ArcelorMittal, is a low-temperature (~110 °C) aqueous process to produce Fe metal plates batchwise (SIDERWIN, n.d.; Lavelaine and Maizières, n.d.; IERO 2014).

R&D breakthroughs needed. The main challenge for low-temperature electrolytic ironmaking is a potentially slow reaction rate. Increasing up to > 60 °C to 100 °C may be beneficial (Stinn and Allanore 2020). In addition, intermittent production, though beneficially decreasing electricity purchased, also poses its own challenges, since capex utilization will be lower, increasing the levelized cost of steel. System designs to prove out whether intermittent operation is economically favorable is needed, as summarized in Table 6.

Table 6. Low-temperature electrolytic ironmaking key challenges and R&D needs

Benefits	Key challenges	R&D needs
• More amenable to time-flexible production • Potential for lower ironmaking energy use • Cheaper equipment	• Slower chemical reactions at low temperature • H_2 evolution at cathode (for aqueous systems)	• Continuous reactor designs • Chemistries and designs to increase reaction rate • Cost-effective ways to produce Fe intermittently

3. Biomass-Based Ironmaking

Route overview and benefits. In these routes, biomass-derived reductant feedstocks are used instead of the incumbent fossil feedstocks. A central potential benefit of biomass-derived feedstocks is the potential for them to drop into the existing ironmaking production chain with little retrofit. For example, biocharcoal may be able to replace coking coal in blast furnaces (Suopajärvi, Pongrácz, and Fabritius 2013). Biomass retrofit thus presents an opportunity to quickly reduce ironmaking emissions. The design of new biomass-fueled ironmaking furnaces also provides alternative benefits, such as flexibility to match the reactor design to locally available biomass, which may be important given geographic logistical considerations.

Prior art and current work. Biomass – for example wood – has been used as a feedstock reducing agent for ironmaking throughout history. A recent resurgence in interest in the potential for biomass-based ironmaking has been driven primarily by climate concerns, and this research is reviewed elsewhere (Suopajärvi et al. 2017). The main biomass-based commercial ironmaking routes today are found in Brazil, for example by the company Plantar Siderurgica, but the carbon emissions from these processes are still significant, so this bio-steel is not considered to be carbon neutral (Sonter et al. 2015).

R&D breakthroughs needed. For biomass to be a truly zero-emissions option for ironmaking, several challenges must be addressed. Assessment of the lifecycle emissions of any biomass pathway is key: All stages are important, from the land-use change associated with harvesting biomass, to biomass processing emission control (torrefaction and further thermochemical enhancements such as gasification and pyrolysis), and charcoal production method (Suopajärvi and Fabritius 2013). These processing methods also increase the cost of the metallurgical biomass feedstock, a second central challenge for this route. Finally, the use of biomass for energy or manufacturing purposes must be weighed against competition for other uses, and pathways must be identified that are regionally sustainable (Mandova et al. 2018). For biomass to become a significant route in the zero-emissions ironmaking ecosystem, addressing these concerns is key, as summarized in Table 7.

Table 7. Biomass-based ironmaking key challenges and R&D needs

Technology & benefits	Key challenges	R&D needs
Retrofits/Drop-in • Relatively easy to drop biochar into BFs • Near-term solution Greenfield • Flexibility to match to location/type of biomass • Flexibility to design facilities for technology	• Production cost, including logistics and technology • Lifecycle emissions (including land-use change) • Availability, including geographic limitations • Competition with cropland and with other biofuel uses	• LCA to identify low-emissions feedstocks, production pathways, and transportation scenarios • Technologies to decrease biomass reductant cost • Technologies to offset biomass reductant cost, e.g., higher-value products co-production

4. Emerging Thermochemical Ironmaking Routes

Many non-fossil reductants may be considered. Here we overview the breakthroughs needed generally, and explore the representative example of renewable syngas.

Route overview and benefits. Thermochemical ironmaking using non-fossil, non-biomass fuels may be advantageous for several reasons. First, as opposed to the electrode surface area limitation of electrolytic ore reduction (current density limitation), thermochemical reactors have the possibility of obtaining faster throughput, due to their utilization of the full volume of reactors and the intimate mixing of reactants. Since pure H_2 gas reduction is currently being piloted, any proposed alternative route may need to articulate specific benefits relative to H_2 DRI, most importantly cost and/or feedstock availability benefits.

In the specific example case of renewable syngas, this technology pathway would build on the existing mature syngas-based DRI process (NG-DRI) by using sustainable syngas. One possible route would be to a "closed loop," to capture the CO_2 and turning it back into CO using renewable energy, releasing O_2 byproduct. A benefit of this pathway is that the ironmaking technology is mature and globally scaled already, so R&D is only needed for the CO_2 looping retrofit equipment and integration. Another possible route would be an "open loop," in which CO_2 is not captured at the flue stream, but is captured from the air by direct air capture or biomass, and then converted into syngas for use at the ironmaking plant.

Prior art and current work. The NG-DRI process, which represents ~4% of global steel production, first converts natural gas to syngas (CO + H_2) and then this syngas is used in ironmaking (Atsushi, Uemura, and Sakaguchi, n.d.). Sustainable syngas closed looping has not been explicitly studied. Current research applicable to "open loop" sustainable syngas ironmaking includes: direct air capture (Breyer et al. 2019), zero-emissions $CO_2 \rightarrow CO$ conversion technologies (Rafiee et al. 2018), and biomass gasification (Ren et al. 2019).

R&D breakthroughs needed. Pathways for thermochemical ironmaking from alternative (non-fossil, non-bio) reductants are relatively understudied. More technology-oriented research is needed to establish which feedstocks may be utilized effectively at scale, especially in comparison to H_2 DRI pilot projects. The R&D needs are described below in Tables 8 and 9.

Table 8. Sustainable syngas-based ironmaking key challenges and R&D needs

Benefits	Key challenges	R&D needs
• Mature reductant chemistry • Solves H_2 endothermicity problem by using some CO reductant	• Closed loop: Flue CO_2 capture and regeneration cost, gas separations and handling • Open loop: Cost and scale of the CO_2 capture and conversion technique (e.g., DAC, biomass gasification)	• Closed loop: Low-cost CO_2 to CO reforming, possibly alongside/integrated with H_2O to H_2 reforming • Open loop: Low-cost, large-scale renewable syngas production

Table 9. Emerging thermochemical ironmaking routes: key challenges and R&D needs

Benefits	Key challenges	R&D needs
• Depending on reductant, potential for several parameters to be more favorable, including availability, handling, levelized steel production cost, cost per CO_2 abated, etc.	• Cost of reductant production/ reductant synthesis technology • New reductants may need new reactor types • Cost of retrofit of existing reactor types • Meeting composition specifications for downstream steelmaking furnaces	• Low-cost zero-emissions synthesis of reductants at scale (e.g., electrosynthesis) • New reactors specifically designed for any given reductant • For retrofits, modelling and small-scale integration demonstrations

Cross-cutting R&D Needs and Conclusions

Decarbonizing ironmaking is crucial for global GHG emissions mitigation, but zero-emissions ironmaking technologies are not yet cost-competitive with fossil-based technologies. To achieve cost parity, R&D is needed. This report summarizes recommendations for several early-stage ironmaking routes with the potential to achieve zero GHG, global scalability (~2 Gt steel/yr) and low steel cost. Several cross-cutting R&D needs are recognized:

- Process intensification and new reactor designs to best utilize sustainable energy carriers
- Modular reactors to ease technology de-risking, scale-up and commercialization
- Since iron not containing elemental carbon may be produced by some novel ironmaking routes, improved understanding of the melting and transport behavior of carbon-free iron (>99% Fe by weight) may be needed to avoid re-oxidation and other potential problems
- Integration of zero-emissions ironmaking technologies into the existing steel products value chain must be considered, including synchronization with steelmaking processes and testing to meet iron specifications for iron insertion into steelmaking furnaces

We hope the information contained herein will both be useful to current steel industry practitioners and facilitate the ability of non-industrial researchers to support and de-risk technology concepts that have the strongest likelihood of becoming commercially viable.

Acronyms

BECCS	Bioenergy with carbon capture and storage
BF-BOF	Blast furnace – basic oxygen furnace
CAPEX	Capital expenditures
CCUS	Carbon capture, use and storage (or sequestration)
DAC	Direct air capture of CO_2
DRI	Direct reduced iron
EAF	Electric arc furnace
NG-DRI	Natural gas direct reduced iron
OPEX	Operating expenditures

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