CEBA
Clean Energy Buyers Association

POWERING UNITED STATES PRIMARY STEEL DECARBONIZATION

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EXECUTIVE SUMMARY

In the race to decarbonize global economies, steel has become a focal point due to its highly carbon-intensive production processes. In 2020, the production of primary and secondary steel accounted for about 7% of global carbon dioxide equivalent (CO_2e)[1] emissions [1]. While many steel decarbonization studies and reports have been released in recent years, none adequately quantify the electricity required to decarbonize steel.[2]

To begin to fill this gap, CEBA modeled the electricity requirements to transition carbon-intensive primary steel[3] production processes in the United States to utilize a range of advanced decarbonization technologies[4] through 2050. Based on interviews with 22 experts in the field, our analysis assumes that primary steelmaking will remain geographically consistent — concentrated in Indiana, Illinois, Michigan, Ohio, and Pennsylvania — due to established infrastructure and labor relations. Our model demonstrates the electricity demand implications based on potential technology adoption timelines, and the CO_2e emissions intensity given a future grid that corresponds with National Renewable Energy Lab (NREL) modeling of the grid generation mix through 2050.

Our modeling demonstrates that primary steel decarbonization will demand significant increases in electricity generation — approximately 174 terawatt hours (TWh) per year, which is an increase of 159 TWh over business-as-usual by 2050 — to serve a mix of advanced technologies. For context, this represents roughly 10% of the anticipated electricity demand in 2050 across the seven states hosting primary steel production. **Further, to decarbonize this amount of electricity would require 28 gigawatts (GW) of solar and wind along with 53 GW of battery storage.**

Meeting the carbon-free electricity (CFE) demands for steel decarbonization and broader electrification trends across sectors will require access to low-cost renewables and expanded transmission capacity. This expansion is essential for moving low-cost power and enhancing grid reliability with intermittent resources from renewables. Given the distances between low-cost CFE sources and primary steel production centers, comprehensive regional and interregional transmission planning is necessary to support steel and broader industrial decarbonization [2, 3].

Including steel decarbonization in statewide electricity demand forecasts is crucial for planning a reliable and affordable national electricity system. These forecasts will guide grid mix and transmission planning to meet increased demand. Proactive and integrated regional transmission planning is particularly important in states aiming to retain steel jobs and economic benefits. Further analysis is needed to identify the optimal scaling of electricity infrastructure for the steel decarbonization transition, with significant CO_2e reduction potential if plant siting aligns with broader grid decarbonization efforts.

SECTION 1: OVERVIEW OF UNITED STATES STEEL INDUSTRY

1.1 PRIMARY STEEL PRODUCTION TECHNOLOGIES

Various technological processes for steel production have vastly different carbon footprints. This report focuses on primary steel production in the United States; this type of steel is made with iron ore and currently relies on coal and natural gas-intensive processes. While primary steel production-related processes take place in just 11 mills and account for only 37% of steel produced in the United States, these processes account for 76% of CO_2e emissions from the United States steel industry. The larger secondary steel production industry, which uses scrap as a base feedstock for electric arc furnaces (EAFs) and is largely electricity-based, has a much smaller carbon footprint, constituting 63% of production but only 24% of emissions. Table 1 outlines the information.

Current methods of primary steel production:

1. **The blast furnace-basic oxygen furnace (BF-BOF) process** is highly carbon-intensive and accounts for about 31% of total United States steel production and 73% of United States steel emissions. The BF-BOF process begins by using coke (a coal-based fuel) and metallurgical coal to reduce iron ore in a blast furnace (BF) at 1,600°C. The molten iron then flows directly into a basic oxygen furnace (BOF) for oxidization to remove excess carbon, and combines with other alloying elements to produce crude steel [4, 5].

2. **The direct reduced iron-electric arc furnace (DRI-EAF)** process is much less carbon-intensive than the BF-BOF process and produces about 6% of steel in the United States and 3% of United States steel emissions. The DRI-EAF pathway uses a gas reducing agent, traditionally natural gas, to reduce iron ore to direct reduced iron. This solid form of metallic iron is then combined with other alloys in an EAF to produce crude steel [4, 5]. Notably, several grades of steel that are required by the automotive and defense industries are currently only produced via the BF-BOF pathway. However, EAFs have continued to advance since their initial development and are on track to be able to produce all key grades of steel by 2030 [6].

TABLE 1
United States Based Primary Steel Production, Emissions, and Emissions Intensity

	Production (% compared to overall steel production)	Emissions (% compared to overall steel production emissions)	Emissions Intensity (t CO_2e/t CS)[5]
Primary Production	**37%**	**76%**	
BF-BOF process	31%	73%	2.2
DRI-EAF process	6%	3%	1.1
Secondary Production	**63%**	**24%**	
Scrap based EAF process	63%	24%	0.4

Sources: Production [7, 8]; Emissions [9]; Emissions Intensity [10, 11, 12]

Advanced decarbonization technologies for primary steel production:

1. **Carbon Capture, Utilization, and Sequestration (CCUS):** Both coke BF-BOF and NG DRI-EAF plants can use CCUS to reduce on-site scope 1 process emissions and off-site grid-based scope 2 emissions. CO_2 capture technology could be retrofitted to the one currently operating stand-alone BOF plant, seven integrated BF-BOF plants, and three DRI plants. Commercialization of BF-BOF + CCUS technology is expected by 2035, with a maximum plant-wide emission abatement potential of 80%. DRI + CCUS technology is already operational in Abu Dhabi, United Arab Emirates, but with abatement of only 45% of direct reduction process and 26% of total plant emissions[6] in 2022 [13]. CCUS, which is electricity-intensive per unit of CO_2 captured, can also be installed to reduce net emissions from the conventional electricity generation that will be needed to a certain extent for other electricity-based steel production.

2. **Hydrogen (H_2):** Hydrogen can be injected directly into existing BF-BOF processes and can replace up to 30% of the NG feedstock without modifications at NG-DRI plants [14]. The plants could be converted to 100% H_2, at added cost, for further decarbonization. Hydrogen injection improves BF-BOF process efficiency and has the potential to reduce scope 1 emissions by almost 20%. Hydrogen DRI has the potential to eliminate the need for fossil-fuel based blast furnaces currently used in iron making. Hydrogen DRI-EAF technology is expected to commercialize by 2028 and is less electricity intensive than CCUS. Some thought leaders suggest that steelmaking should be considered the highest and best use of green H_2 and receive preferential access to green H_2 resources [15].

3. **Direct-ore electrolysis (Electrification):** There are currently two promising technologies for the decarbonization of primary steel production, and they are also the furthest from commercialization. Both technologies use direct-ore electrolysis to purify iron in the first step.
    a. **Molten oxide electrolysis (MOE),** developed by Boston Metal, uses clean electricity to convert all iron ore grades into high-quality liquid metal.

b. Electrowinning, developed by Electra, is a process that uses an acid solution and clean electricity to pull pure iron ore out of low-grade ores.

To complete the steel production process, both electrification technologies are coupled with EAFs to replace existing BF-BOF primary steel production with MOE-EAF and electrowinning-EAF plants, respectively. These technologies could be commercially available at an early adoption stage in 2035 [1]. However, given the remaining lifetimes and relining schedules for existing United States BF-BOF plants, full implementation is expected to be delayed to 2040.

Table 2 illustrates a representative 3-million-ton plant in Indiana, comparing the year of viability, electricity required, emissions intensity, and emissions for different technologies.

TABLE 2
2035 Emissions Projections* by Technology for Representative Plant in Indiana

Representative Plant	Year of Viability	Total Electricity Requirements (MWh/year)	Emissions (tCO_2e/year)	Emissions Intensity (tCO_2e/t steel)
BF-BOF	Existing	1,068,000	6,365,628	2.12
BF-BOF-H_2	Immediate	4,156,260	5,780,780	1.93
BF-BOF + CCUS	2035	15,944,298	3,171,367	1.06
H_2-DRI-EAF	2028	10,440,000	2,097,240	0.70
MOE-EAF	2035	12,000,000	2,364,000	0.79
Electrowinning-EAF	2035	11,001,000	2,193,171	0.73

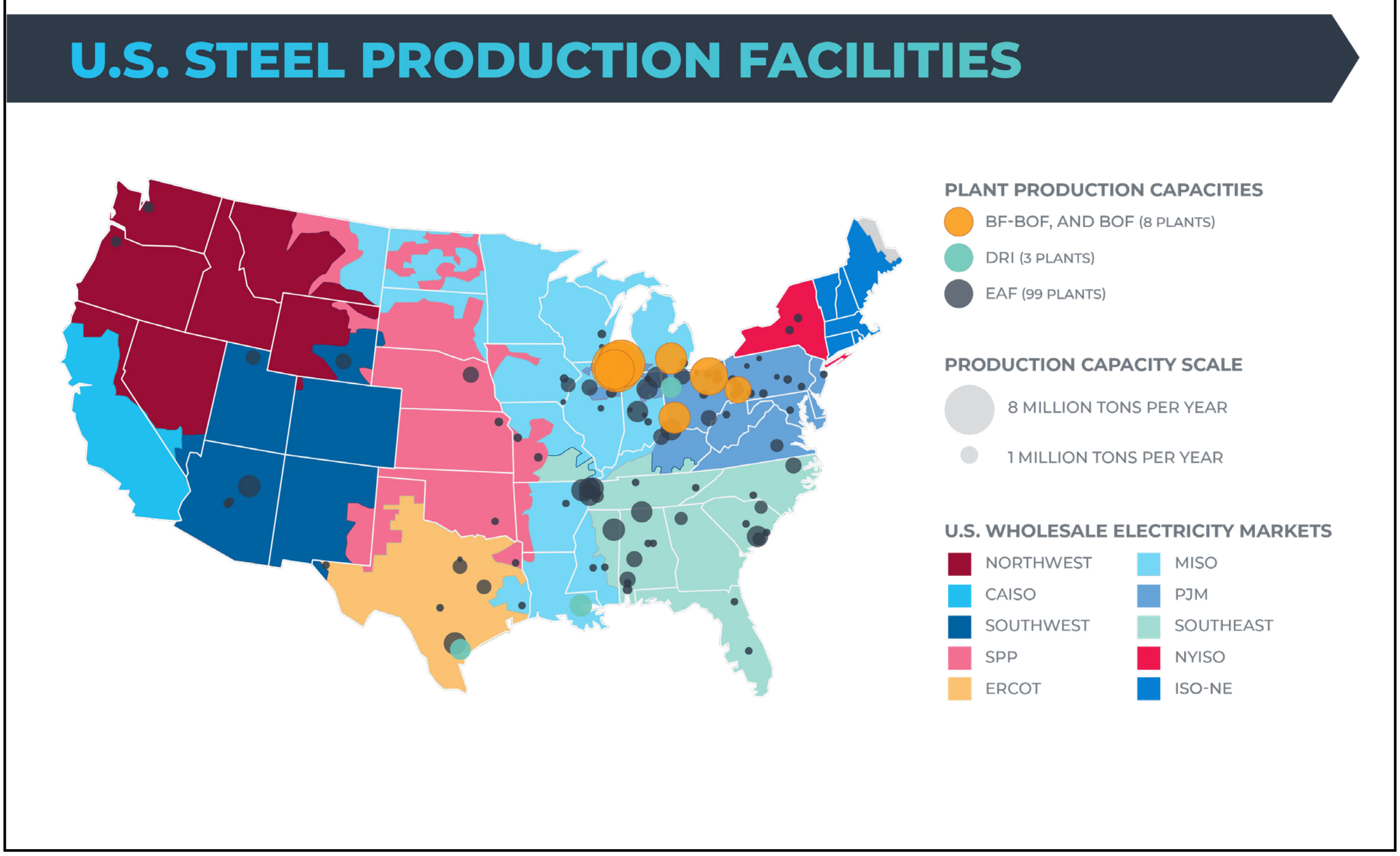
**The 2035 grid emissions factor in Indiana is projected to be 0.17 tCO_2e/MWh.*

1.2 UNITED STATES STEEL PRODUCTION LANDSCAPE AND DEMAND FORECAST

The United States ranks as the fourth-largest global steel producer, with a total annual production capacity of nearly 130 million metric tons (Mt). About 75% of that capacity is used, yielding over 80 Mt of steel annually, of which nearly 30 Mt is primary steel [16, 7]. Despite the strong domestic steelmaking capabilities, the United States meets about 28% of its demand with imports in 2022 [17].

Geographically, United States primary steel production clusters in the Great Lakes region, with all BF-BOF plants located in just five states: Indiana, Illinois, Michigan, Ohio, and Pennsylvania [18]. These plants are served by the Midcontinent Independent System Operator (MISO) and PJM wholesale electricity markets. Producers generally site EAFs in the Midwest and Southeast to leverage proximity to automotive manufacturing customers, lower electricity costs, and major waterways for transport [4, 19, 18]. DRI facilities, like Nucor's Louisiana plant and ArcelorMittal's Texas plant, sit near sources of natural gas [20, 21]. Figure 1 illustrates this landscape, and Table 3 details the current United States primary steel plants.

FIGURE 1
United States Steel Production Facilities



Sources: [22, 23, 19]

TABLE 3
United States Primary Steel Plants, 2024

Plant	State	Owner	RTO/ISO	Process	Production Capacity[7] (Mtpa*)	CO_2e Emissions (t CO_2e/year**)
Riverdale Steel	IL	Cleveland-Cliffs Inc.	PJM	BOF	1.00	1,623,821
Burns Harbor Steel	IN	Cleveland-Cliffs Inc.	MISO	BF, BOF	5.00	8,361,941
Indiana Harbor Steel	IN	Cleveland-Cliffs Inc.	PJM	BF, BOF	7.254	12,131,503
Gary Works	IN	U.S. Steel Corp.	MISO	BF, BOF	7.80	13,044,627
Nucor Steel Louisiana	LA	Nucor Steel Louisiana, LLC	MISO	NG-DRI	2.50	1,244,135
Dearborn Steel	MI	Cleveland-Cliffs Inc.	MISO	BF, BOF	3.00	5,073,475
Cleveland Steel	OH	Cleveland-Cliffs Inc.	PJM	BF, BOF	4.10	6,965,823
Middletown Steel	OH	Cleveland-Cliffs Inc.	PJM	BF, BOF	3.00	5,096,944
Toledo DRI	OH	Cleveland-Cliffs Inc.	PJM	NG-DRI	1.90	999,824
Edgar Thomson	PA	U.S. Steel Corp	PJM	BF-BOF	2.90	4,778,148
ArcelorMittal Texas DRI	TX	Voestalpine Texas, LLC	ERCOT	NG-DRI	2.00	919,718

**Million Tons per annum*
***Metric Tons CO_2e/year*

Globally, steel demand is projected to increase by at least a third by 2050 [5, 1]. Outpacing global averages, United States' demand is expected to grow by 45% from 2023 levels by 2050 [1]. Projected growth is expected to be driven by demand from the automotive, building, and energy sectors. Along with anticipated growth for steel generally, demand for near-zero emissions steel[8] is rapidly growing. For example, alliances like the First Movers Coalition evolved to support corporate commitments to reduce supply chain emissions. In the United States alone, demand for near-zero-emissions steel could exceed six Mt by 2030 [24].

Recent policies aim to accelerate the onshoring of manufacturing and industrial electrification. For example, federal incentives through the Bipartisan Infrastructure Law of 2021 (BIL) and Inflation Reduction Act of 2022 (IRA) will likely drive domestic steel demand through their promotion of domestic, clean manufacturing [25]. The IRA is also likely to impact overall steel demand through 2035 through incentives for investment in renewable energy development like wind and solar, for which steel is a critical input [26].

Complementary initiatives in the IRA and BIL are simultaneously moving near-zero-emissions steel production within reach. IRA and BIL-related investments in the nation's capacity to generate and transmit CFE and establish clean hydrogen hubs indicate progress toward the infrastructure necessary for primary steel decarbonization.

SECTION 2: STEEL DECARBONIZATION ELECTRICITY MODELING

To date, modeling studies on steel decarbonization pathways have not adequately addressed the electricity requirements for advanced technologies. This report draws heavily on previous studies[9] and complements the Mission Possible Partnership (MPP)'s Net-Zero Steel Transition Strategy report (2022) to begin to fill the research gaps and identify the electricity and emissions implications for primary steel process electrification. We build upon MPP's Carbon Cost Scenario, which can be considered 1.5 °C-aligned due to projections for earlier and greater uptake of near-zero-emissions technology.[10]

2.1 ASSUMPTIONS

Primary Steel Production

Our model utilizes current primary steel plant data from Global Energy Monitor (GEM) [19] and assumes a 2% production growth from 2024 through 2033 and 1% from 2034 to 2050 based on projections from both the United States Department of Energy (DOE) and MPP [6, 1].

Based on interviews with 22 private and public sector experts, our analysis also assumes that primary steelmaking will remain geographically consistent, concentrated in Indiana, Illinois, Michigan, Ohio, and Pennsylvania, considering established infrastructure and labor relations.

Technology Diffusion

We modeled a business-as-usual (BAU) scenario and a 1.5 °C-aligned scenario, which is a mix of advanced technologies in line with technology adoption timelines provided by the International Energy Agency's (IEA's) 1.5 °C Scenario and MPP's Carbon Cost Scenario.

BAU scenario: We established a BAU scenario for comparison, in which the BF-BOF production route provides almost all primary steel, with a small portion of the feedstock iron provided by existing natural gas DRI facilities. The geographies remain the same, with a focus on states like Indiana, and the MISO and PJM wholesale electricity markets.

This scenario represents the continuation of current technology dependencies, with plant owners relining blast furnaces when the investment decision approaches, and existing DRI furnaces continuing the use of natural gas as the reduction feedgas.[11] When the increase in production exceeds capacity across the suppliers beginning in 2045, we assume that excess demand will be met by importation and increased availability of high-quality steel from scrap-based production technologies so no additional plants are constructed.

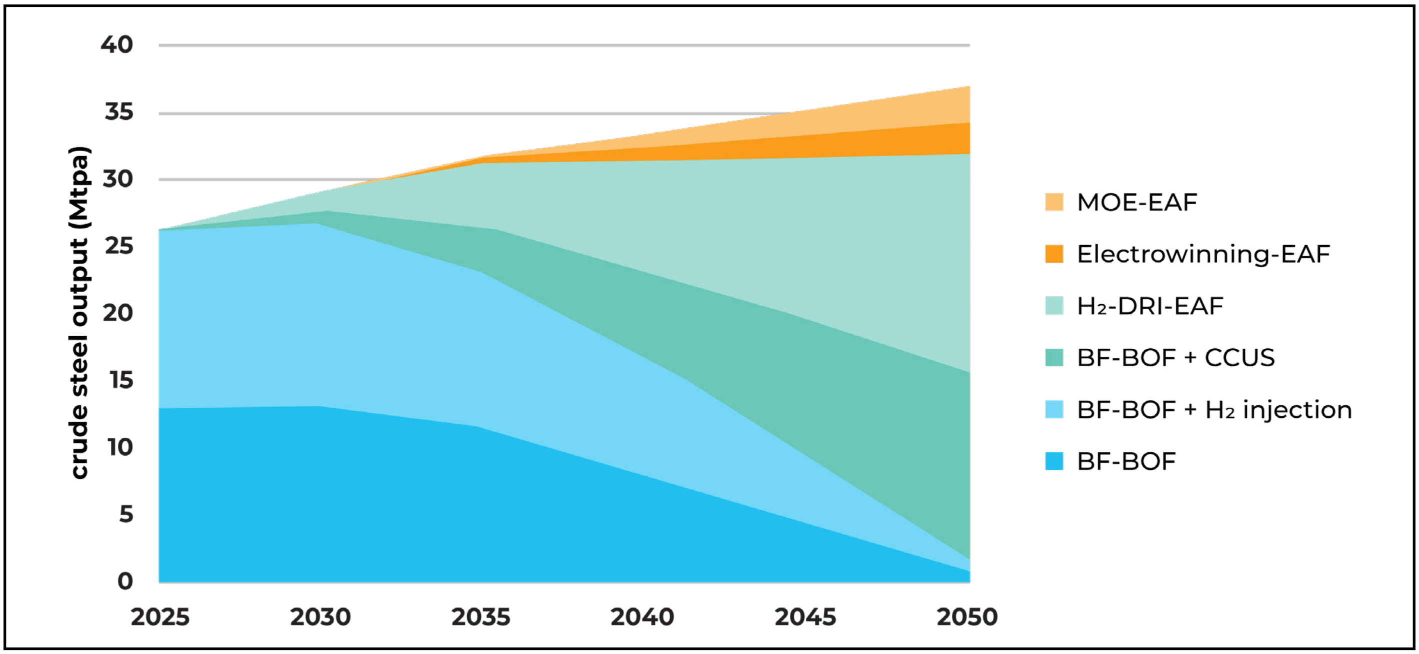
1.5 °C-aligned scenario: The 1.5 °C-aligned scenario models a pathway based on IEA's 1.5 °C Scenario[12] and MPP's Carbon Cost Scenario assessment of technology diffusion rates through 2050. It presents a plausible mix of production technologies (i.e., CCUS, H_2, and electrification) given market readiness and accounting for end-of-life considerations for the existing fleet of production facilities.

BF-BOF facilities are equipped with H_2 injection technologies and begin to phase in CCUS capabilities, albeit at a slow rate to align with large-scale commercialization timeframes. Replacement of existing technologies is delayed until relining investment decisions come due.

BF-BOF facilities are eventually replaced as H_2-DRI facilities begin to be phased in starting in 2028, while an equal mix of MOE-EAF and electrowinning-EAF technologies begin to be added in 2035. In 2035, the forecasted technology share is 10% CCUS-equipped, 15% H_2-based, and 2% direct electrolysis processes. By 2050, this increases to 37% CCUS-equipped, 44% H_2-based, and 14% direct electrolysis processes.

Figure 2 illustrates the production share by technology under our 1.5 °C-aligned scenario from 2025 through 2050, accounting for anticipated technology diffusion and end-of-life constraints for existing facilities.

FIGURE 2
United States Primary Steel Production Pathway: 1.5 °C-aligned Scenario



Electricity Demand

To calculate the annual electricity demand (TWh/year) from 2023 to 2050, we utilized the steel production and technology diffusion assumptions as described above, along with electricity consumption rates for each steel production technology. Although it is reasonable to expect improved efficiencies of the advanced steel technologies over time, the model does not anticipate such increases to be realized within the lifespans of the early generation technologies that we model.

To inform the grid mix and storage infrastructure sizing, we utilized annualized capacity factors from the National Renewable Energy Laboratory (NREL) Cambium 2022 model's Mid-case with 100% decarbonization by 2035 without tax credit phaseout scenario (100% grid decarbonization scenario), in lieu of separate advanced energy systems modeling. This method informs a potential grid mix scenario that could support near-zero-emissions steel production. The method is susceptible to underestimating infrastructure requirements due to the lack of granular, hour-by-hour, and CFE potential analysis; however, it provides approximate figures and demonstrates where further analysis is necessary.

Emissions Factors

To assess the emissions from the electricity demand of primary steel decarbonization over time, we utilized grid emissions factors by region and state from the NREL Cambium 2022 model's Mid-case without tax credit phaseout scenario (mid-case scenario), which estimates electricity generation capacities (MWs), volumes (MWhs), and power generation technology mixes in the United States annually through 2050. Cambium accounts for a range of market forces and incentives, including the BIL and IRA.[13] Cambium assumes modest electrification of industry, but it does not model a significant level of steel electrification, meaning the electricity requirements that we estimate are additional to Cambium's. To assess production direct emissions (scope 1), we utilized data from key sources for our model, which are summarized in Appendix A.

2.2 MODEL RESULTS

Overview

Under the BAU scenario, the demand for electricity increases in line with steel production, starting at 11 TWh/year in 2025 and reaching 15 TWh/year by 2050, representing an approximate 40% increase over 25 years. Similarly, emissions increase from 62 Mt CO_2e/year in 2025 to 83 Mt CO_2e/year in 2050, representing an approximate 33% increase, despite anticipated grid decarbonization in this timeframe. The persistent emissions trend underscores the significant role of on-site scope 1 process emissions in comparison to grid-related emissions for this BF-BOF-focused pathway.

The 1.5°C-aligned scenario sees a substantial rise in electricity demand, with 26 TWh/year in 2025 (more than double that of the BAU scenario), and reaching 174 TWh/year by 2050, an increase of 159 TWh from the BAU scenario. However, in contrast to the BAU scenario, the 1.5 °C-aligned scenario achieves a significant reduction in CO_2e emissions, decreasing from 64 to 36 Mt CO_2e/year, an approximate 44% reduction over 25 years. If actual grid decarbonization outpaces NREL's Cambium model's Mid-case scenario, then even greater emissions reductions are possible.

Over the period modeled, the annual emissions gap between the two scenarios increases, with the 1.5 °C-aligned scenario resulting in a 57% annual emissions reduction relative to BAU by 2050. Below, Table 4 provides a summary of annual electricity demand and CO_2e emissions for both the BAU and 1.5 °C-aligned scenarios over time.

TABLE 4
BAU vs. 1.5 °C-aligned Scenario Annual Electricity Demand & CO_2e Emissions

Year	2025	2030	2035	2040	2045	2050
Annual Electricity Demand (TWh/year)						
BAU	11	12	13	14	15	15
1.5 °C-aligned	26	51	76	106	138	174
Percent Increase over BAU	**136%**	**317%**	**469%**	**655%**	**841%**	**1028%**
Annual Emissions (Mt CO_2e/year)						
BAU	62	66	72	75	79	83
1.5 °C-aligned	64	62	59	50	43	36
Percent Annual Emissions Reductions over BAU	**-2%**[14]	**7%**	**18%**	**33%**	**46%**	**57%**

Electricity Demand

Our modeling demonstrates that decarbonizing steel requires enormous quantities of electricity — 174 TWh per year, or 159 TWh over BAU — in 2050 to power process electrification. These electricity requirements far outstrip what can be produced onsite, necessitating grid-access to sufficient volumes of affordable CFE. Since incumbent plants are predominantly sited in urban industrial settings with limited access to CFE resources, their decarbonization will require long-distance transmission to deliver cost-effective CFE to demand centers.

Electricity is drawn from the grid, which is generated from a mix of renewable energy and fossil fuel sources. Hence, decarbonization of the modeled grid-powered steel sector is directly dependent on the decarbonization of each region's grid as well as imported electricity from surrounding regions. Figures 3 and 4 demonstrate projected annual electricity demand broken down by state for primary steel decarbonization under the 1.5 °C-aligned scenario, and the percentage of that demand compared to current anticipated statewide demand, respectively.

Importantly, these projections can highlight the geographies with expected high electricity demand from primary steel decarbonization and its significant impact on planned statewide demand. For example, by 2050, the electricity demand from primary steel decarbonization is expected to be highest in Indiana and Ohio, at 51% and 22%, respectively. In Indiana, primary steel decarbonization is projected to constitute a significant 57% of the anticipated statewide demand by 2050, while in Ohio, it is projected to constitute 18%. This highlights the need to update statewide demand forecasts with industrial decarbonization-informed load forecasts, which can inform the required grid mix and transmission planning processes to accommodate significant demand increase.

FIGURE 3
1.5 °C-aligned Scenario, Electricity Demand from Primary Steel Decarbonization by State

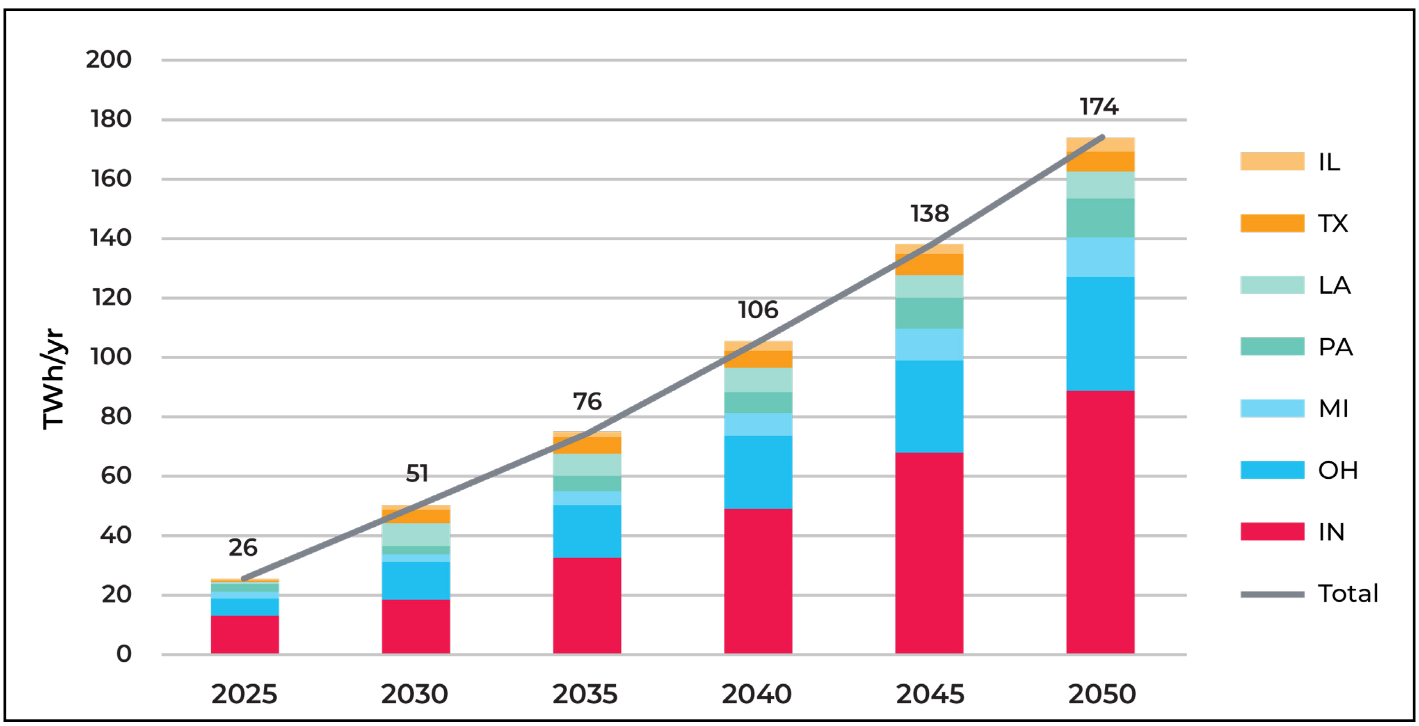
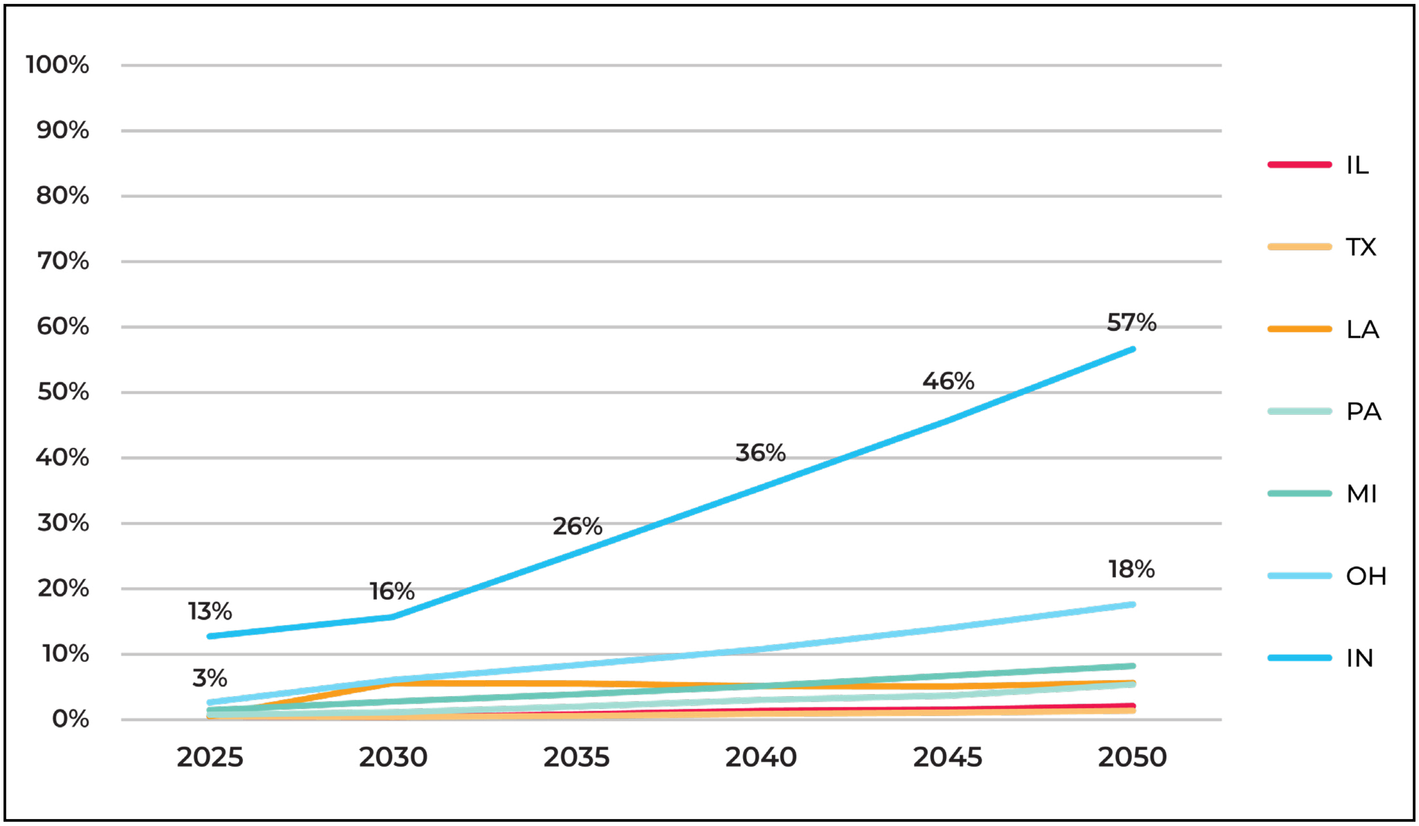


FIGURE 4

1.5 °C-aligned Scenario, Percentage of Electricity Demand from Primary Steel Decarbonization Compared to Anticipated Electricity Demand by State

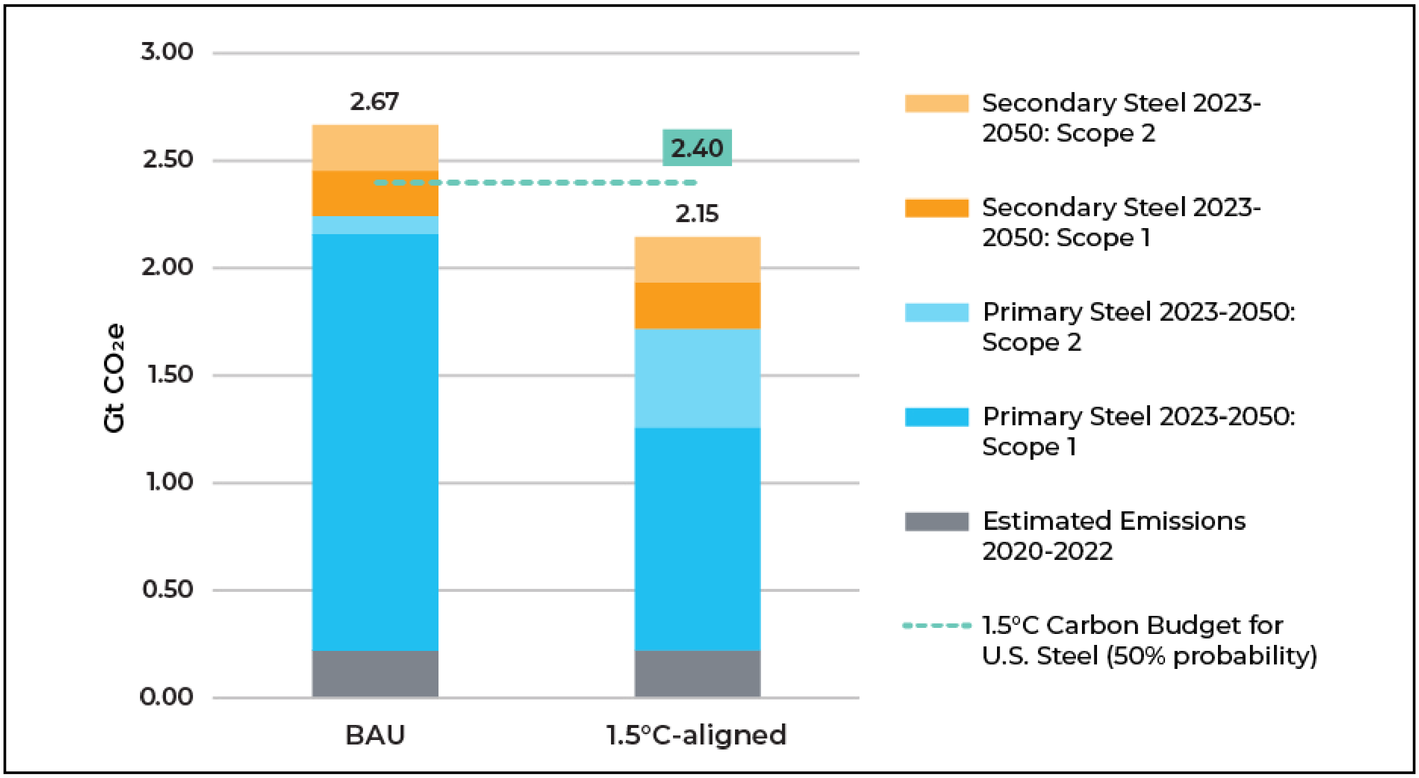


Emissions

Figure 5, on page 15, demonstrates that the BAU scenario surpasses the United States steel sector's carbon budget, while the 1.5 °C-aligned scenario remains within its limit.[15] Examination of scope 2 emissions reveals that grid-based emissions increase with the electrification of primary steel production. Scope 2 emissions from primary steel rise from 3% of total cumulative emissions 2020-2050 in the United States steel sector under the BAU scenario to around 22% under the 1.5 °C-aligned scenario. This underscores the importance of grid decarbonization in further reducing emissions to keep the United States well below the carbon budget.

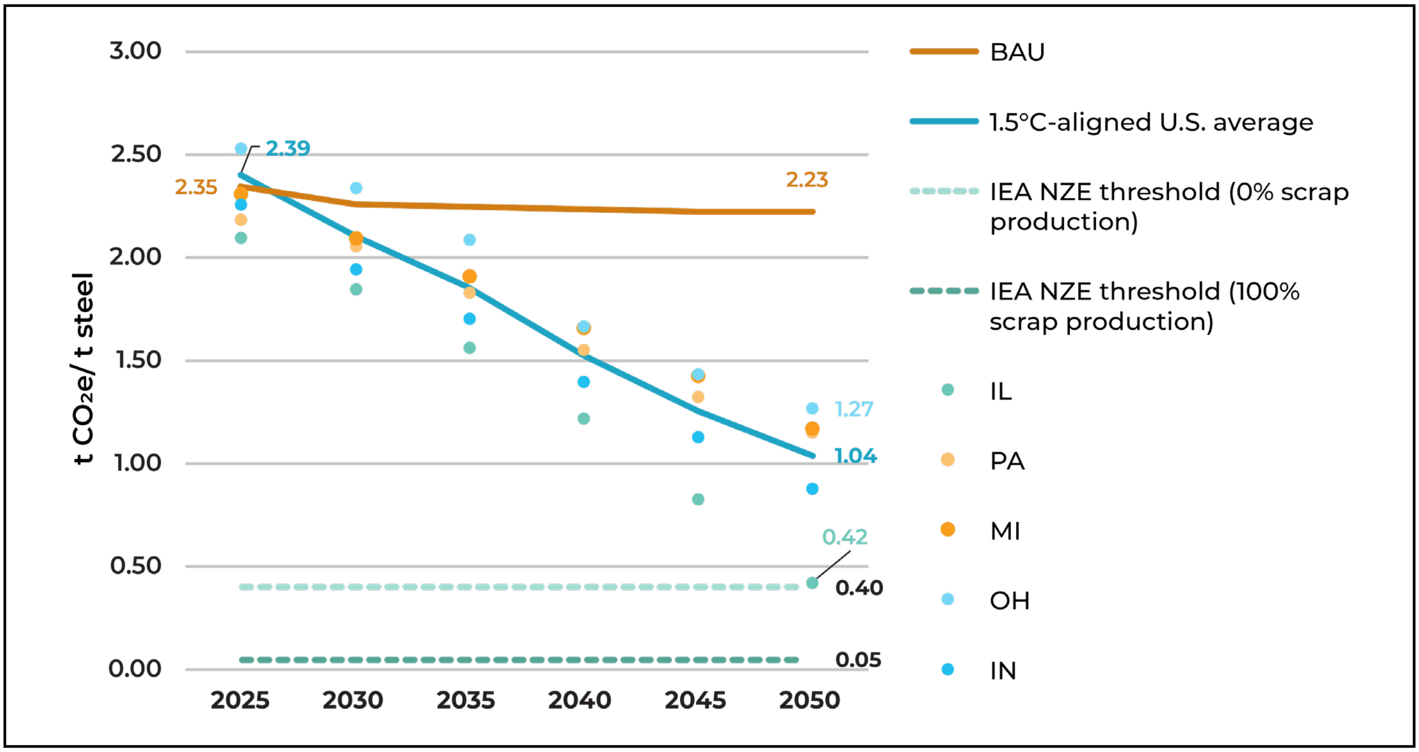
FIGURE 5

1.5 °C Carbon Budget for United States Steel Sector and Cumulative Emissions 2020-2050



Although the 1.5 °C-aligned scenario remains within the United States steel carbon budget, our model[16] suggests that the average United States primary steel emissions intensity exceeds the IEA and ResponsibleSteel near-zero-emissions steel benchmark of 0.4 tons CO_2e/ton steel[17] by 2050. A few market leaders have signaled capabilities to offer near-zero-emission primary steel over the coming decades, however the associated production volume is insufficient to meet anticipated demand. State-level modeling under the 1.5 °C-aligned scenario suggests that by 2050, Illinois will come closest to the benchmark, with the lowest average of 0.42 tons CO_2e/ton steel, while Ohio will be furthest from the benchmark, at 1.27 tons CO_2e/ton steel in 2050. Figure 6 illustrates this trend.

FIGURE 6
Average Primary Steel Emissions Intensity



SECTION 3: STAKEHOLDER ANALYSIS

CEBA conducted 22 stakeholder interviews with iron and steel market participants (producers, end buyers, investors), NGOs operating in the steel and/or energy sectors, and other experts in the field, offering a range of perspectives and insights. These interviews and a detailed literature review informed the model as described above and subsequent recommendations in this report.

Key decision-makers in the steel and energy sectors include a relatively small set of businesses, utilities, and policymakers. We recommend targeted engagement with the most influential entities to hasten CFE deployment and complementary transmission infrastructure, which will facilitate primary steel decarbonization through the utilization of advanced technologies. These key stakeholders and their respective roles within the steel industry, energy market, and potential near-zero-emissions steel transition are outlined below.

BUSINESSES

Steelmakers: Key industry players include Cleveland-Cliffs, U.S. Steel, Nucor, and ArcelorMittal. Decisions about steel are concentrated in the hands of a few major steelmaking companies and their customers' board members, numbering in the hundreds globally. Steelmakers should be regularly engaged at the executive and board levels to make meaningful climate commitments and to use their considerable political and financial capital to hasten CFE infrastructure development, including interregional transmission.

Primary Steel Customers: Large customers, such as automakers and manufacturing companies, drive demand for near-zero-emissions steel and can influence energy policy and decisions to site facilities in grids with lower projected grid emissions factors.

UTILITIES

Electric Utilities: Public utilities and investor-owned utilities should include load forecasts for steel decarbonization on their roadmaps. Currently, only a handful of large-scale utilities (i.e., Duke Energy, ComEd NIPSCO, and Duquesne Light Company) serve the majority of primary steelmakers. In regions with high potential for future primary steel production, like Texas, it would be strategic to engage CenterPoint and Oncor to support CFE infrastructure.

POLICYMAKERS

Federal Policymakers: At the federal level, critical policymakers include the Federal Electricity Regulatory Committee (FERC) and the United States Department of Energy (DOE), including its Loan Programs Office (LPO) and Grid Deployment Office (GDO), which conducts the "National Transmission Planning Study". Notably for priority states listed in Table 5. DOE's 2023 National Transmission Needs Study found that regions in greatest need of transmission growth are in the middle of the country, including the Texas, Mountain, Plains, and Midwest regions [3]. Furthermore, the Needs Study found that interregional transfer capacity anticipated in 2035 would require 3,519% relative growth from the 2020 system for the Plains-Texas transfer, and 730% relative growth for the Midwest-Plains transfer for a high load and high clean energy growth scenario [27]. Given the volume of required transmission and generation to support load forecasts, the United States Department of Interior should also be engaged to include industrial CFE demand in its reports on renewable energy and transmission development on public lands.

State Policymakers: In key states for existing and forecasted primary steelmaking, public utility commissions and other decision-making entities should be engaged (Table 5). Lower-priority states for engagement include Illinois, Louisiana, Michigan, Pennsylvania, and Georgia.

TABLE 5
Priority States and Decision-making Entities for Load Forecasting

State		Policy Bodies
Indiana	59% of BF-BOF production capacity in the United States	Office of Energy & Defense Development (OED), Indiana Utility Regulatory Commission (IURC), and Department of Natural Resources (DNR)
Ohio	21% of BF-BOF production capacity in the United States	Public Utilities Commission of Ohio, the Power Siting Board, and the Energy Resources Division of the Ohio Government Department of Development
Texas	High potential for electrification and/or H_2	Public Utilities Commission of Texas, the Railroad Commission of Texas, the Texas Energy Planning Council, and the Texas Commission on Environmental Quality

Most states currently have some kind of renewable portfolio or clean energy standard, but state policies vary in ambition (Table 6). For example, Indiana, which hosts the majority of current BF-BOF production, has no stated plans beyond a renewable portfolio goal of 10% by 2025.

TABLE 6
CFE Standards in Primary Steelmaking States

Primary Steelmaking State	CFE Standard
Illinois	Clean Energy Standard: 50% by 2040, 100% by 2050
Indiana	Renewable Portfolio Goal: 10% by 2025
Louisiana	Clean Energy Goal: 100% by 2050
Ohio	Renewable Portfolio Standard: 8.5% by 2026
Michigan	Clean Energy Standard: 60% by 2030, 100% by 2040
Pennsylvania	Renewable Portfolio Standard: 18% by 2021

Source: [28]

In the future, it would be strategic to prioritize new steelmaking facilities in states with lower grid emissions factors, but incumbency considerations make it uncertain that a significant amount of steelmaking will relocate to meet emission reduction targets.

Regional Policymakers: Regional electricity and transmission market managers — regional transmission organizations (RTOs) and independent system operators (ISOs) — are also key stakeholders. Specifically, PJM and MISO are critical stakeholders because they serve existing primary steelmakers and share territories in Indiana, Illinois, and Michigan. It would also be beneficial to engage the Electric Reliability Council of Texas (ERCOT) and the Southeastern Electric Reliability Council (SERC) because future steelmaking facilities are anticipated within their service territories due to proximity to customers, available logistics, and lower power and labor prices.

CONCLUSION

A window of opportunity to decarbonize primary steel production was opened with the passage and implementation of the BIL and IRA because they encourage domestic industrial production, promote enhanced transmission, and support enabling technologies like CCUS, green H_2, and emerging technologies like direct-ore electrolysis. That opportunity is strengthened by growing corporate demand for near-zero-emissions steel, low-cost CFE, and a more interconnected and resilient grid.

Even with these tailwinds, much concerted effort is still needed to achieve near-zero-emissions steel. As mentioned in Section 2, modeling results from NREL indicate that anticipated grid decarbonization efforts alone will not support sector-wide production of near-zero-emissions steel that meets the IEA and ResponsibleSteel benchmark of 0.4 tons CO_2 /ton of steel by 2050.

Our modeling demonstrates that decarbonizing steel requires enormous quantities of electricity — 174 TWh per year in 2050, an increase of 159 TWh over BAU—to power process electrification. These electricity requirements far outstrip what can be produced onsite, necessitating grid-access to sufficient volumes of affordable CFE. Expanding generation with natural gas would bring high risks in terms of price volatility, speed, and eventual costs for CCUS. Renewables are the lowest-cost, lowest-risk strategy to meet demand.

Since incumbent plants are predominantly sited in urban industrial settings with limited access to CFE resources, their decarbonization will require long-distance transmission to deliver cost-effective CFE to demand centers. Near-zero-emissions steel will require:

- Spurring technology adoption of CCUS, H_2, and direct-ore electrolysis,
- Expanding the nation's grid,
- Improving regional and interregional transmission planning, and
- Increasing CFE generation to reduce grid emissions factors.

As multinational companies work to comply with evolving international climate disclosure rules, efforts to eliminate scope 1-3 emissions will continue to grow. Leveraging the power of consumer demand, progress can be accelerated by amplifying the consumer voice with steelmakers, utilities, and policymakers. Efforts to decarbonize the grid for primary steel production will have cascading benefits for all industrial electrification, including the greening of secondary steel, which is already electrified.

Any long-term planning of steel facility siting should prioritize location. In an electrifying industry, emissions intensity and electricity costs depend on grid generation mixes, and extensive modeling by NREL anticipates dramatic shifts in mixes over the next 30 years because of state decarbonization goals and federal investments such as the IRA, as well as decreasing costs for renewable energy. Grid mixes and improvements in transmission of CFE should be heavily weighted in facility siting.

RESEARCH RECOMMENDATIONS

While this analysis provides an overview of the potential electricity requirements and associated CO_2e emissions reductions for primary steel decarbonization, additional analysis is required for more robust projections. At the highest level, we recommend a more complex technoeconomic analysis of the generation and transmission requirements for primary steel advanced decarbonization technologies.

Ideally, such a study would investigate the cumulative electricity demands of multiple industries as they collectively decarbonize through electrification. While it is important to evaluate the iron and steel industries separately, the grid is interconnected, and industrial symbiosis could be applied to configure optimal resource allocation. Such a study would ideally include participation from a national laboratory and/or major research university to help elevate the findings on a national stage and in decision-making forums.

In-depth energy systems modeling would be necessary to determine the grid mix required to replace current fossil fuel-based power generation and support overall capacity expansion. Energy storage infrastructure must be combined with intermittent renewables to meet industrial power demands on an hour-by-hour basis. Hydropower, nuclear, and geothermal-based power can provide reliable base loads, which are especially important in the transition period as energy providers learn to cope with increasing shares of renewables.

Furthermore, renewable energy variability and demand flexibility process matching can help reduce infrastructure demand and overall costs. Some examples of demand flexibility in the steel supply chain include flexible low-temperature electrolyzers for hydrogen production, long-term storage of iron as hot briquetted iron (HBI), and EAFs operating in batch mode. For direct electrification, electrowinning is a flexible low-temperature process, while MOE operates continuously at around 1,600 °C.

Other specific areas for further study include:

- Spatially explicit optimization modeling with direct inputs of renewable energy data, which would be a powerful tool to identify the ideal locations for installing electrified steel production sites. The current model relies on grid connection, yet a combination of grid and behind-the-meter CFE would enable a more comprehensive evaluation of local renewable and nuclear potential.
- Broadening of the analysis to include prospective greenfield sites (i.e., new locations) in addition to brownfield sites (i.e., existing plants).
- Incorporate analysis of the impact of United States policy and steel industry decarbonization strategies on technology uptake to inform modeling steel decarbonization pathways.
- Combine primary and secondary steelmaking in the analysis, since these two categories are becoming less distinct over time. Additionally, although secondary steelmaking is currently less carbon-intensive than primary steelmaking, it is still a significant source of United States electricity demand in aggregate, representing an estimated 1% of the grid.

- Compare a high-natural-gas with a high-CFE overall portfolio by running planning scenarios with various portfolios, accurately representing technology cost and risk assumptions.
- Economic and political analysis of facilitating federal policy pathways, including:
  - A transmission investment tax credit,
  - A national policy on interregional transmission planning,
  - Plenary siting authority for regional and interregional transmission planning at FERC (analogous to what pipelines have today), and
  - A coordinated and comprehensive national reindustrialization policy for industrial expansion and reshoring.

APPENDICES

APPENDIX A

Key data inputs and sources used in the model.

KEY DATA	SOURCE
Current steel production volume	GEM [19]
Steel production growth	DOE [6], MPP [1]
Electricity consumption rates for each steel production technology	BF, BOF: Fan [11] BF, BOF, H_2: Shatokha [29] H_2DRI, EAF: Vogl [10] MOE, EAF: Fan [11] Electrowinning, EAF: Lechtenbohmer [30] NGDRI: Fan [11] H_2: IEA [31] CCUS: MPP [1]
Grid emissions factors	NREL's Cambium 2022 model's Mid-case (without tax credit phaseout) scenario [32, 33]
Capacity factors (for CFE production and storage capacity calculation)	NREL's Cambium 2022 model's Mid-case with 100% Decarbonization by 2035 (without tax credit phaseout) scenario [32, 33]
Production direct emissions (from electricity)	BF, BOF: Fan [11] BF, BOF, H_2: Fan [11] H_2DRI, EAF: Rissman [15] NGDRI, EAF: Rissman [15] CCUS: IEEFA [34]
Production direct emissions (from process)	BF, BOF: Fan [11] BF, BOF, H_2: Shatokha [29] H_2DRI, EAF: Fan [11] MOE, EAF: Rissman [15] Electrowinning, EAF: Rissman [15] NGDRI: Rissman [15] CCUS: IEEFA [34]

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ENDNOTES

1 CO_2e emissions are also commonly known as greenhouse gas (GHG) emissions.

2 These studies include DOE's "Pathways to Commercial Liftoff: Industrial Decarbonization" (2023) [6], MPP's 'Making Net-Zero Steel Possible' (2022) [1], RMI's 'Opportunities for Near-Zero-Emissions Steel Production in the Great Lakes' (2023) [18], and ACEEE's 'Sustainable Metals Manufacturing Opportunities in Indiana' (2023) [35].

3 Primary steel currently accounts for 76% of CO_2e emissions from the U.S. steel industry.

4 Advanced decarbonization technologies include: 1) carbon capture, utilization, and storage (CCUS); 2) Hydrogen (H_2); and 3) direct-ore electrolysis (electrification).

5 Tons of CO_2e per ton of crude steel.

6 Total plant emissions include scope 1, direct emissions from all plant process, and scope 2, purchased electricity.

7 For BOF and BF-BOF plants, the production capacity numbers refer to steel production. For NG-DRI plants, the production capacity numbers refer to iron production.

8 “Near-zero emissions steel” is also known as “low-carbon steel” or “green steel.”

9 These studies include DOE's "Pathways to Commercial Liftoff: Industrial Decarbonization" (2023) [6], MPP's 'Making Net-Zero Steel Possible – Steel Transition Strategy' (2022) [1], RMI's 'Opportunities for Near-Zero-Emissions Steel Production in the Great Lakes' (2023) [18], and ACEEE's 'Sustainable Metals Manufacturing Opportunities in Indiana' (2023) [35].

10 Recent anecdotal evidence can highlight disagreements with the technology diffusion timelines utilized herein. For example, H_2-DRI-EAF has seen promising early deployment, while several CCUS projects have been scaled back or eliminated. However, for consistency, our methodology was selected to align with documented MPP and IEA studies.

11 Full or partial relining is a costly maintenance step for blast furnace facilities and can be used as a decision point for plant replacement with more modern, lower-emissions facilities. Once a facility is relined, it will extend integrated BF-BOF production by approximately 17 years.

12 The IEA’s scenario assumes a carbon-free grid by 2045, while the mid-case Cambium scenario that underpins our model does not envision that until significantly after 2050. As a result, our model does not anticipate near-zero-emissions steel production during the modeled timeframe of 2024-2050. Further techno-economic analysis is required to identify the optimal technology mixes and locations to maximize the decarbonization of primary steel production.

13 For further details on the Cambium model, visit https://www.nrel.gov/analysis/cambium.html. The 2022 version was used for modeling for this report as it contained the most current Cambium numbers available at the time we modeled (late 2023).

14 Annual emissions of the 1.5 °C-aligned scenario are higher than BAU in 2025 because we immediately begin to blend in H_2 (grid-based), and the carbon-intensive grids make the emissions from H_2 production high in the early years. The emissions decrease over time as the grid gets cleaner.

15 This carbon budget of 2.40 Gt CO_2e is calculated by CEBA using the United States steel production's proportionate share of the global steel sector's carbon budget of 56 Gt CO_2e from 2020-2050, as developed by MPP. It did not account for the higher percentage of scrap steel used in the U.S. compared to the global average. Thus, the United States steel sector's carbon budget may be lower than indicated.

16 Our model utilizes grid emissions factors from NREL's Cambium mid-case scenario.

17 The 0.4 tons CO_2e/ton near-zero-emissions steel benchmark is based on 0% scrap. The benchmark for 100% scrap is 0.05 tons CO_2e/ton steel. The United States scrap usage is between 0% and 100%; therefore, the IEA and ResponsibleSteel near-zero-emissions steel benchmark for the United States is somewhere between 0.4 and 0.05 tons CO_2e/ton steel.

Thank You!

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