The Costs and Distributional Impacts of Decarbonizing the Iron and Steel Industry in the United States

Paulina Jaramillo, Valerie J. Karplus, P. Chris Pistorius, Edson Severnini*†

December 6, 2023

Abstract

Industrial decarbonization promises to mitigate global climate change and deliver environmental and health benefits to surrounding communities. We examine these potential impacts in the case of iron and steel production in the United States. First, we describe iron and steel production processes, major CO_2 emissions sources, and associated uncertainties. Second, we generate engineering estimates of the costs of CO_2 abatement approaches and apply them to estimate the costs of decarbonizing U.S. iron and steel plants, both for the integrated route (30% of current production), which uses iron ore via the blast furnace-basic oxygen furnace (BF-BOF) and for the electric arc furnace (EAF) route (70% of current production), which produces steel primarily from scrap using electricity. We compare two potential scenarios, one that preserves the current integrated route and another that considers a shift to EAF-based production with a higher quantity of ore-based metallics (direct reduced iron, DRI), holding today's product portfolio constant. We then characterize variation across U.S. plant locations in how measures of air pollution ($PM_{2.5}$ concentrations) change with proximity to the furnaces and examine other local population characteristics as a starting point for analyzing how the impacts of decarbonization investments will be distributed and estimate how measures of air pollution ($PM_{2.5}$ concentrations) change with proximity to the furnaces. We conclude that if deep reductions in CO_2 emissions via the DRI-EAF route can be accomplished at existing BF-BOF sites, it may deliver both cost savings and community environmental and health benefits.

Keywords: Decarbonization, Steel Plants, Technoeconomic Analysis, Air Pollution, Particulate Matter, Socioeconomic Characteristics

JEL Codes: Q40, Q52, Q53

---

*Jaramillo: Carnegie Mellon University, pjaramil@andrew.cmu.edu. Karplus: Carnegie Mellon University, vkarplus@andrew.cmu.edu. Pistorius: Carnegie Mellon University, pcp@andrew.cmu.edu. Severnini: Carnegie Mellon University, IZA, and NBER: edsons@andrew.cmu.edu.

†We thank Lint Barrage, Ken Gillingham, participants at the RFF Industrial Sector Modeling Workshop, the NBER Pre-Conference on the Economics of Decarbonizing Industrial Production (sponsored by the Alfred P. Sloan Foundation), and our INDABA meetings for invaluable comments and suggestions. INDABA stands for *Industrial Decarbonization Analysis, Benchmarking, and Action*, a partnership we have created with other universities and the industry with funding from the National Science Foundation (NSF) to study decarbonization in the iron and steel industry. We are grateful to Elina Hoffmann, Annabel Hu, and Katherine Jordan for outstanding research assistance. The authors gratefully acknowledge financial support from Carnegie Mellon University and the NSF Award #OISE 2230743.

1 Introduction

Steel is widely used in industrialized economies and is essential for the energy transition. As an input to the construction, automotive, appliances, and many other uses, steel is a differentiated product that is energy and CO_2 intensive to produce today. Decarbonized process options are known, but implementing them would require sizable new capital investments that may further need supporting infrastructure such as clean electricity and carbon dioxide capture and sequestration (CCS).

Economic studies rarely differentiate industrial activity at the process level, although as we will discuss here, this differentiation can be critical to evaluate the costs of industrial decarbonization technologies. Here, four-digit NAICS codes are unlikely to be sufficient: "3312 - Steel Works, Blast Furnaces (Including Coke Ovens), and Rolling Mills" includes plants with up to a 30-fold variation in their CO_2 intensity based on direct emissions. This analysis considers what level of granularity is adequate to capture CO_2 abatement costs and their impact on industry decisions.

We develop an analysis of the cost of abating CO_2 emissions at the production process level for the United States. We do so by differentiating abatement interventions by production route and process step, using a combination of engineering and economic information. We discuss how this approach improves our ability to capture interactions that may alter the effectiveness of alternative abatement technologies. For instance, CO_2 capture and sequestration is most cost-effective for high volumes of CO_2 emissions, so efficiency measures that reduce CO_2 emissions may increase the marginal cost of abatement associated with using CCS to treat the remaining CO_2. We further discuss the pitfalls of process aggregation, which is commonly done in retrospective empirical studies, and the ways our approach may generalize to other "hard-to-abate" industries, such as cement and chemicals.

Our analysis also explores variations in air quality, workforce, education, and racial composition surrounding U.S. steel plants. It aims to uncover the intricate relationships between proximity of steel plants, differences in air quality, and socioeconomic disparities, highlighting environmental justice concerns. In particular, the research estimates changes in air pollution near BF-BOF and EAF facilities, shedding light on how decarbonization investments might affect these areas. While the current worldwide share of steel production using an EAF is 32%, the International Energy Agency's (IEA) Net Zero by 2050 scenario indicates that over half (53%) of steelmaking capacity needs to use EAF technology by 2050 to meet that goal (Swalec and Grigsby-Schulte, 2023). The findings of our study suggest that increasing DRI-EAF steel production to cover a larger share of national steel demand may generate not only cost savings to the industry, but also community environmental and health benefits, and deep reductions in CO_2 emissions by the middle of the century.

2 U.S. iron and steel production: CO_2 emissions and abatement opportunities

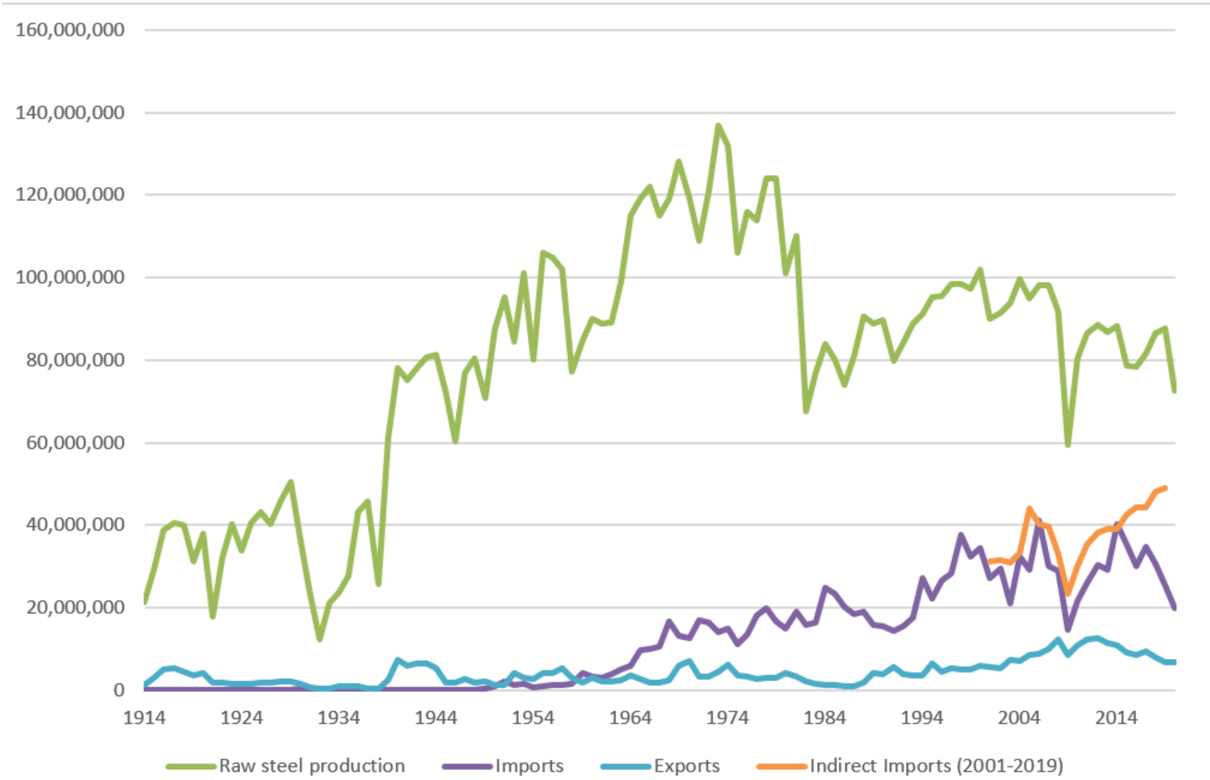
U.S. producers face pressure to report and address CO_2 emissions from three "Scopes": Scope 1 includes energy and process CO_2 emissions inside the firm boundary, Scope 2 includes CO_2 emissions due to generation of electricity or heat used by the firm, and Scope 3 includes CO_2 emissions from upstream (e.g., mining, ore processing, transport of intermediate inputs) and downstream (e.g., manufacturing of auto parts and automotive use) activities. Upstream Scope 3 emissions are often easier to quantify than downstream Scope 3 emissions, due to the complexity of tracking energy and CO_2 emissions across a range of supply chain stages and final product categories. We focus our analysis on abating Scope 1 and 2 CO_2 emissions from ironmaking and steelmaking processes, which account for approximately 90% of total CO_2 emissions[1]. Below we discuss the major sources of CO_2 emissions from the iron and steel supply chain and the cost and effectiveness of abatement strategies.

[1] We draw the accounting boundary at CO_2 emissions per ton of crude steel, consistent with the methodology of the World Steel Association. We do not include CO_2 emissions downstream of this point in the process, including most of what would be considered downstream Scope 3

2.1 Sources of CO_2 emissions from today's iron and steelmaking

Globally, the iron and steel industry 8% of end-use energy demand and 7% of energy sector CO_2 emissions (International Energy Agency, 2020). In the United States, it totals 2% (U.S. Department of Energy, 2022), reflecting mainly greater reliance on scrap-based EAF steelmaking (70% or production in the U.S.), relative to the world as a whole (30% of total production). In the U.S., demand for steel is mainly construction, followed by automotive, machinery, and household appliances. Over several decades, U.S. steel demand has been increasingly met by foreign production, both in the form of finished and semi-finished products and indirect imports (e.g., auto parts), as reported in Figure 1. In 2022, shipments from U.S. steel plants totalled 82 million metric tons, compared with 30 million metric tons of finished and semifinished steel imports (Tuck, 2023).

Figure 1: U.S. Crude Steel Production, Exports, Imports, and Indirect Imports

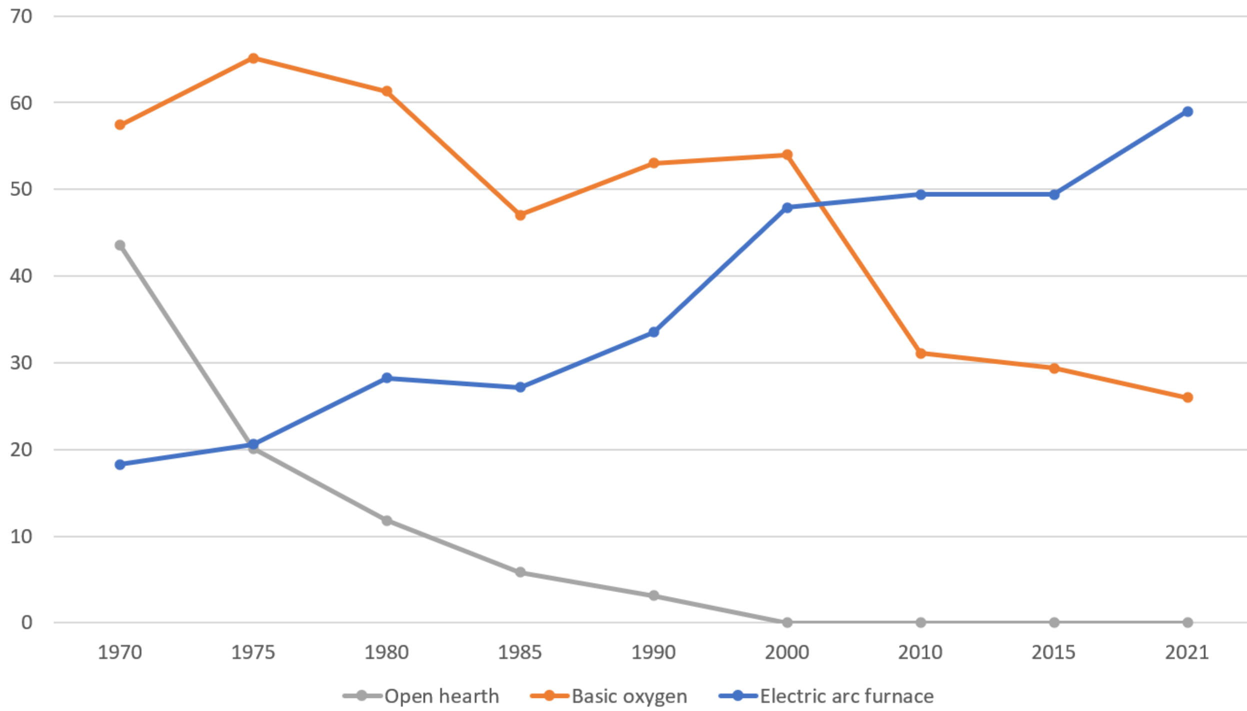


Notes: This figure displays U.S. steel production and trade statistics. Indirect imports, which include steel that has become part of manufactured products such as auto parts or cars, are only available for 2001-2019 (World Steel Association, 2023).

Our analysis focuses on the ironmaking and steelmaking steps in the two major steelmaking routes, the integrated and EAF routes, used in the U.S. and world today. The integrated route begins with iron ore and uses the blast furnace-basic oxygen furnace (BF-BOF) processes to produce steel. Once iron ore is mined and concentrated to obtain the desired form and composition of feed material (e.g., pellets, sinter), iron ore is reduced to elemental iron at high temperatures. Today, this ironmaking step largely occurs in the nine remaining blast furnaces in the U.S. using coke as a reductant, producing liquid iron and substantial CO_2 emissions. Integrated steelmaking accounts for around 60% of the industry's emissions, despite representing on 30% of total production. Iron is either fed directly in liquid form or remelted and combined with 18-28% scrap in the basic oxygen furnace (Association for Iron and Steel Technology, 2023), where its composition is refined, then transferred to ladle metallurgy for further adjustments and cast into steel slabs or other forms, depending on the desired product.

The electric arc furance (EAF) route has developed rapidly over the past 40 years and today supplies around 70% of U.S. steel production, compared to 30% in the 1980s (see Figure 2). The EAF process uses electric arcs at temperatures of 1700 degrees Celcius to melt (primarily) scrap steel, followed by the introduction of oxygen and other additives to refine its composition. Depending on product composition requirements, an EAF may use an increasing share of ore-based metallics to compensate for poor scrap quality or unavailability. Over time, EAFs have proven able to make a wider range of steels and are anticipated to continue to improve and even meet demanding quality thresholds that to date only integrated producers have been able to deliver (e.g., exposed automotive). In the future, EAF steelmaking may face constraints on the availability of high quality scrap steel that will necessitate raising the share of ore-based metallics on average in the EAF charge, although requirements will vary based on specific requirements of each steel grade.

Figure 2: Production (mtpa) of steel by furnace process in the United States, 1970-2021



Notes: This figure displays BOF and EAF steel production in the United States over time. "Mtpa" stands for million tonnes per annum. Source: (U.S. Geological Survey Data, 2023)

2.2 Methodology: Cost of reducing iron and steelmaking CO_2 emissions

Our analysis focused on technologies that could be deployed to reduce CO_2 emissions from iron and steel production in the near term. In developing our two scenarios, we excluded abatement technologies for which (1) the maximum expected CO_2 emissions reduction associated with deployment at existing facilities was small and (2) the technology was not additive or compatible with pathways to deep decarbonization. In doing so, we aimed to avoid a common fallacy present in abatement cost curve construction, wrongly assuming that multiple incompatible abatement opportunities are additive. For example, hydrogen injection in a blast furnace to limit CO_2 emissions from the reduction step would lower the cost effectiveness of carbon capture and sequestration, because it would dilute CO_2 in the top gas stream and thereby reduce CO_2 captured while capital and variable costs remained largely unchanged. For the same reason, we do not consider the substitution of natural gas for coke in the blast furnace as a CO_2 reduction opportunity, although it has been commonly employed.

We perform an analysis of the variable cost per ton of crude steel and life-cycle CO_2 emissions associated with the deployment of two pathways to deep decarbonization:

- **A "route-specific" (RS) scenario** which preserves existing blast furnace iron production (nine remaining furnaces) and installs carbon capture and sequestration to abate CO_2 emissions. The EAF route decarbonizes through a combination of clean electricity and a shift to natural gas-based direct reduced iron (DRI), which displaces CO_2-intensive pig iron. The DRI furnace is capable of using high blends of hydrogen (90% or more), should cost-effective, decarbonized supply become available over time.

- **A "substitution-in-place" (SP) scenario** that continues the shift to EAF production, which has to-date been driven by economics, requiring current integrated route production to be replaced by DRI-EAF production, initially using natural gas but with the option to use high blends of hydrogen, if available. We consider the implications of siting new production where existing production is located.

Integrated route CO_2 reduction. Due to the CO_2 intensity of using coke as a reductant in the blast furnace, most studies foresee deep reductions in CO_2 emissions from the BF-BOF route are only possible if the CO_2 in the top gas can be captured and sequestered. This abatement strategy has several implications. First, it increases electricity as an input to the ironmaking, because it is needed to operate the capture device, compress the CO_2, and transport it to the sequestration site. Second, while the capture unit can be sized for any given plant's CO_2 volume, the CCS process benefits from economies of scale. Therefore, abatement cost will be inversely related to plant size and CO_2 emissions volume. Third, to be effective, installation of carbon capture must be accompanied by investments in CO_2 offtake, including dedicated pipelines and sequestration sites. These investments, which are largely external to steel producers, are a major source of uncertainty surrounding the success of this pathway.

EAF route CO_2 reduction. Evaluating abatement pathways for the EAF route must consider uncertainty in the availability of high quality scrap steel, which will determine the share of DRI or other ore-based metallics in the EAF charge. For purposes of this analysis, we assume that demand for ore-based metallics in the EAF is independent of total demand for steel in the United States[2]. We consider both natural gas and hydrogen as reductants used in DRI production, reflecting the fact that both could be used in varying ratios within the same furnace setup. We consider a natural gas pathway, a 100% hydrogen pathway, a 50% hydrogen and 50% natural gas pathway, and a pathway that involves carbon capture with 90% CO_2 removal installed on the DRI furnace.

Inputs to our technoeconomic assessment were drawn from peer-reviewed papers and technical reports, with values and sources described in Appendix Table A.1. Variable costs are reported as undiscounted cost by input per ton of crude steel and summed for each pathway. Capital costs are reported per annual ton of capacity, also undiscounted and without financing costs.

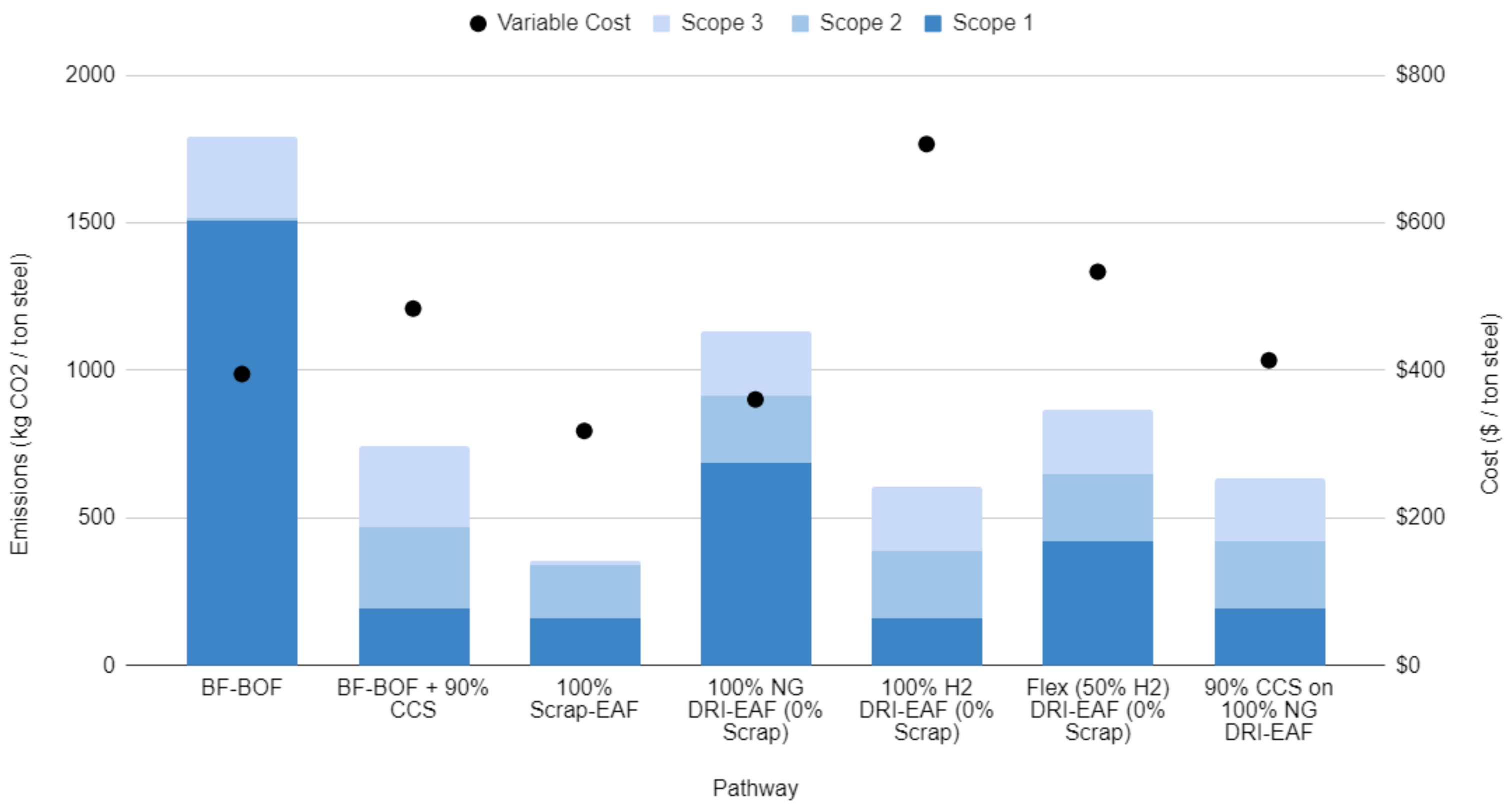
3 Results: Technoeconomic and abatement cost analysis

3.1 Comparison of pathways

The comparison of pathways in terms of variable cost and CO_2 emissions (by scope) is shown in Figure 3.

[2]This assumption is plausible, given that ore-based metallics represent on average around 5% of a EAF charge today and even if higher shares are needed to replace integrated route production, the average requirement across the U.S. EAF fleet is unlikely to exceed 15%. These assumptions can be further examined in sensitivity analysis.

Figure 3: Costs and CO_2 emissions associated with current and future iron and steel production technologies



Notes: This figure reports the core results of our technoeconomic and abatement cost analysis. The bars represent emissions and the dots the variable costs.

For the integrated route, even with 90% carbon capture, CO_2 emissions only fall by approximately 60%, for several reasons. First, Scope 3 emissions, which largely correspond to mining, processing, and transport, are unaffected, and remain the constant across all pathways that use virgin ore. Second, Scope 2 emissions rise due to the need for electricity to run the carbon capture unit (energy required for compression and transport is not included), which is assumed to be provided by grid electricity and assumes the U.S. average CO_2 emissions intensity. Scope 1 emissions correspond to the residual 10% of plant emissions not covered by the carbon capture unit.

For the EAF route, steel production has much lower CO_2 emissions because its primary input, scrap, has already undergone the CO_2 intensive reduction step and there is no need for mining virgin ore. If 100% scrap is used, emissions are approximately 0.4 tons CO_2 per ton of crude steel, due to the electricity input to the furnace (Scope 2) and process CO_2 emissions, which are a byproduct blowing oxygen into the furnace to burn out impurities (Scope 1). If instead ore-based metallics (e.g., pig iron) comprise part of an EAF charge, the Scope 3 CO_2 emissions would be higher. We assume in moving to decarbonized production that a higher share of ore-based metallics will be needed to dilute impurities that compound over successive rounds of recycling and as a hedge against potential disruptions in scrap markets.

Comparing pathways with DRI, we find that costs largely rise in proportion to CO_2 emissions reductions, with NG-DRI-EAF steel production comparable in variable cost to today's integrated route. Increasing the use of hydrogen as a reductant in the DRI process to 50% brings CO_2 emissions down by an additional 0.2 tons per ton of crude steel, but increases cost by around 50%. Going to 100% hydrogen reduces CO_2 emissions further, but the reduction is offset by the need for more energy to preheat the input gas stream (as the hydrogen reduction reaction is endothermic) and by the need to add carbon for carburization. In part due to these considerations, reducing CO_2 emissions with 90% CCS on NG-DRI-EAF steel production is more cost effective, if CCS is available.

3.2 Costs of CO_2 abatement

Comparing the cost of CO_2 abatement in our two scenarios requires construction of a counterfactual. We assume that the counterfactual today is defined by current CO_2 emissions from today's BF-BOF production and a counterfactual EAF case that requires 15% ore-based metallics in an EAF charge.

Table 1: Assumptions for CO_2 reduction scenarios

Measure	**Quantity**	**Source**
U.S. BF-BOF capacity (2021)	40 mtpa	WSA (2022)
U.S. BF-BOF production (2021)	26 mtpa	WSA (2022)
U.S. EAF capacity (2021)	89 mtpa	WSA (2022)
U.S. EAF production (2021)	59 mtpa	WSA (2022)
Pig iron input for EAF, 15% of charge	8.9 mtpa	Assumption

Notes: This table reports current capacity and production for the BF-BOF and EAF production separately. Given the relative stability of U.S. steel production around 80 mtpa, we assume in our scenarios that abatement actions address CO_2 emissions from existing production.

The assumptions on total capacity to be decarbonized in Table 1 and estimated incremental capital and variable costs of decarbonization by process are shown in Table 2. Based on the above analysis, maintaining BF-BOF steelmaking and decarbonizing with CCS is slightly less expensive on a capital cost basis ($23 billion in the RS scenario versus $25 billion, accounting for the cost of constructing new DRI and EAF production). However, when comparing incremental variable cost, the BF-BOF pathway is substantially more expensive compared to the DRI-EAF pathway ($4.8 billion versus $3.5 billion), because moving to the EAF pathway only requires a modest amount of low CO_2 DRI production to be constructed and leverages the CO_2 emissions advantage of the EAF. While EAF producers spend more on total for decarbonized electricity in the SP scenario, the total amount of zero C electricity that is required in the RS scenario is higher.

Comparing the CO_2 emissions reductions that occur in the two scenarios, the SP scenario is superior, with an 80% reduction in the SP scenario compared to a 71% reduction in the RS scenario.

Table 2: Estimated cost of lowering CO_2 emissions in the iron and steel in two scenarios and associated CO_2 intensities and CO_2 emissions reductions

"Route specific" (RS) scenario	**Quantity**
BF-BOF incremental capital cost	$16 billion
BF-BOF incremental variable cost per year	$2.3 billion
EAF incremental capital cost for DRI (15% of EAF charge)	$7.2 billion
EAF incremental variable cost per year for DRI	$2.5 billion
EAF zero C electricity cost per year	$0.8 billion
CCS zero C electricity cost per year	$0.5 billion
U.S. average CO_2 emissions per tcs	0.289 t CO_2 per tcs
% reduction in CO_2 emissions from iron and steel	71%
"Substitution-in-place" (SP) scenario	**Quantity**
BF-BOF incremental capital cost	$0 billion
BF-BOF incremental variable cost per year	$0 billion
EAF incremental capital cost for new EAF	$12.4 billion
EAF incremental capital cost for DRI	$12.8 billion
EAF incremental variable cost per year for DRI	$3.5 billion
EAF zero C electricity cost per year	$1.2 billion
U.S. average CO_2 emissions per tcs	0.213 t CO_2 per tcs
% reduction in CO_2 emissions from iron and steel	80%

Notes: Price of scrap is assumed to be $258 per ton. Zero C electricity credits are assumed to be available at $0.03/kWh to cover the incremental cost of supplying decarbonized electricity to EAF steel plants.

Together, these results suggest that more industry-wide CO_2 reduction could be acheived with a slightly higher capital cost and a lower variable cost, which pays back the initial investment (undiscounted) within two years. We now move to explore the sociodemographic and air quality characteristics of today's steel communities, which form a starting point for assessing the implications for them of decarbonizing through each of the two scenarios examined here.

3.3 Methodology: Air pollution and socioeconomic characteristics near steel plants

In recent decades, the spatial distribution of industrial facilities, particularly steel plants, has raised critical questions regarding environmental justice, socioeconomic disparities, and public health. This analysis examines the intersectionality between proximity to steel plants, air quality differentials, and socioeconomic disparities, particularly focusing on the implications for environmental justice. The presence of steel plants often acts as a focal point for investigating environmental inequalities, as communities adjacent to these industrial facilities frequently experience higher levels of air pollutants, posing significant health risks. Moreover, these areas commonly exhibit distinct socioeconomic characteristics, marked by disparities in income levels, access to resources, and demographic compositions.

Of the two dominant technologies for steel production in the United States, BF-BOF plants primarily use iron ore, coke, and fluxes to produce steel, emitting high levels of carbon dioxide and local pollutants. EAF facilities, on the other hand, rely on scrap steel and electricity, resulting in lower levels of emissions and energy than BF-BOF. The analysis will exploit this dimension of heterogeneity, as steelmakers plan to partially transition to EAF in their path toward achieving sustainable steel production.

3.3.1 Plant locations and BF-BOF vs. EAF differences

In the United States, the geographical distribution of steel plants varies significantly based on the predominant steelmaking processes used. Historically, the BF-BOF technology has been prevalent, leading to the concentration of steel plants primarily in regions endowed with raw materials such as iron ore, coal, and limestone. As a result, BF-BOF plants have been concentrated in traditional industrial regions, as displayed in Figure 4. States like Pennsylvania, Indiana, and Ohio have housed numerous BF-BOF facilities due to their access to essential resources and transportation networks. These facilities, while integral to steel production, emit substantial quantities of air pollutants due to their reliance on raw materials and high-temperature combustion processes. As noted earlier, only about 30% of the current steel production in the U.S. comes from BF-BOF plants.

Conversely, the adoption of EAF technology has spurred the establishment of steel plants in diverse locations, including areas closer to scrap metal sources and major urban centers. By using scrap steel as their primary input, EAF plants have a comparatively cleaner production process with reduced emissions of particulate matter and greenhouse gases. This shift towards EAF technology has led to the emergence of steel plants in states like Texas, Florida, and Arkansas, fostering a more geographically dispersed distribution of steel manufacturing facilities, as depicted in Figure 4. The differences in steel plant locations based on steelmaking technologies highlight the evolving landscape of the U.S. steel industry, reflecting a transition towards more environmentally sustainable practices and a diversification of geographic clusters for steel production.

3.3.2 Air pollution and socioeconomic characteristics examined and data sources

The analysis of the intersectionality between proximity to steel plants, air quality variations, and socioeconomic disparities relies on two comprehensive and diverse data sources. Integrating these diverse datasets enables a holistic examination of the complex interrelationships between industrial proximity, air quality dynamics, and socioeconomic disparities, thereby fostering a more nuanced understanding of environmental justice concerns in these regions.

Satellite-derived PM2.5 pixel level data obtained from van Donkelaar et al. (2021). They developed a method to estimate monthly PM2.5 levels over the entire globe from 1998 to 2019. Their approach integrates satellite-based aerosol optical depth retrievals, chemical transport modeling, and ground-based measurements. The resulting dataset contains annual mean PM2.5 concentrations in micrograms per cubic meter ($\mu g/m^3$) at an exceptionally detailed resolution of 0.01^o x 0.01^o, approximately covering an area of 0.7 x 0.7 miles. This satellite-derived data offers a robust basis for evaluating the dispersion patterns of particulate matter in areas neighboring steel plants, enabling a nuanced understanding of the spatial distribution of air pollution and its proximity to industrial sites.

Complementing the PM2.5 data, socioeconomic variables come from the American Community Survey (ACS) 5-Year Data spanning the periods of 2010-2014 and 2015-2019. The ACS furnishes granular information at the census tract level, encompassing key socioeconomic indicators crucial for assessing disparities. Variables such as income levels, the proportion of the population below the poverty line, educational attainment (including the percentage of college graduates), racial demographics (including the share of African Americans or the share of nonwhites more broadly), and labor market characteristics (such as unemployment rate and the share of individuals out of the labor force) offer insights into the socioeconomic fabric of communities surrounding steel plants. These multi-year ACS datasets, spanning periods after the Great Recession but pre-dating the COVID-19 pandemic, provide a comprehensive temporal snapshot of socioeconomic conditions, facilitating the analysis of long-term trends and disparities in areas close to steel manufacturing facilities.

3.3.3 Descriptive analysis and difference in differences

We start with a descriptive analysis entailing an intricate examination of PM2.5 concentrations and socioeconomic characteristics across varying distances from steel plants, stratified by the predominant steelmaking technologies (BF-BOF vs. EAF) and temporal periods (2010-2014 and 2015-2019). It involves categorizing proximity into distance bins (0-2 miles, 2-5 miles, 5-10 miles, 10-20 miles, and 20-30 miles) from steel facilities, assessing PM2.5 concentrations from the van Donkelaar et al. (2021)'s dataset, and socioeconomic attributes sourced from ACS data. Examining PM2.5 levels and socioeconomic variables across these distance bins and time periods offers insights into how proximity to steel plants and the transition from BF-BOF to EAF might have influenced air quality and community demographics. Descriptive statistics are crucial for understanding the spatial and temporal dynamics of environmental and social factors. They provide a snapshot of mean PM2.5 concentrations and socioeconomic indicators such as income, poverty levels, educational attainment, racial demographics, and labor market characteristics, enabling comparisons among different distances, steelmaking technologies, and temporal periods.

Then we conduct a difference in differences (DiD) analysis examining changes in the averages of PM2.5 concentrations and socioeconomic variables within BF-BOF and EAF areas relative to a chosen reference distance bin, the zone within 0-2 miles from steel plants. This empirical approach enables the isolation of the differential impact of the BF-BOF steelmaking technology relative to the EAF technology by contrasting the changes in averages of these attributes over technology and distance. In practice, this research design involves comparing the difference by distance relative to the 0-2 miles bin for BF-BOF areas versus the difference by distance relative to the 0-2 miles bin for EAF areas. By examining the differential changes in PM2.5 concentrations and socioeconomic characteristics resulting from the shift to EAF compared to BF-BOF across different distances, this method offers a nuanced understanding of the specific effects attributed to the change in steelmaking technologies. It provides valuable insights into the broader implications of transitioning to EAF in the United States and the global plans to adopt EAF technology, elucidating how such shifts may impact environmental justice, air quality, and socioeconomic disparities across varying proximities to steel plants.

There are 9 BF-BOF and 58 EAF facilities in our sample. The 8 EAF facilities built after 2019 are not included in the analysis because we use ACS data for only two periods before the COVID-19 pandemic (2010-2014 and 2015-2019). For the BF-BOF analysis, there are 9 tracts where they are located and 5,082 surrounding tracts (within 30 miles of the plants). For the EAF analysis, there 58 tracts where they are located and 14,772 surrounding tracts.

The standard errors in the DiD analysis are robust and clustered at the furnace level. According to the design-based approach to clustering (Abadie et al., 2023), the largest unit that the treatment is assigned should be selected as the clustering unit. In our setting, treatment is assigned at the furnace level.

3.4 Results: Air pollution and socioeconomic characteristics near steel plants

3.4.1 Air pollution

The descriptive analysis reveals a pronounced gradient in average PM2.5 levels across distance bins relative to BF-BOF steel plants, depicting a substantial decline in air pollution as distance increases, as depicted in Figure 5. This is comparable to the magnitude reported in Currie, Voorheis and Walker (2023)'s study on the impact of the 2005 implementation of the PM2.5 National Ambient Air Quality Standards (NAAQS): a 0.73 $\mu g/m^3$ reduction in PM2.5 levels. Notably, this gradient contrasts sharply with the relatively stable or negligible gradient observed around EAF facilities, indicating significantly lower PM2.5 levels and a lack of substantial spatial variation in air pollution emanating from these cleaner steel production processes. Moreover, the analysis indicates a noteworthy decrease in PM2.5 levels across the periods of 2010-2014 and 2015-2019. This decline could potentially be attributed to the implementation and enforcement of NAAQS and other stringent environmental policies during this timeframe, contributing to the amelioration of air quality in regions surrounding steel plants.

The difference in difference analysis accentuates the disparity in air pollution gradients between areas associated with BF-BOF and EAF steel production, as displayed in Figure 6.[3] This approach showcases a clear gradient in pollution around BF-BOF plants relative to the cleaner steel production facilitated by EAF, emphasizing the differential impacts of these steelmaking technologies on air quality. The analysis underscores the discernible differences in pollution levels between areas near BF-BOF and those around EAF facilities, attributing the comparatively higher pollution gradient to the traditional BF-BOF steelmaking process. This stark contrast underscores the environmental advantages associated with the transition towards cleaner steel production via EAF technology, highlighting the potential for reduced

[3] This figure controls only for time-period fixed effects. Appendix Figure A.1 adds controls for income, share of college graduates, and share of African Americans. The pattern is remarkably similar.

environmental burdens and improved air quality in communities surrounding steel plants adopting more sustainable production methods.

3.4.2 Socioeconomic characteristics

The descriptive analysis of average socioeconomic variables also unveils gradients across varying distances from steel plants. The examination reveals a discernible gradient in income levels and other socio-demographic characteristics as distance from steel plants increases, as shown in Figures 7-10. Specifically, closer proximity to facilities is associated with lower average incomes, a lower proportion of college graduates, and a higher proportion of African Americans and of individuals out of the labor force. Notwithstanding, the population density close to the plants is lower, as reported by Figure 11.[4] Moreover, Appendix Figures A.3-A.5 indicate higher shares of individuals below the poverty line, nonwhite, and unemployed in closer proximity to steel plants. However, in contrast to the clear gradient observed in air pollution, the socioeconomic disparities by distance concerning steel plants show variations that are not as consistently pronounced across all socioeconomic indicators.

Also, contrary to the clearer gradient observed in air pollution levels between BF-BOF and EAF areas, the difference in differences analysis yields a more nuanced narrative regarding socioeconomic disparities. While the analysis of air pollution reveals a substantial gradient favoring EAF technology in mitigating pollution levels, the socioeconomic disparities exhibit less straightforward patterns across the BF-BOF and EAF areas concerning varying distances from steel plants, as displayed in Appendix Figures A.6-A.14. This is particularly the case for the share of African Americans and the share of the broader category of nonwhites.

Unlike the stark gradients observed in air pollution, the DiD analysis demonstrates a less consistent or clear-cut gradient in socioeconomic variables between BF-BOF and EAF sites across proximity bins. This nuanced analysis implies that while certain socioeconomic vari-

[4] Because there are many more EAF than BF-BOF plants in the United States, total population is much larger in areas closer to EAF facilities, as shown in Appendix Figure A.2.

ables may exhibit disparities between steelmaking technologies, the influence of distance from the plants might not uniformly shape these disparities. Factors beyond simple proximity, such as historical contexts, community characteristics, and local policies, likely contribute to the intricate socioeconomic landscape surrounding steel plants, rendering the relationship between steelmaking technologies and socioeconomic disparities more multifaceted than the gradient observed in air pollution.

3.4.3 Discussion and interpretation

The proximity to steel plants engenders discernible disparities in air quality and socioeconomic profiles between nearby and distant locations. Areas in close proximity to steel plants exhibit markedly poorer air quality due to elevated concentrations of particulate matter. These pollutants may pose substantial health risks to residents, leading to heightened incidences of respiratory ailments and cardiovascular diseases. Moreover, communities residing near steel plants exhibit lower socioeconomic characteristics, characterized by higher concentrations of lower-income households and marginalized populations. This conjunction of industrial proximity and disadvantaged demographics amplifies concerns regarding environmental justice, where vulnerable communities may face disproportionate exposure to environmental hazards without commensurate access to resources, exacerbating health disparities and underscoring the intricate link between industrial activities, socioeconomic status, and environmental equity.

The distribution of particulate matter demonstrates a distinct gradient between locations in proximity to BF-BOF steel plants and those near EAF facilities. Close to BF-BOF plants, there exists a pronounced gradient in particulate matter concentrations, showcasing significantly higher levels due to emissions from these traditional steelmaking processes. Conversely, areas near EAF plants display a less pronounced or negligible gradient in PM2.5 concentrations due to the cleaner production process that uses scrap steel. The transition of steel production from BF-BOF to EAF represents a positive trajectory for the future, wherein the global steel industry aims to reduce its environmental footprint. This shift promises significant improvements in air quality, as EAF technology minimizes the emission of harmful pollutants associated with traditional steelmaking processes. Embracing this transition may contribute substantially to mitigating environmental impacts, enhancing air quality, and promoting sustainable steel production practices worldwide.

3.5 Preliminary Conclusions

We performed an integrated analysis of the costs of decarbonizing U.S. iron and steel production and considered characteristics of communities that would be affected by these decisions, as a step towards understand each pathways' distributional effects. Our analysis has thus far reached several conclusions:

First, it is important to recognize the interdependencies among process steps when evaluating decarbonization strategies. While our analysis of iron and steel decarbonization did not exhaustively quantify these dependencies in the technology options modeled, incorporating them, along with design and operational flexibility, may change the economics of investment decisions. Therefore, when developing models, it can be problematic to represent a fixed set of decarbonization technology options competing with one another for adoption at a particular process step, or to aggregate process steps together, as the decision may depend on how steeply costs are increasing in further CO_2 reductions from a particular technology pathway (e.g., the cost of adding CCS to natural gas DRI production or switching to hydrogen as a reductant) and on any interactions with the economics of other process steps (e.g., ore extraction and processing cost, waste gas recycling used in on-site power generation).

Second, we find that replacing integrated BF-BOF production with DRI-EAF (or even DRI-BOF) production may be a more cost-effective decarbonization pathway compared to a strategy that lowers CO_2 emissions from the integrated route using CCS. For both routes, the cost and effectiveness of CCS in removing CO_2 emissions is a major uncertainty. If CCS is not available, shifting to DRI-EAF production still allows an operator to substitute zero

CO_2 hydrogen for natural gas as a reductant, further lowering CO_2 emissions albeit at a high cost based on today's available technologies. Another important dependence is on the share of ore-based metallics (e.g., DRI) and additional process innovation required to make the full range of steel grades in an EAF that are currently covered by integrated production.

Third, communities near integrated production experience worse air quality, relative to communities near EAFs, suggesting that if CCS installation does not address air quality issues. There may be additional local air quality benefits of a transition from BF-BOF to DRI-EAF (or even DRI-BOF) production.

Fourth, future work should consider comparing the transition in place for integrated production with one that constructs DRI-EAF production in places with the most favorable combination of infrastructure (e.g., rail transport, geology for CO_2 sequestration, low electricity prices), considering that access to inputs shaped location choices when integrated BF-BOF production was built over the past century. Juxtoposing alternative projections of plant location with detailed socioeconomic characteristics of proximate communities will allow us to assess the economic, labor, and environmental dimensions of equity associated with approaches to a transition to deeply decarbonized iron and steel production.

Globally, the steel industry faces a significant challenge in decarbonizing its operations. Despite growing awareness and commitments toward net zero emissions by 2050, only a third of the top 50 steel producers have set such targets, though they are responsible for over 60% of the sector's emissions. While there's been a rise in plans for low-emissions, green steel production, the construction of emissions-intensive blast furnaces still dominates announcements (GEM, 2023*b*). Newly announced blast furnace capacity surpasses low-emissions iron and steel capacity by 2.5 times, with global figures of 208.2 million tonnes per annum (mtpa) for blast furnaces compared to 83.6 mtpa for low-emissions projects. Moreover, an additional 68.1 mtpa of blast furnace capacity is currently under construction. This discrepancy highlights the challenge in transitioning the industry toward sustainable steel production despite growing initiatives for cleaner methods.

Recent developments, however, indicate an increasing shift toward EAF steelmaking. In March 2022, the planned capacity proportions closely mirrored the worldwide existing operating capacity, with 67% for BF-BOF and 33% for EAF, suggesting no anticipated change in future operating capacity shares. Nevertheless, by March 2023, there has been a notable change in plans, with 43% of the projected capacity now leaning towards gas and electricity-based EAF, while only 57% intends to utilize the coal-based BF-BOF method (Swalec and Grigsby-Schulte, 2023). Our findings may aid in crafting incentives and policies to shape a clear roadmap for the steel industry's path toward decarbonization.

References

Abadie, Alberto, Susan Athey, Guido W Imbens, and Jeffrey M Wooldridge. 2023. "When Should You Adjust Standard Errors for Clustering?" *Quarterly Journal of Economics*, 138(1): 1–35.

Association for Iron and Steel Technology. 2023. "Basic Oxygen Furnace Roundup." Association for Iron and Steel Technology.

Currie, Janet, John Voorheis, and Reed Walker. 2023. "What Caused Racial Disparities in Particulate Exposure to Fall? New Evidence from the Clean Air Act and Satellite-Based Measures of Air Quality." *American Economic Review*, 113(1): 71–97.

GEM. 2023*a*. "Global Steel Plant Tracker." Global Energy Monitor (GEM), March 2023, (v2) release.

GEM. 2023*b*. "A Matter of Ambition: Examining the Steel Industry's Commitment to Net Zero by 2050." Global Energy Monitor (GEM) – Leadership Group for Industry Transition (LeadIT).

International Energy Agency. 2020. "Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking." International Energy Agency.

Swalec, Caitlin, and Astrid Grigsby-Schulte. 2023. "2023 Pedal to the Metal: It's Time to Shift Steel Decarbonization Into High Gear." *Global Energy Monitor (GEM) Report*, Available at https://globalenergymonitor.org/wp–content/uploads/2023/07/GEM_SteelPlants2023.pdf.

Tuck, Cris Candice. 2023. "Mineral Commodity Survey, Iron and Steel." U.S. Geological Survey.

U.S. Department of Energy. 2022. "Industrial Decarbonization Roadmap." U.S. Department of Energy.

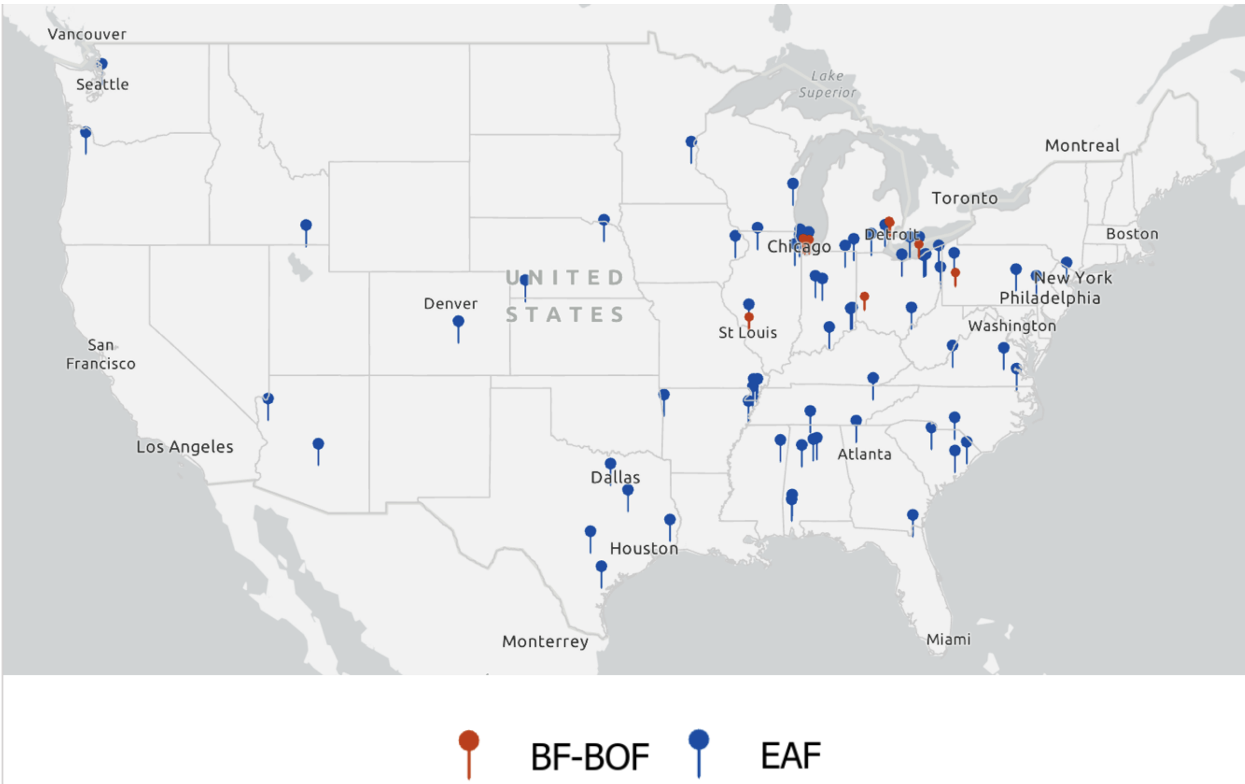
U.S. Geological Survey Data. 2023. "Iron and Steel Statistical Compendium (U.S. raw steel production, by furnace process and by steel type)." U.S. Geological Survey.

van Donkelaar, Aaron, Melanie S. Hammer, Liam Bindle, Michael Brauer, Jeffery R. Brook, Michael J. Garay, N. Christina Hsu, Olga V. Kalashnikova, Ralph A. Kahn, Colin Lee, Robert C. Levy, Alexei Lyapustin, Andrew M. Sayer, and Randall V. Martin. 2021. "Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty." *Environmental Science & Technology*, 55(22): 15287–15300.

World Steel Association. 2023. "worldsteel data." World Steel Association.

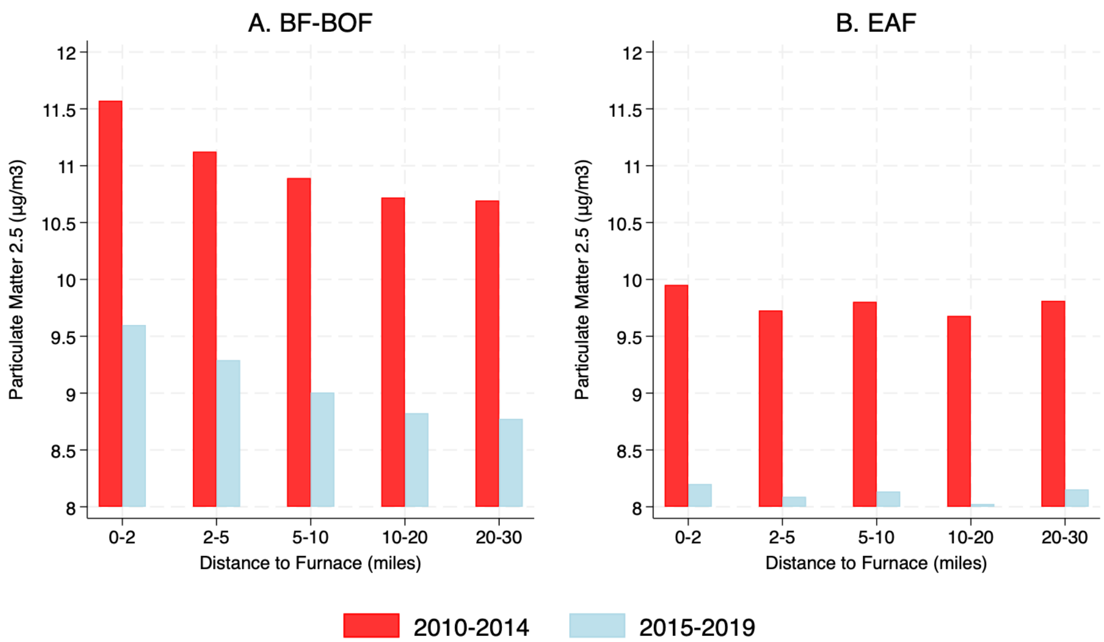
Figures and Tables

Figure 4: Map of Current BF-BOF and EAF Facilities in the United States



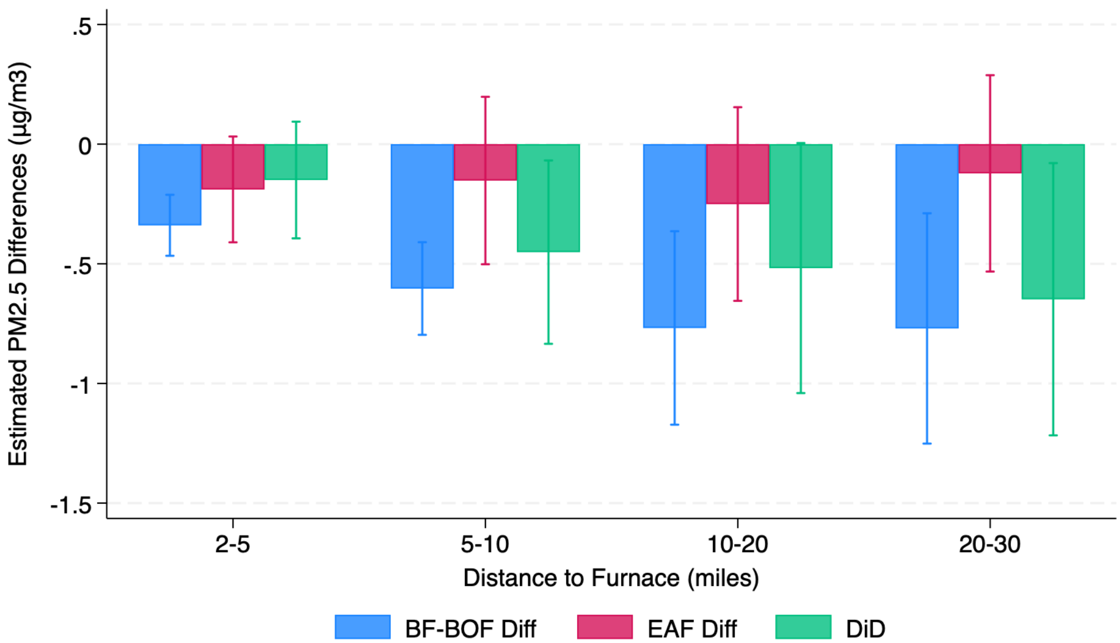
Notes: This figure displays the 9 BF-BOF and the 66 EAF facilities in operation in the United States. The data for the map comes from GEM (2023*a*).

Figure 5: Average PM2.5 Levels by Distance to Steel Plants



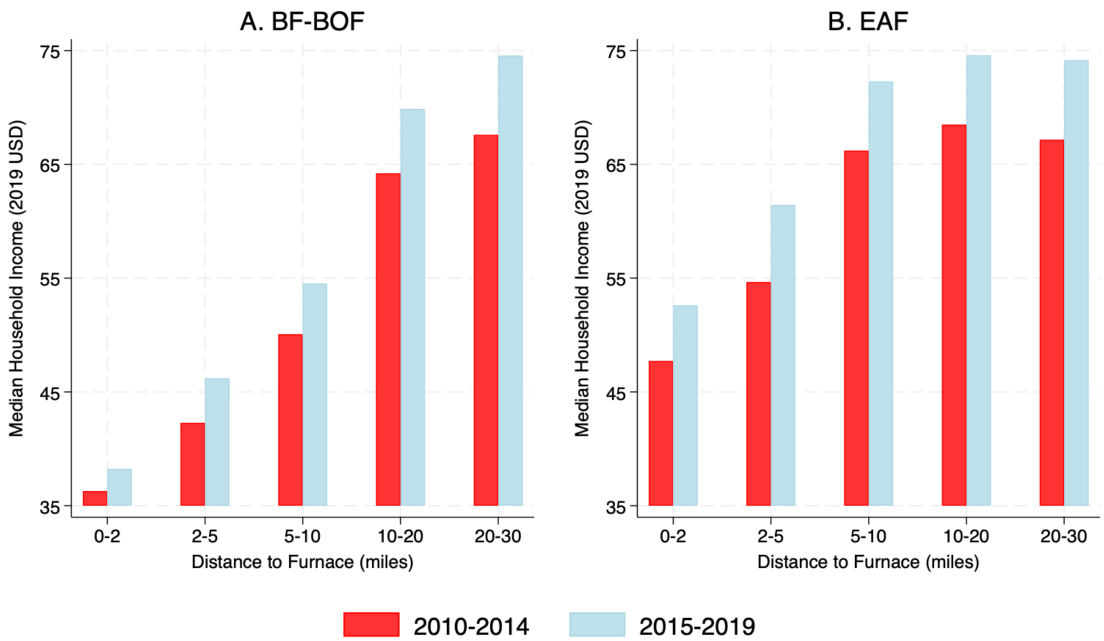
Notes: This figure displays average PM2.5 levels across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data. There are 9 BF-BOF and 58 EAF facilities in our sample. The 8 EAF facilities built after 2019 are not included in the analysis because we use ACS data for only two periods before the COVID-19 pandemic (2010-2014 and 2015-2019). For the BF-BOF analysis, there are 9 tracts where they are located and 5,082 surrounding tracts (within 30 miles of the plants). For the EAF analysis, there 58 tracts where they are located and 14,772 surrounding tracts.

Figure 6: Estimated PM2.5 Differences Relative to 0-2 Miles from Steel Plants



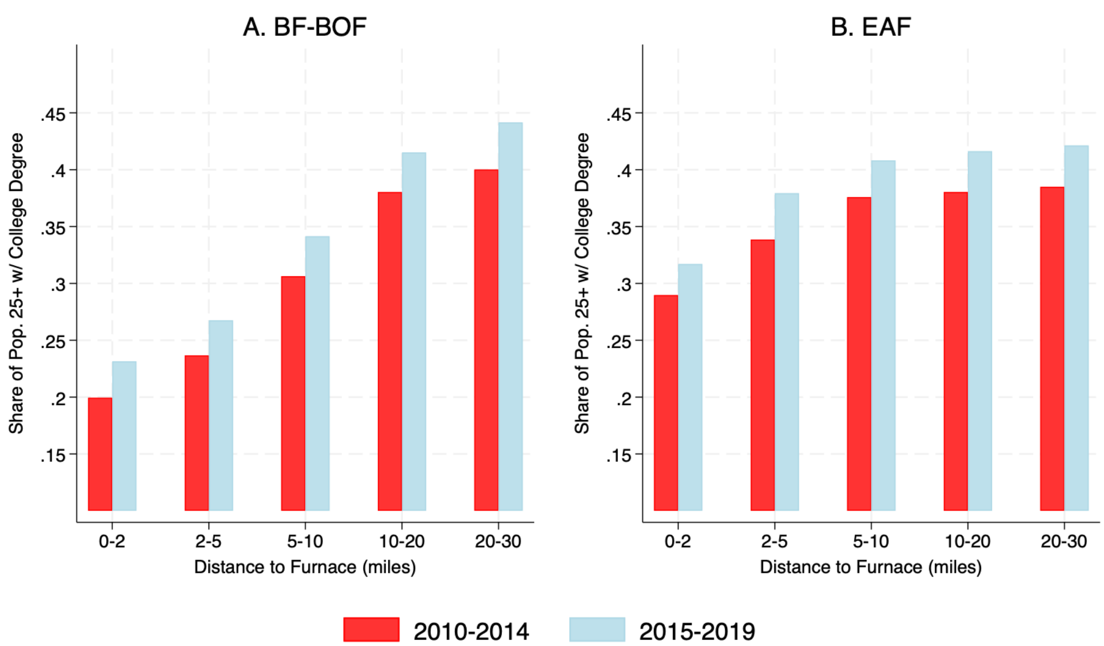
Notes: This figure displays the estimated PM2.5 differences of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure 7: Median Income by Distance to Steel Plants



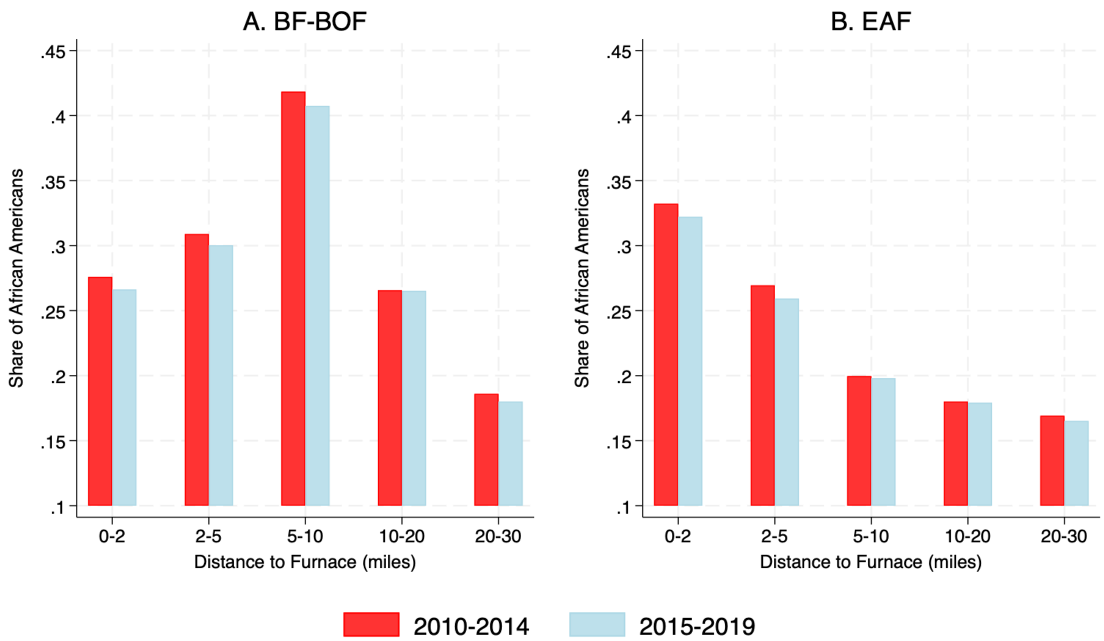
Notes: This figure displays average median income across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure 8: Average Share With College Degrees by Distance to Steel Plants



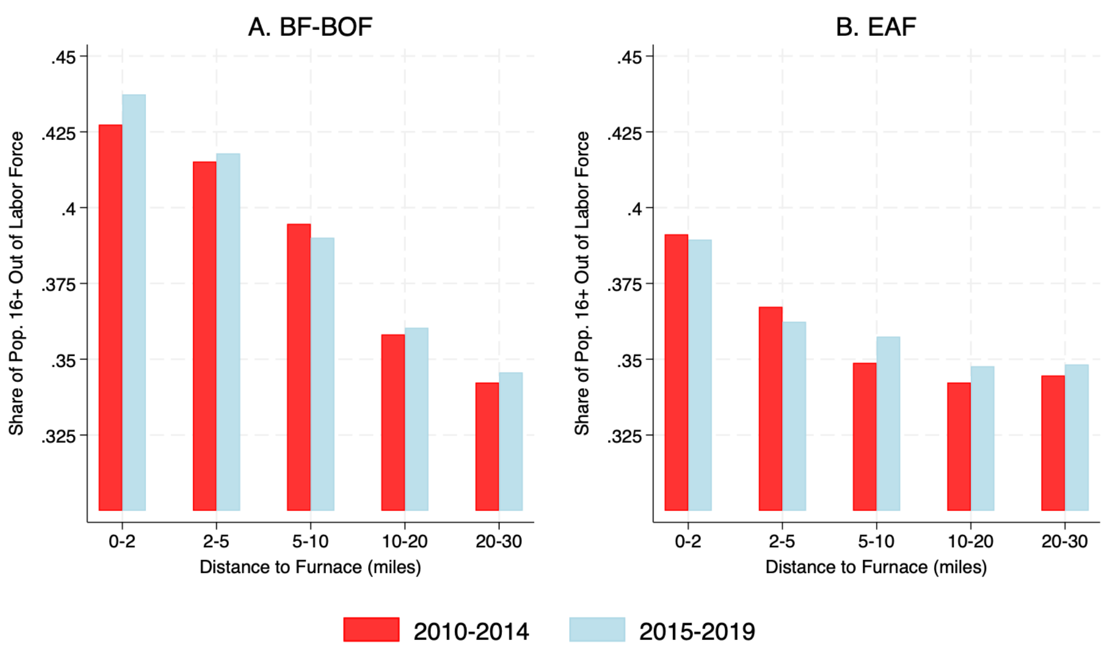
Notes: This figure displays average share of people with college degrees across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure 9: Average Share of African Americans by Distance to Steel Plants



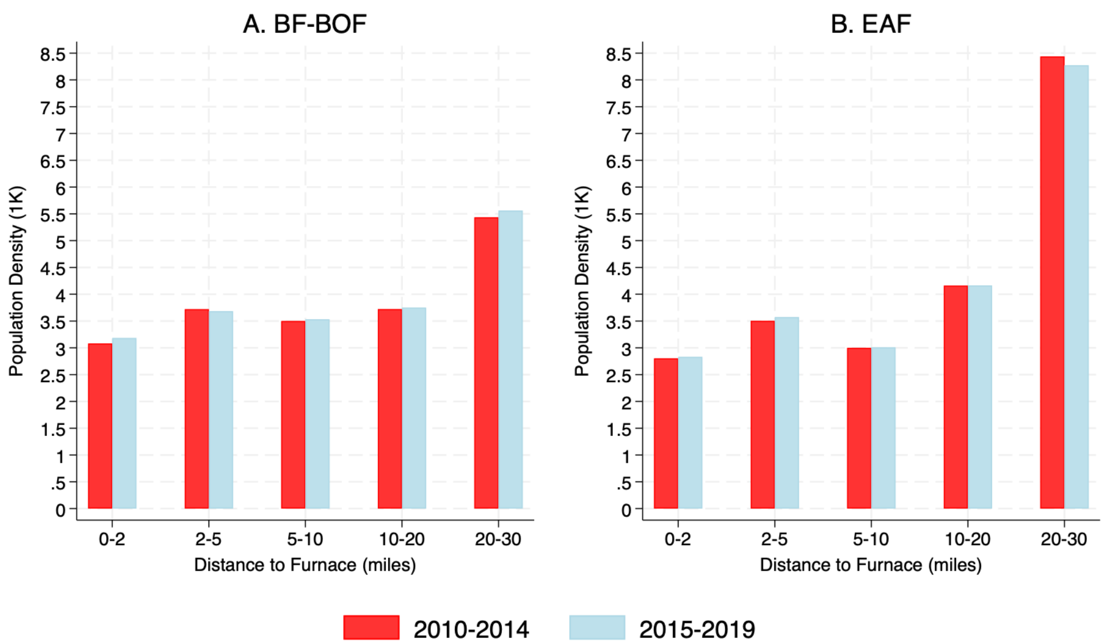
Notes: This figure displays average share of African Americans across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure 10: Average Share of Population Out of Labor Force by Distance to Steel Plants



Notes: This figure displays average share of population out of labor force across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure 11: Population Density by Distance to Steel Plants

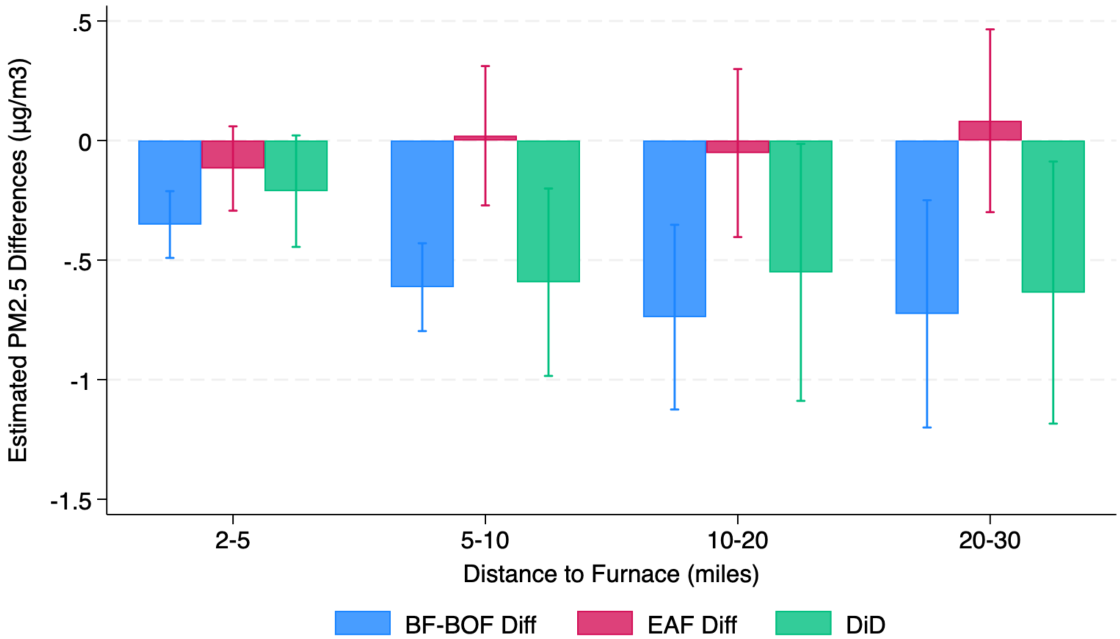


Notes: This figure displays population density across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Online Appendix (Not For Publication)

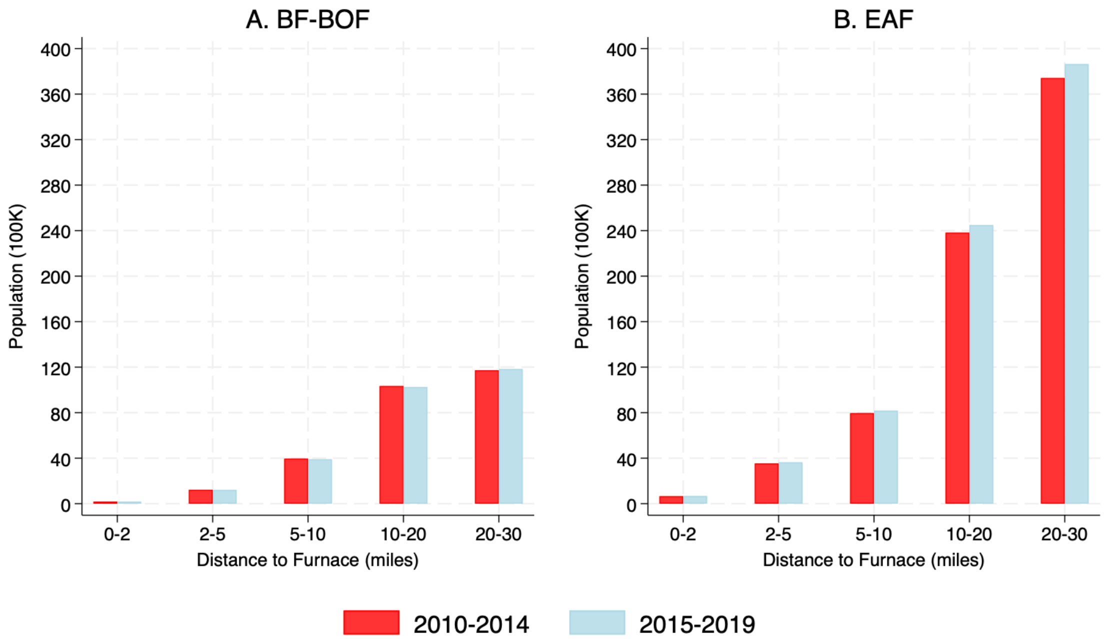
A Appendix Figures and Tables

Figure A.1: Estimated PM2.5 Differences Relative to 0-2 Miles from Steel Plants With Additional Controls



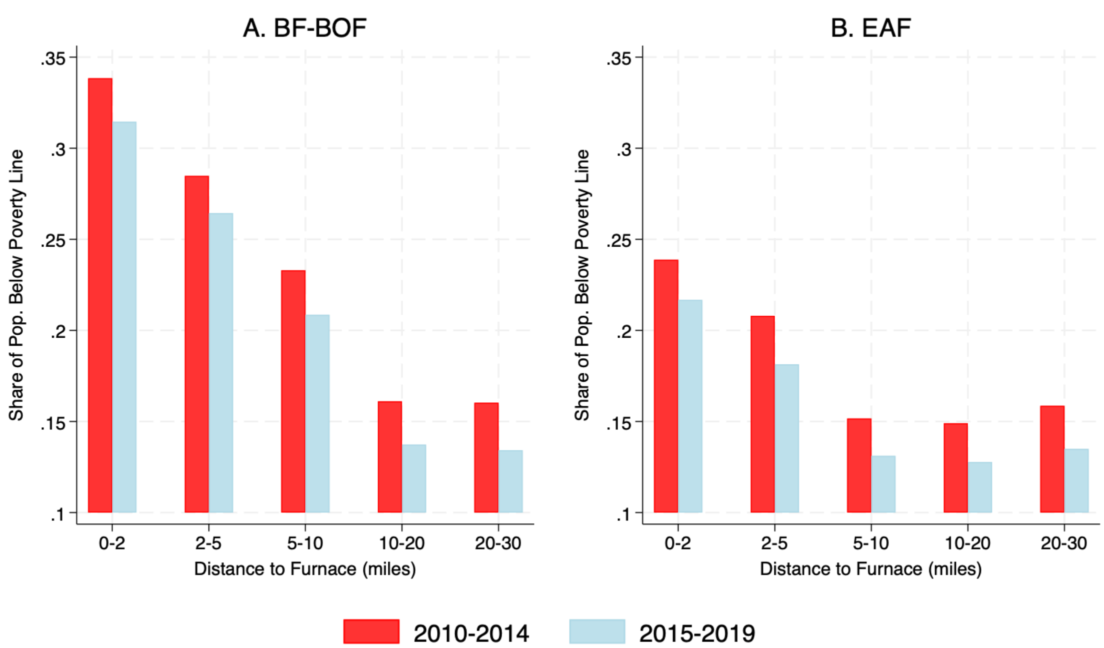
Notes: This figure displays the estimated PM2.5 differences of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019) plus controls for median income, the share of the population 25+ years with college degree, and share of African Americans. The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.2: Population (100K) by Distance to Steel Plants



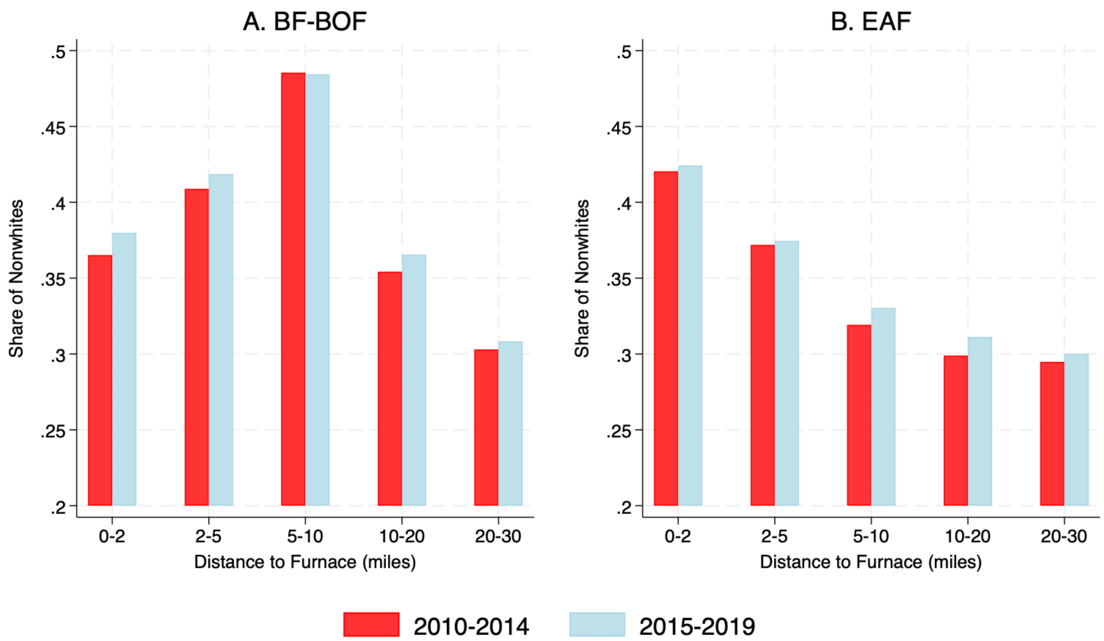
Notes: This figure displays population (1000K) across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure A.3: Average Share Below Poverty Line by Distance to Steel Plants



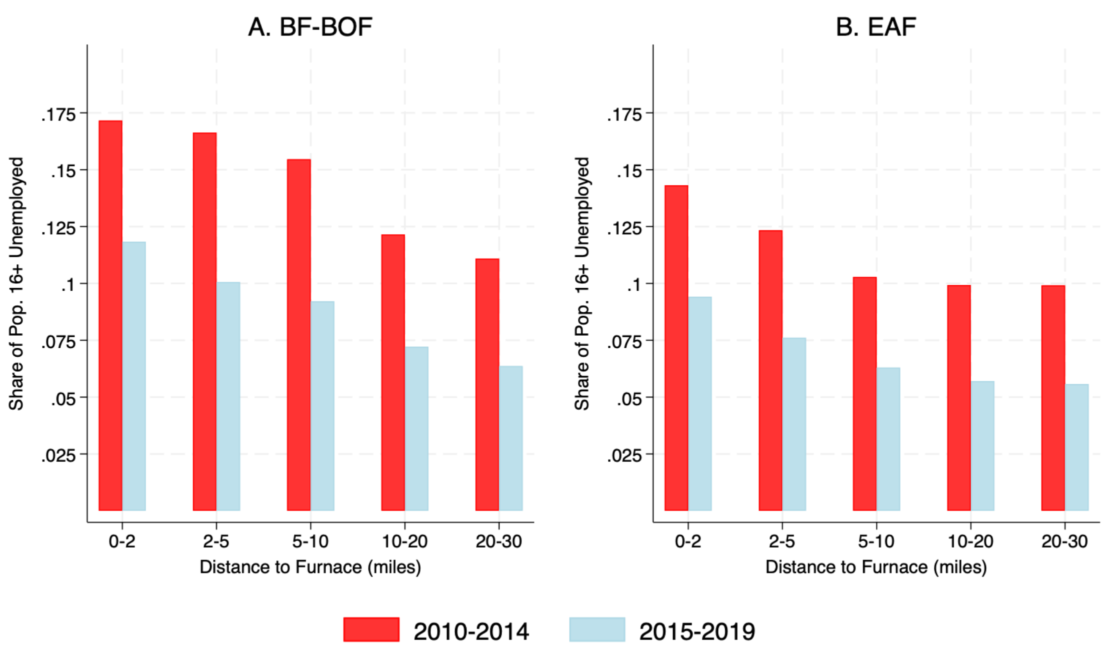
Notes: This figure displays average share of population below poverty line across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure A.4: Average Share of Nonwhites by Distance to Steel Plants



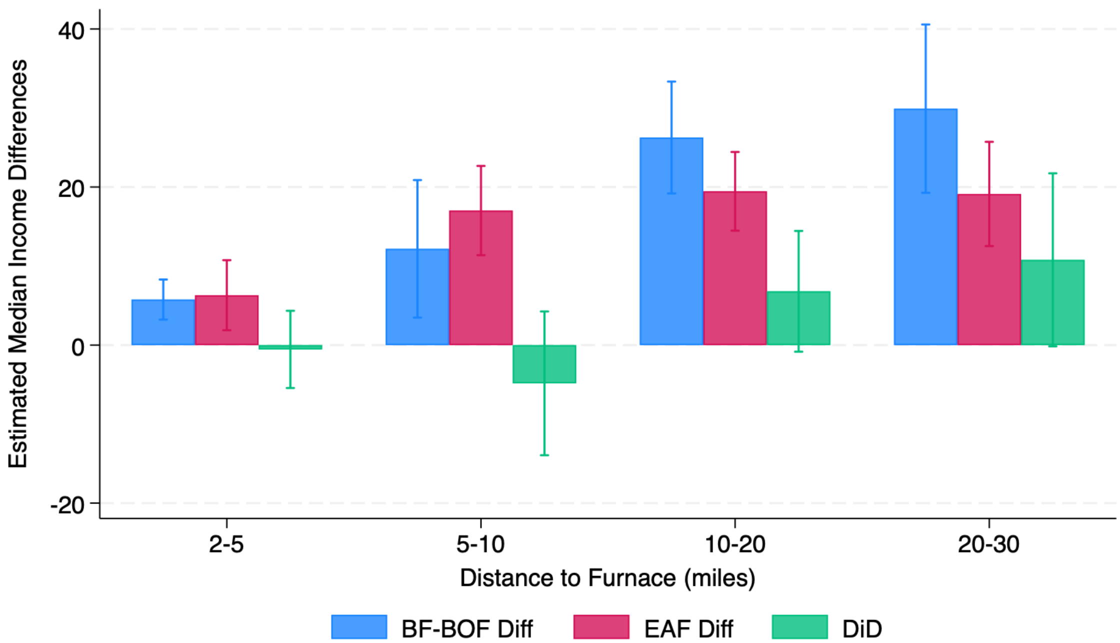
Notes: This figure displays average share of nonwhites across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure A.5: Average Share of Unemployed by Distance to Steel Plants



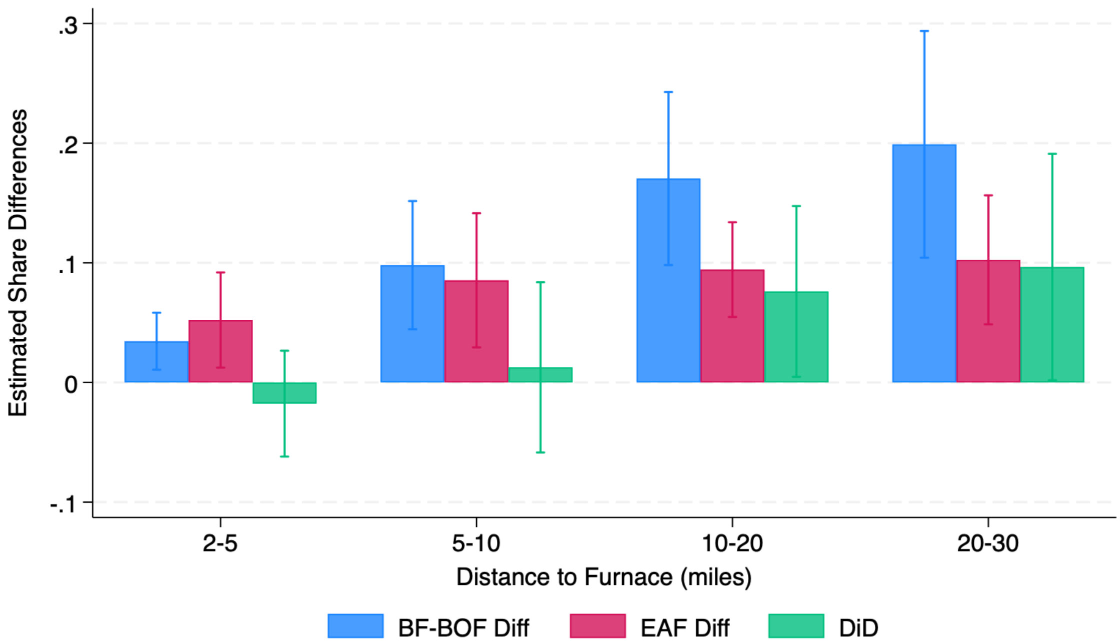
Notes: This figure displays average share of unemployed across census tracts by distance to furnaces producing steel. BF-BOF stands for blast furnace-basic oxygen furnace, and EAF for electric arc furnace. The census tract information comes from the American Community Survey (ACS) 5-Year Data.

Figure A.6: Estimated Median Income Differences Relative to 0-2 Miles from Steel Plants



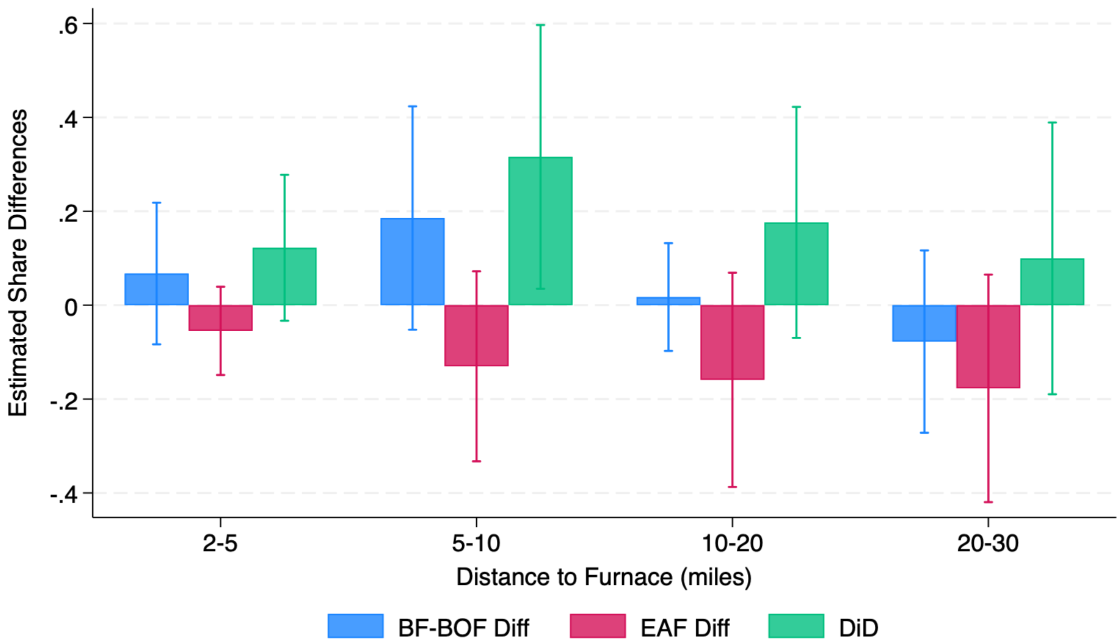
Notes: This figure displays the estimated median income differences of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.7: Estimated Differences in Share of Population 25+ With College Degrees Relative to 0-2 Miles from Steel Plants



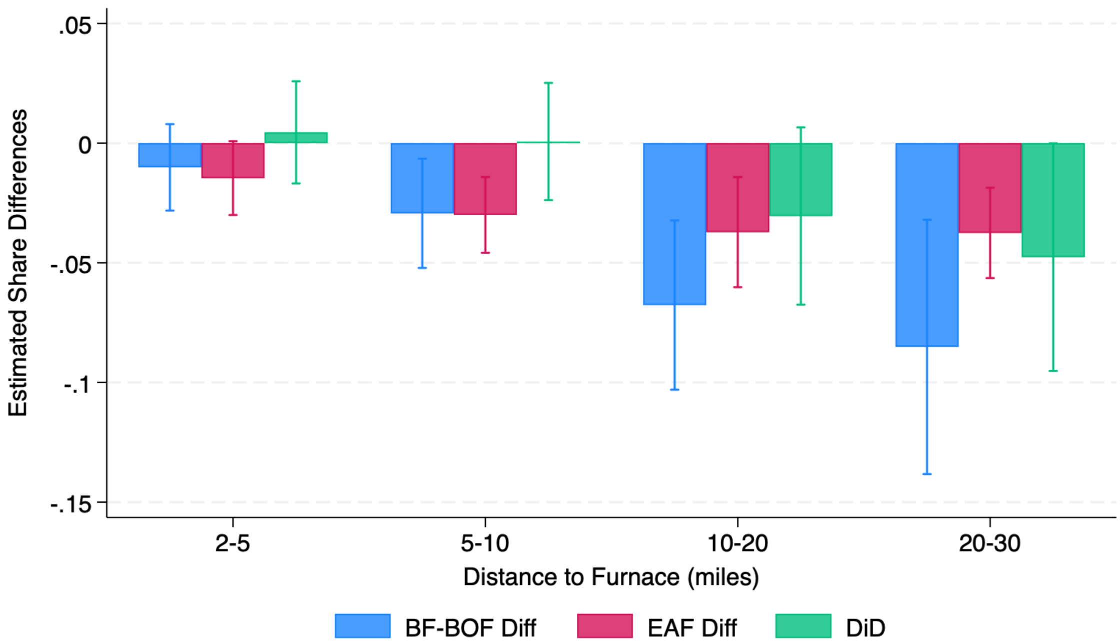
Notes: This figure displays the estimated differences in share of population 25+ with college degrees of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.8: Estimated Differences in Share of African Americans Relative to 0-2 Miles from Steel Plants



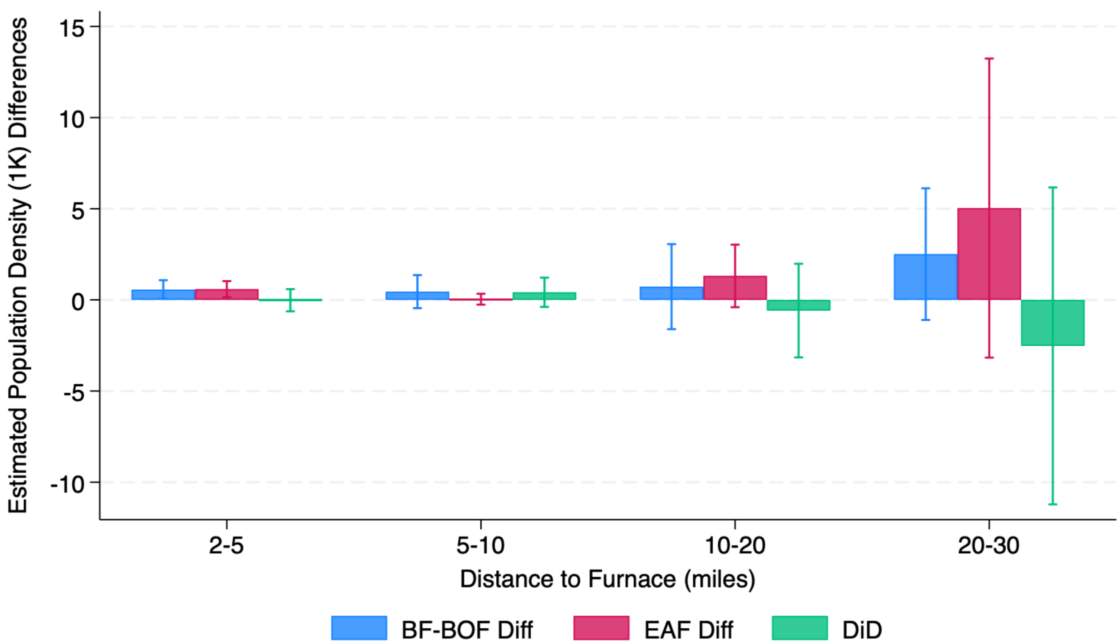
Notes: This figure displays the estimated differences in share of African Americans of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.9: Estimated Differences in Share of Population Out of Labor Force Relative to 0-2 Miles from Steel Plants



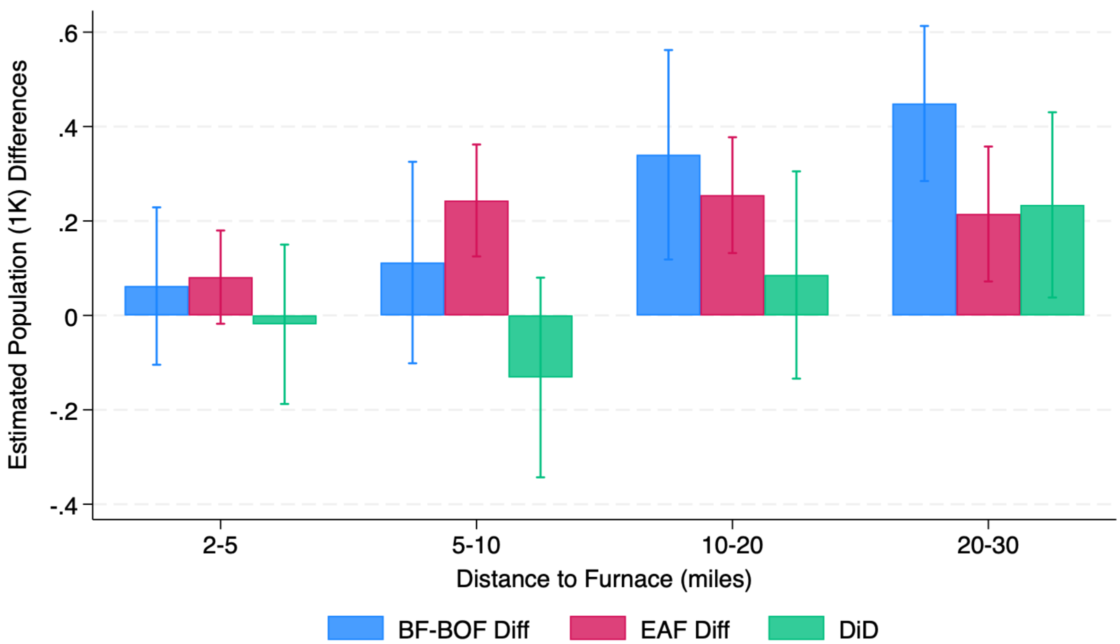
Notes: This figure displays the estimated differences in share of population out of labor force of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.10: Estimated Differences in Population Density Relative to 0-2 Miles from Steel Plants



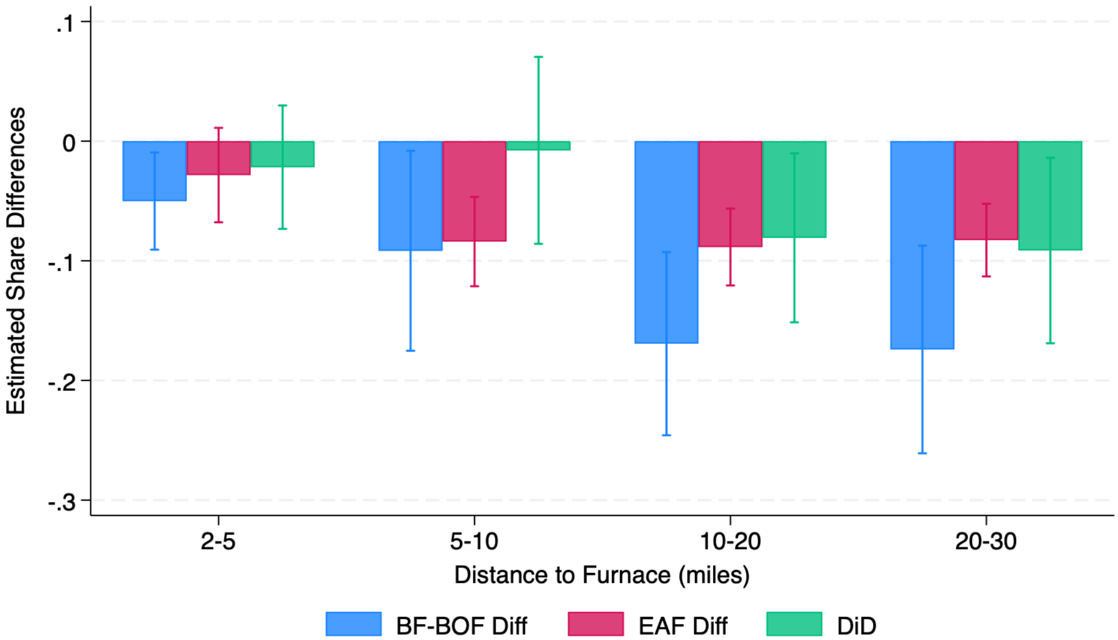
Notes: This figure displays the estimated differences in population density of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.11: Estimated Differences in Population Relative to 0-2 Miles from Steel Plants



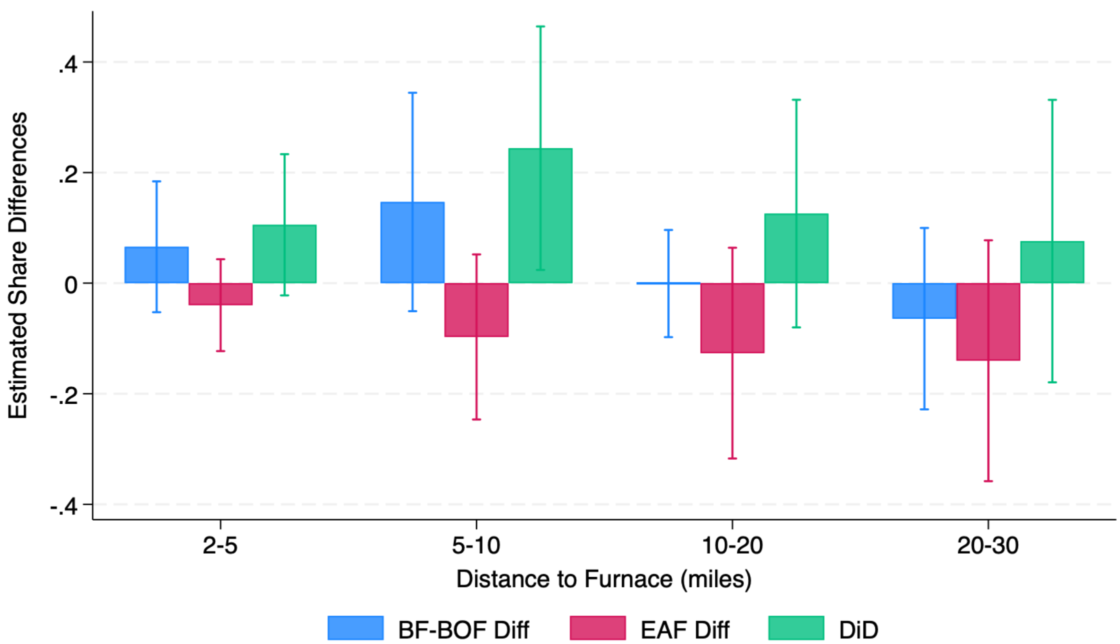
Notes: This figure displays the estimated differences in population of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.12: Estimated Differences in Share of Population Below Poverty Line Relative to 0-2 Miles from Steel Plants



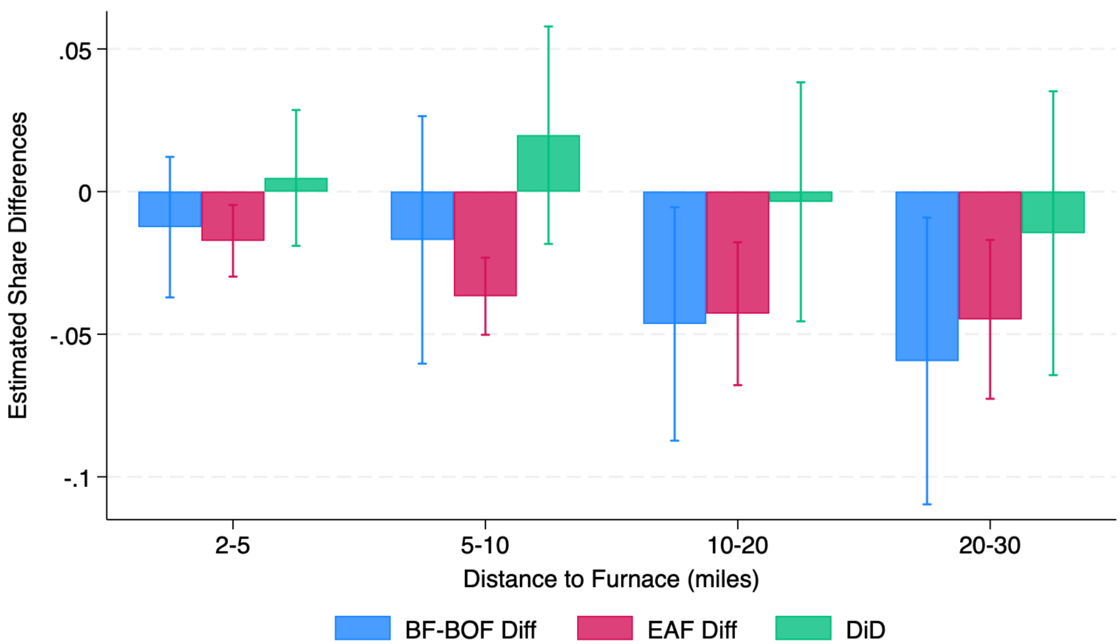
Notes: This figure displays the estimated differences in share of population below poverty Line of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.13: Estimated Differences in Share of Nonwhites Relative to 0-2 Miles from Steel Plants



Notes: This figure displays the estimated differences in share of nonwhites of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Figure A.14: Estimated Differences in Share of Unemployed Relative to 0-2 Miles from Steel Plants



Notes: This figure displays the estimated differences in share of unemployed of each distance bin relative to 0-2 miles from furnace. These differences are estimated in a single regression model that controls for time period fixed effects (2010-2014 vs. 2015-2019). The blue bars represent the differences for BF-BOFs and the cranberry bars for EAFs. The green bars take the difference in differences (DiD) – BF-BOF difference minus EAF difference – for each distance bin. The vertical lines represent 95% confidence intervals based on robust standard errors clustered at the furnace level.

Table A.1: Table of inputs used in the cost analysis.

Inputs	**Quantity**	**Unit**	**Source**
Annual Capacity	2.2	mTons/year	
Annual Production	2	mTons/year	
Mean Steel Worker Salary	66,173	annual wage ($)	Bureau of Labor Statistics
Mean Steel Worker Salary	31.82	hourly wage ($)	Bureau of Labor Statistics
% Fe in DRI	89%	%	
% H_2 in DRI feed	50%	%	
CO_2 capture rate	90%	%	
n-gas	18.22	kmoles/ton Fe°	Pistorius, 2022
DRI Energy Requirement	10	MMBtu	Midrex Flex
Prices	Price ($ per unit)	Unit	Source
Coke	204	ton	Germeshuizen & Blom
Coal	105	ton	Germeshuizen & Blom
Lump Ore	102	ton	Germeshuizen & Blom
Sintered Ore	163.2	ton	
Pelletized Iron Ore	163.2	ton	Germeshuizen & Blom
Scrap Steel	258.4	ton	Germeshuizen & Blom
Limestone / Fluxes	54.4	ton	Germeshuizen & Blom
Oxygen	0.15	NM$\hat{3}$	Intratec
Natural Gas	6.45	MMBtu	Henry Hub 2022 Price (EIA)
Natural Gas	0.02	kWh	unit conversion
Natural Gas	348.3	ton	unit conversion
Electricity	19.54	MMBtu	unit conversion
Electricity	0.067	kWh	2021 Industrial Average (EIA)
H_2 from renewables	4.68	kg	Pistorius, 2022
Electrodes	3.67	kg	FRC Global
Capital costs	Price ($ per unit)	Unit	
Direct reduced iron furnace	$499	ton capacity	Recently constructed U.S. DRI plants
Electric arc furnace	$309	ton capacity	van Ruijin et al. (2016)
Carbon capture and sequestration	$400	ton capacity	
CO_2 Emissions	Emissions (kg CO_2 per unit)	Unit	Source
Scope 1			
Coke	3,257.00	ton	WSA CO_2 Collection
Iron Ore	37	ton	WSA CO_2 Collection
Limestone / Fluxes	440	ton	WSA CO_2 Collection
Natural Gas	52.91	MMBtu	EIA
Natural Gas	0.18	kWh	unit conversion
Natural Gas	2,593.00	ton	WSA CO_2 Collection
Coal	2,953.00	ton	WSA CO2 Collection
EAF/BOF Electrodes	3.66	ton	WSA CO_2 Collection
Oxygen	4	NM$\hat{3}$	Pistorius, 2022
Scope 2			
Electricity	0.39	kWh	US Average 2021, EIA
Electricity	114.27	MMBtu	unit conversion
Scope 3			
Coke	224	ton	WSA CO_2 Collection
Pelletized Iron Ore	137	ton	WSA CO_2 Collection
Sinter	262	ton	WSA CO_2 Collection
Scrap	0	ton	WSA CO_2 Collection
EAF/BOF Electrodes	650	ton	EIA
H2 Green	0	kg	assumed (by definition)
Oxygen	0.34	NM$\hat{3}$	WSA CO_2 Collection