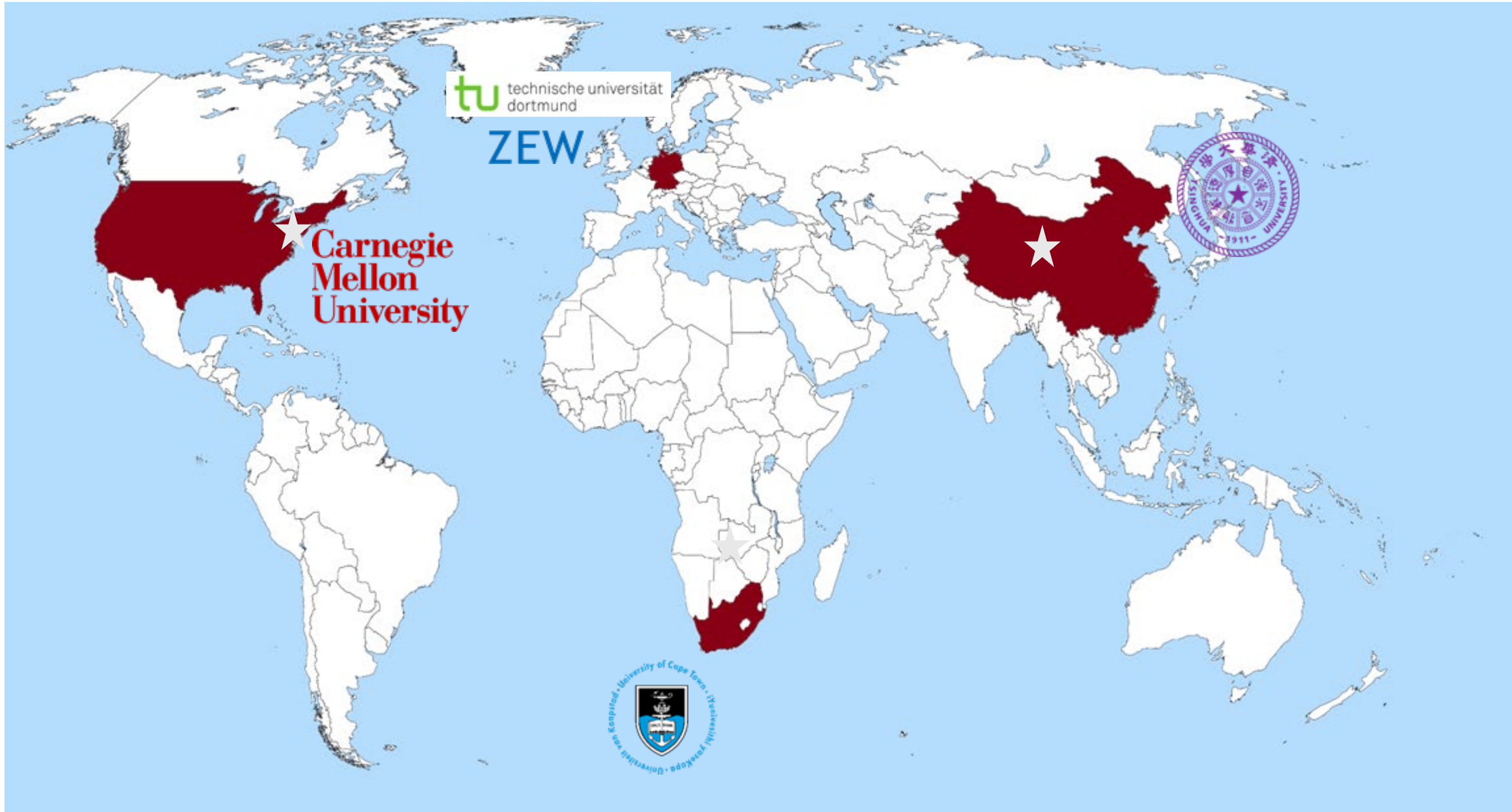
The Costs and Distributional Impacts of Decarbonizing the Iron and Steel Industry in the United States

Paulina Jaramillo **Valerie J. Karplus**
P. Chris Pistorius **Edson Severnini**
Carnegie Mellon University

International Collaboration: Industrial Decarbonization Analysis, Benchmarking, and Action (INDABA) Partnership



Supported by the U.S. National Science Foundation

Institute of Energy,
Environment, and Economy,
Tsinghua University
Beijing, China

ie[3], TU-Dortmund,
Dortmund, Germany

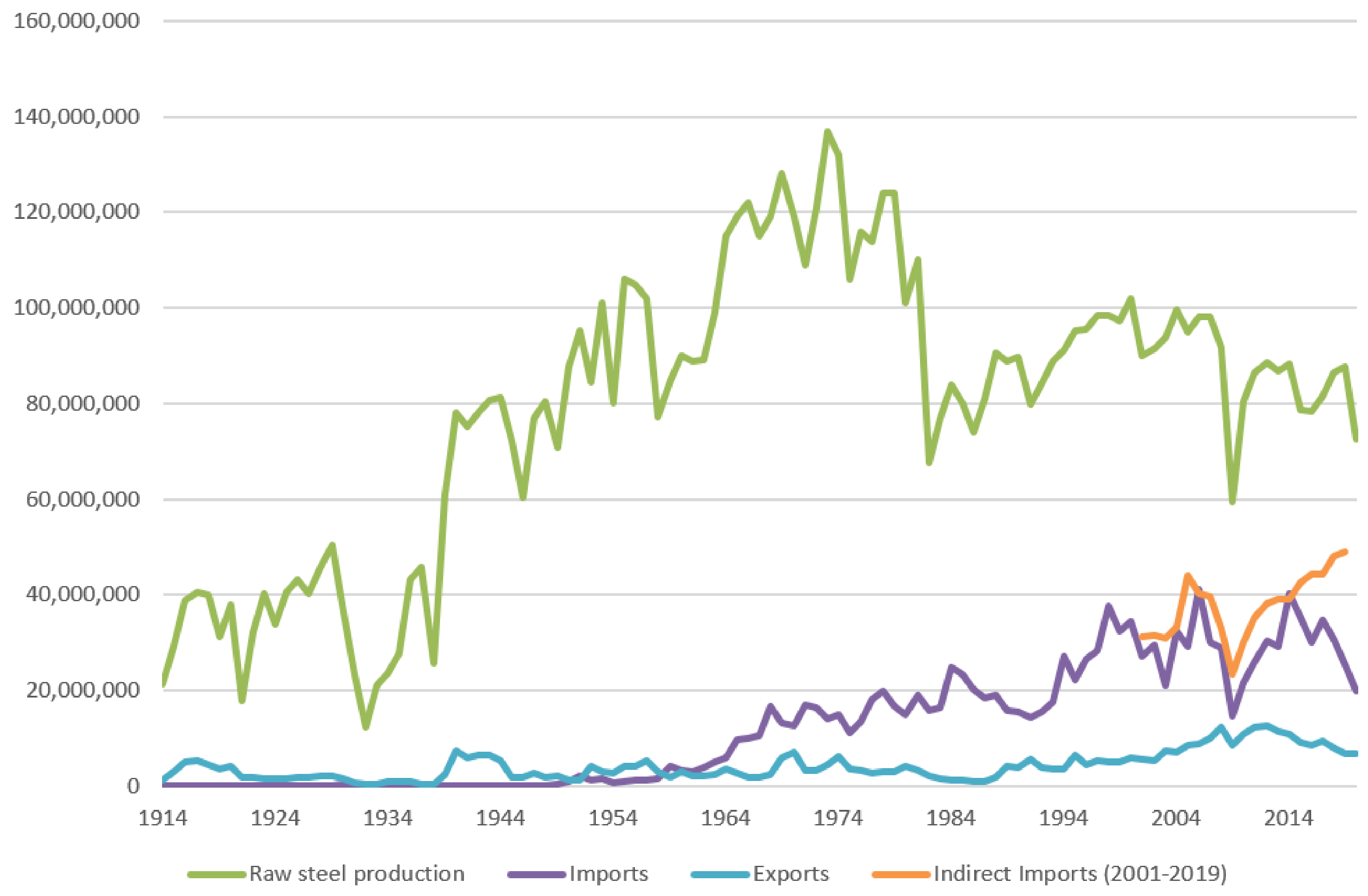
Climate and Environmental
Economics, ZEW Mannheim
Mannheim, Germany

Energy Systems Research Group,
University of Cape Town
Cape Town, South Africa

Carnegie Mellon University
Pittsburgh, United States

CMU Investigator Team:
Paulina Jaramillo and Valerie Karplus, Department of Engineering and Public Policy
Chris Pistorius, Department of Materials Science and Engineering
Edson Severnini, Heinz College of Public Policy and Information Systems

U.S. iron and steel production, imports, exports, and emissions in a global context

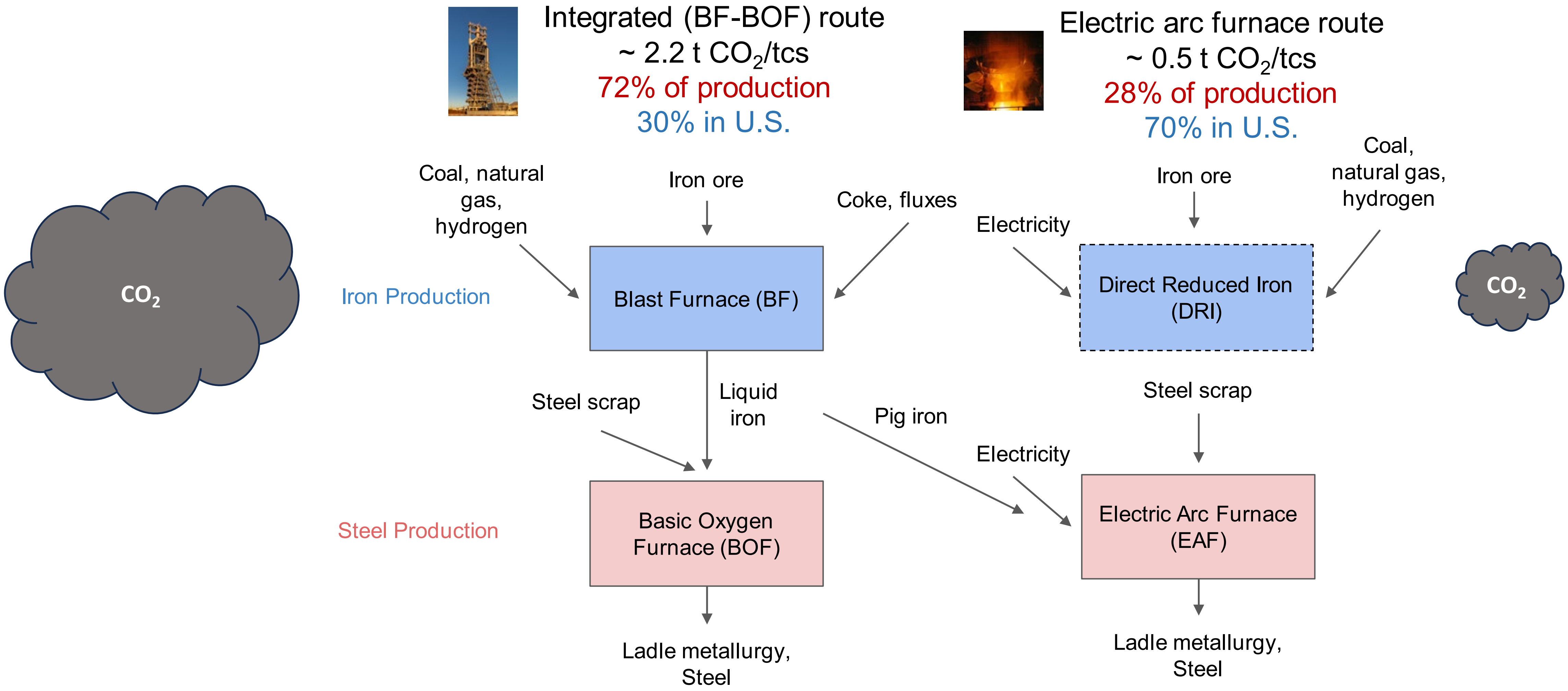


Source: World Steel Association (2022, 2023)

Country	Production in 2022 (thousand tons)	Share
China	1,017,959	54%
India	125,377	7%
Japan	89,227	5%
United States	**80,535**	**4%**
Russia	71,469	4%
South Korea	65,846	3%
Germany	36,849	2%
Türkiye	35,134	2%
Brazil	34,090	2%
Iran	30,593	2%
Other	298,658	16%

7% of global energy related CO_2 emissions
2% of U.S. GHG emissions

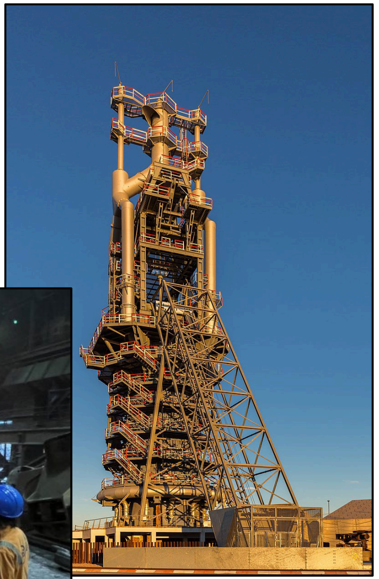
Iron and steel production: Two major routes



Source: World Steel Association (2021).

Iron and steel processes, in living color

Integrated Route



Blast furnace, Valencia, Spain

Basic oxygen furnace, Pittsburgh, PA, USA

Mon Valley Works, Pittsburgh, PA, USA

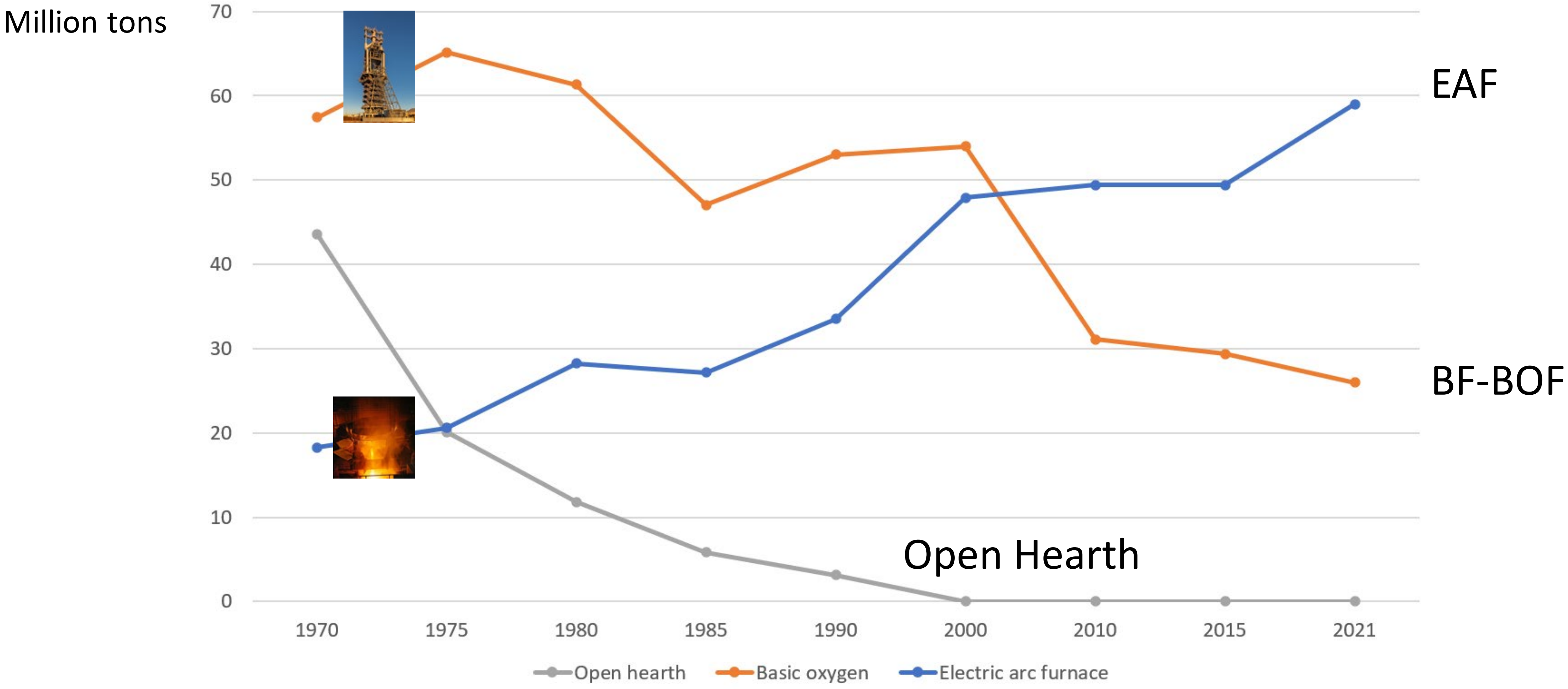
Electric Arc Furnace Route

Direct reduced iron, Corpus Christi, TX, USA

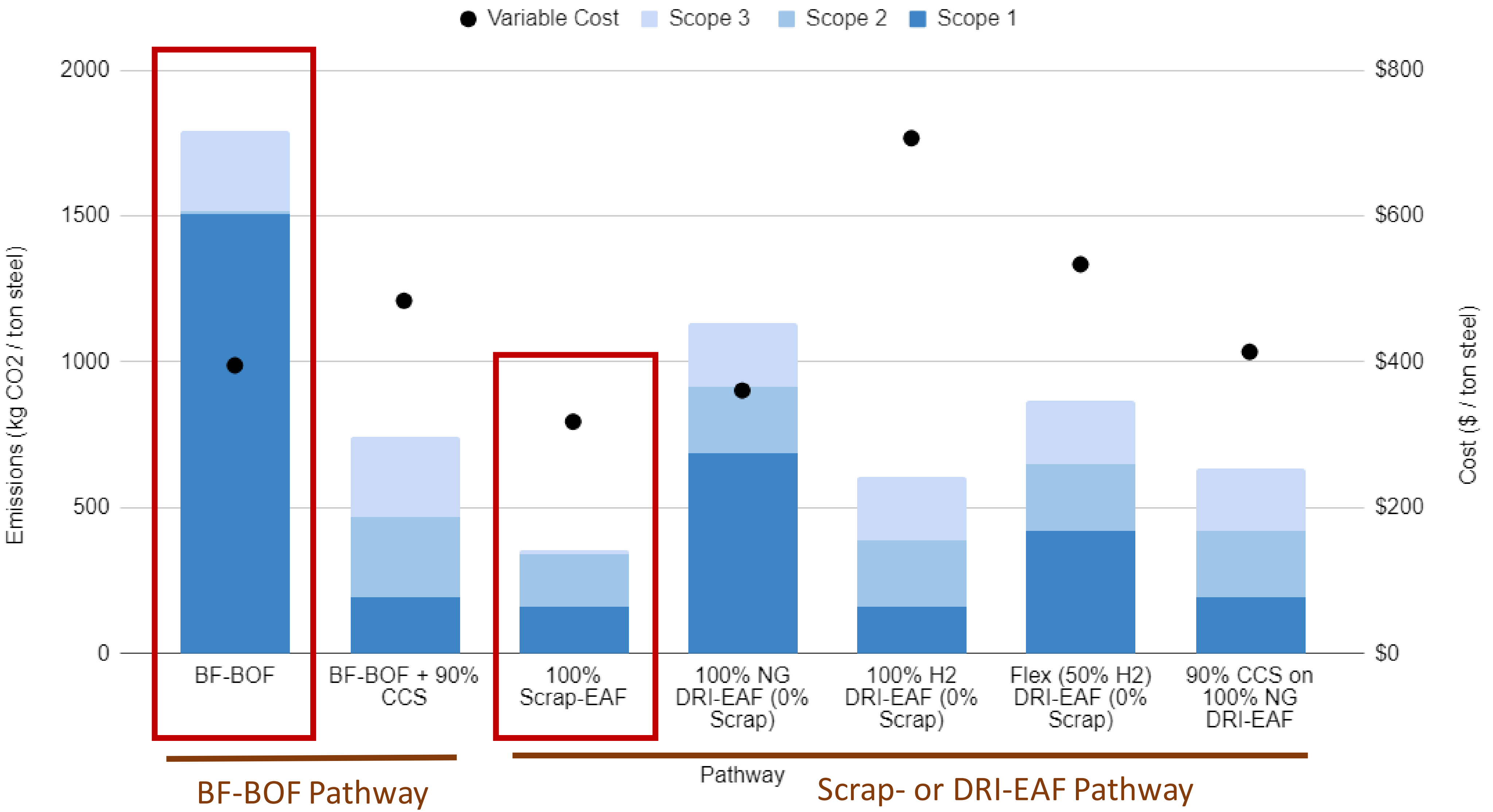
Electric arc furnace, Osceola, AR, USA

Big River Steel, Osceola, AR, USA

The steel production supplied by the EAF route has increased since the early 1990s



We compared the cost of pathways for decarbonizing both BF-BOF and EAF production



Key assumptions used to estimate cost and CO_2 emissions

- Emissions scopes: Scope 1 (direct from production), Scope 2 (mainly electricity), Scope 3 (mainly upstream ore extraction and processing)
- BF-BOF represents Best Available Technology in 2023.
- Electricity CO_2 based on US 2021 grid average, except for H_2 / CCS, which are assumed to only be deployed if they can be operated on zero C electricity.
- The 100% NG DRI, 50% H_2 and 100% H_2 DRI assume the input gas stream is partially used for pre-heating.
- Prices are fixed: cost of H_2 is $4.68/kg (Pistorius, 2022), electricity price of 4 cents/kWh, + 3 cents/kWh for zero CO_2 electricity.

However, direct comparisons may be misleading because…

- Today, BF-BOF and EAF steel are not perfect substitutes – used to make different grades (exposed automotive vs. rebar)
- “Decarbonizing” the EAF route may require considering a higher-emissions counterfactual – increasing share of DRI in the EAF charge (ore-based metallics such as pig iron or DRI are more GHG-intensive than scrap, but necessary to make higher-grade products)
- Our 100% DRI-EAF estimates should be considered as benchmarks that can be used in weighted averages to assess emissions as a function of DRI share in an EAF charge

Our analysis considers two scenarios to evaluate cost of decarbonization

- **A "route-specific" (RS) scenario:** A scenario that maintains BF-BOF and EAF technology shares and deeply reduces CO_2 emissions at least cost (often favored by labor and BF-BOF producers).

- **A "substitution-in-place" (SP) scenario:** A scenario that replaces BF-BOF steelmaking with DRI-EAF steelmaking, with higher ore-based metallics than today's scrap-EAF steelmaking (often favored by EAF producers, climate advocates).

Our scenario analysis holds production fixed, uses literature values for inputs

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.

Costs of deeply reducing CO_2 emissions from iron and steel production in the U.S. – "back of the envelope"

Estimate	RS Scenario	SP Scenario
BF-BOF incremental capital cost	$16 billion	$0 billion
DRI incremental capital cost	$7.2 billion	$11.2 billion
EAF incremental capital cost	$0 billion	$12.4 billion
Total capital cost	$23.2 billion	**$22.6 billion**
BF-BOF incremental variable cost per year	$2.3 billion	$0 billion
EAF incremental variable cost per year	$2.5 billion	$3.5 billion
Total incremental variable cost per year	$5.8 billion	**$3.5 billion**
EAF zero CO_2 electricity cost per year	**$0.8 billion**	$1.2 billion
Average CO_2 emissions per tcs	0.289 t CO2 per tcs	0.213 t CO2 per tcs
% reduction in CO_2 emissions per tcs	71%	80%

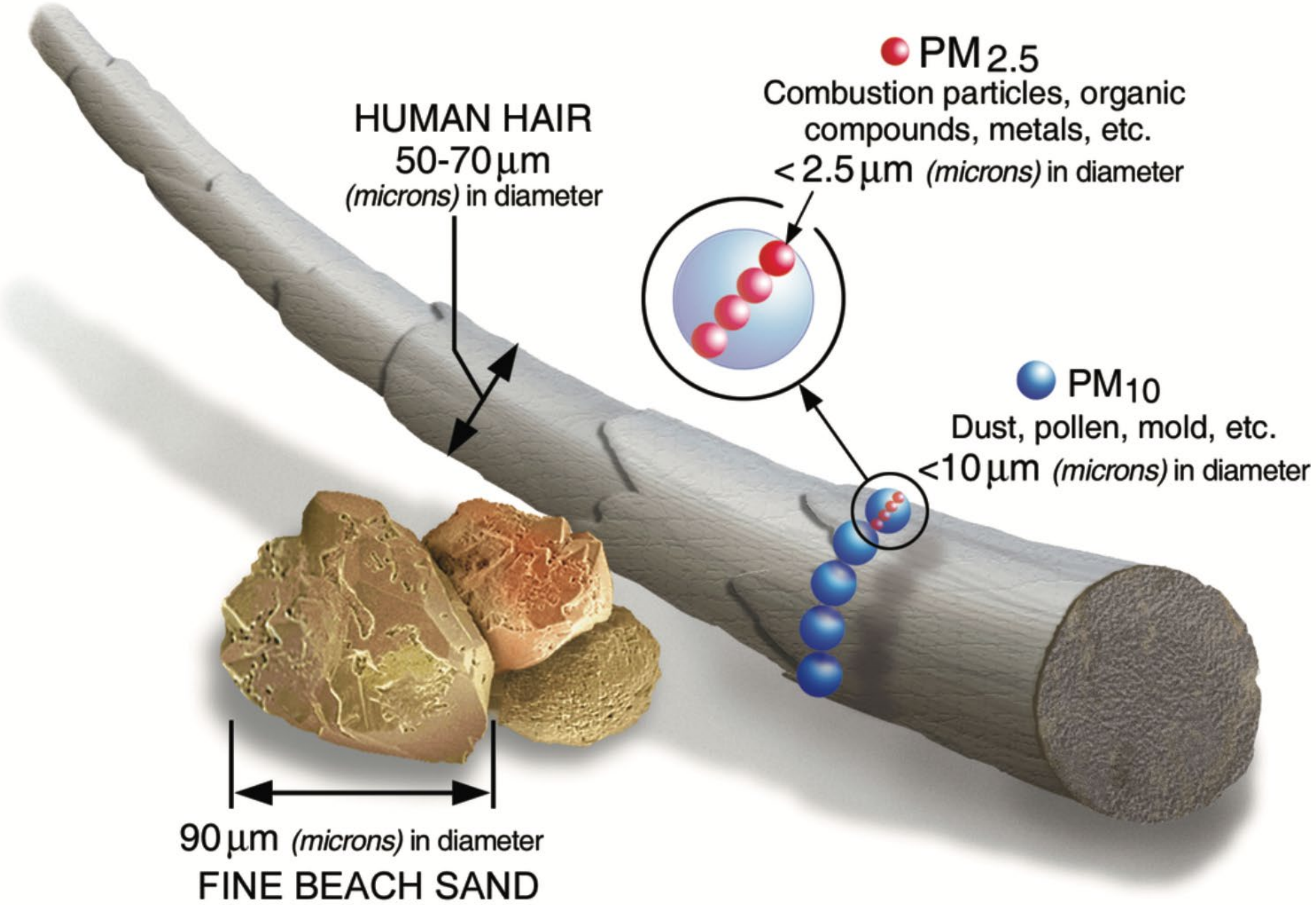
Takeaways so far…

- Overall, if DRI-EAF can meet product requirements, it may represent the most cost effective approach to reducing CO_2 emissions.
- Models that do not recognize the potential to accomplish reductions with more limited DRI may reach the opposite conclusion.
- Important to compare options on both aggregate cost as well as local costs/benefits:
  - Jobs (-)
  - Public revenue generation (?)
  - Air quality (+)

Motivation

- Environmental Justice (EJ) concerns: siting of polluting plants
  - exposure to fine particulate matter of diameters <2.5 μm (PM2.5)
  - PM2.5 identified as the 5th-highest risk factor for mortality globally
- Colmer et al. (Science, 2020): absolute disparities in exposure to PM2.5 have fallen, but relative disparities persist
  - the most polluted census tracts in 1981 remained the most polluted in 2016
  - the most exposed pop subgroups in 1981 remained the most exposed in 2016

Particulate Matter (PM2.5)



Motivation

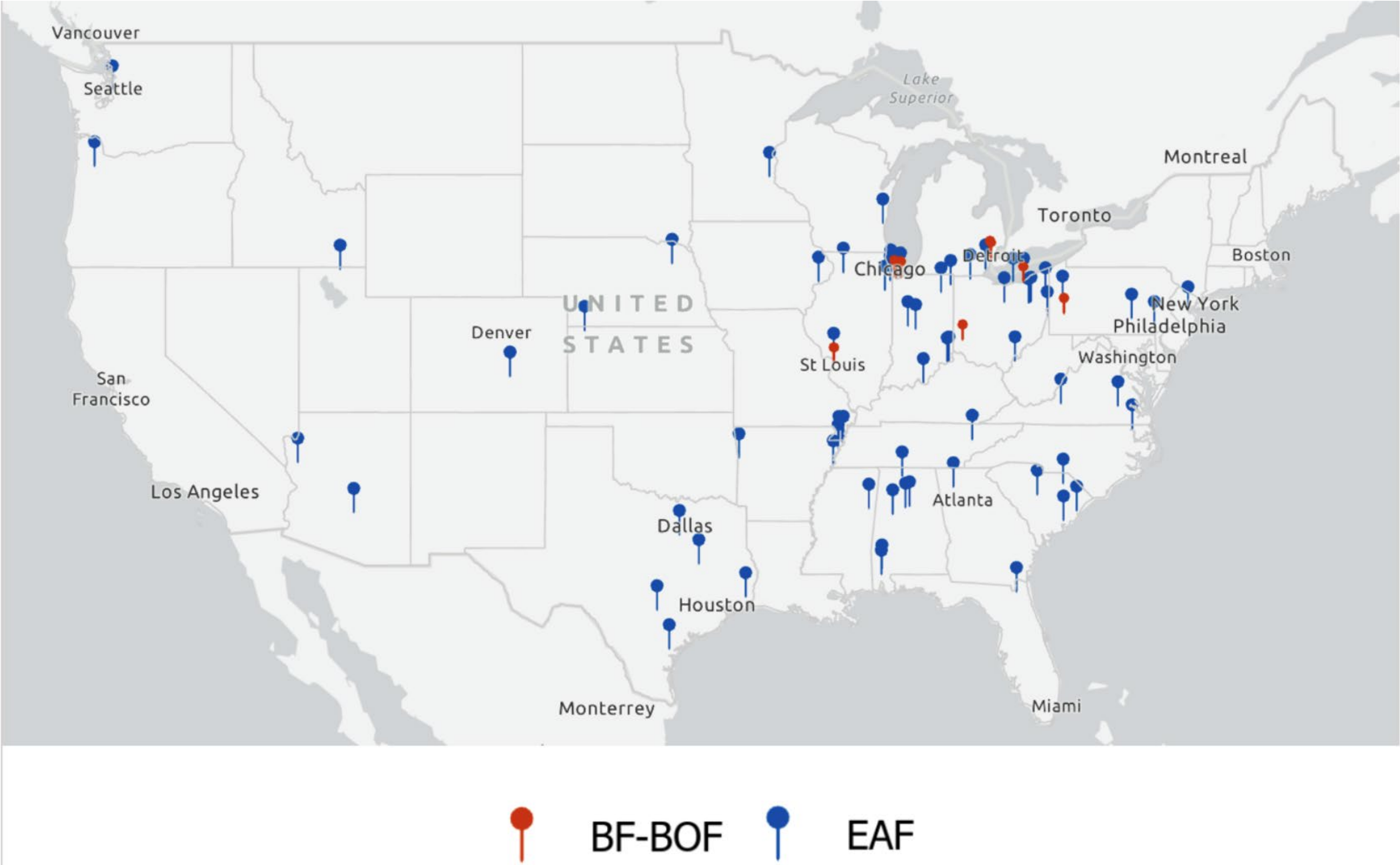
- Jbaily et al. (Nature, 2022): develop a data platform linking demographic to PM2.5 data across the U.S. from 2000-2016
  - zip codes with >avg Black, Asian and Hispanic/Latino populations more exposed to PM2.5 than zip codes with >avg white and Native American populations
  - zip codes with low-income populations exposed to higher PM2.5 levels than zip codes with high-income groups
  - disparities in exposure relative to safety standards set by US EPA and WHO have been **increasing** over time

- Decarbonization may generate co-benefit of PM2.5 reductions
  - Hernandez-Cortes and Meng (JPubE, 2023): California's carbon market (2013)
    - lowered GHG, PM2.5, PM10, and NOx emissions by 3-9% annually between 2012-2017
    - caused EJ gaps in PM2.5, PM10, and NOx from those facilities to narrow by 6-10% annually

This Work: Decarbonizing Steel and Iron Industry

U.S. Steel's Gary Works, on the Lake Michigan shore in Lake County, is the largest steel mill in North America. - Center for Land Use Interpretation

Map of Current U.S. BF-BOF and EAF Facilities



Data

- Location of U.S. furnaces used in iron and steel production
  - Global Energy Monitor (GEM)

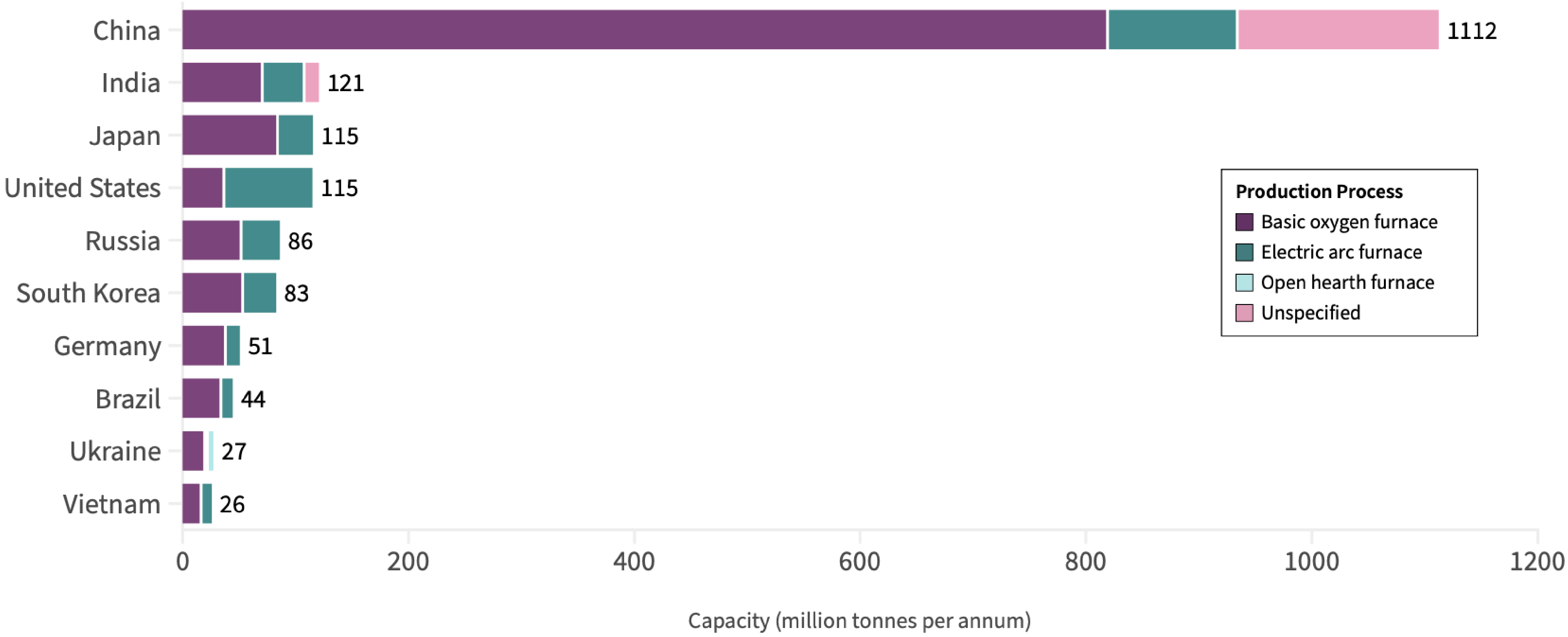
- Demographic and socioeconomic variables
  - median household income (2019 USD)
  - share of population below the poverty line
  - share of 25+ pop. w/ or w/o college degree
  - share of African Americans (or nonwhites)
  - share of 16+ pop. unemployed
  - share of 16+ pop. out of labor force
  - population (total and density)
- American Community Survey (ACS): 5-year averages
  - 2010-2014, and 2015-2019
  - data at census tract level: 600-3,000 people

- PM2.5: van Donkelaar et al. (EST, 2021)
  - annual mean in µg/m3 at 0.01° x 0.01° resolution (0.7 x 0.7 miles)
  - satellite + chem transport model + calibration (ground-based obs.)

Empirical Strategy

- World steel production capacity: **72% BF-BOF** & **28% EAF**
  - March 2022: planned capacity mirrored those proportions
  - March 2023: notable change in plans – 57% BF-BOF & 43% EAF
- U.S. current steel production capacity: **30% BF-BOF** & **70% EAF**
  - this reflects the setting the world is moving toward

Operating steelmaking capacity by technology type



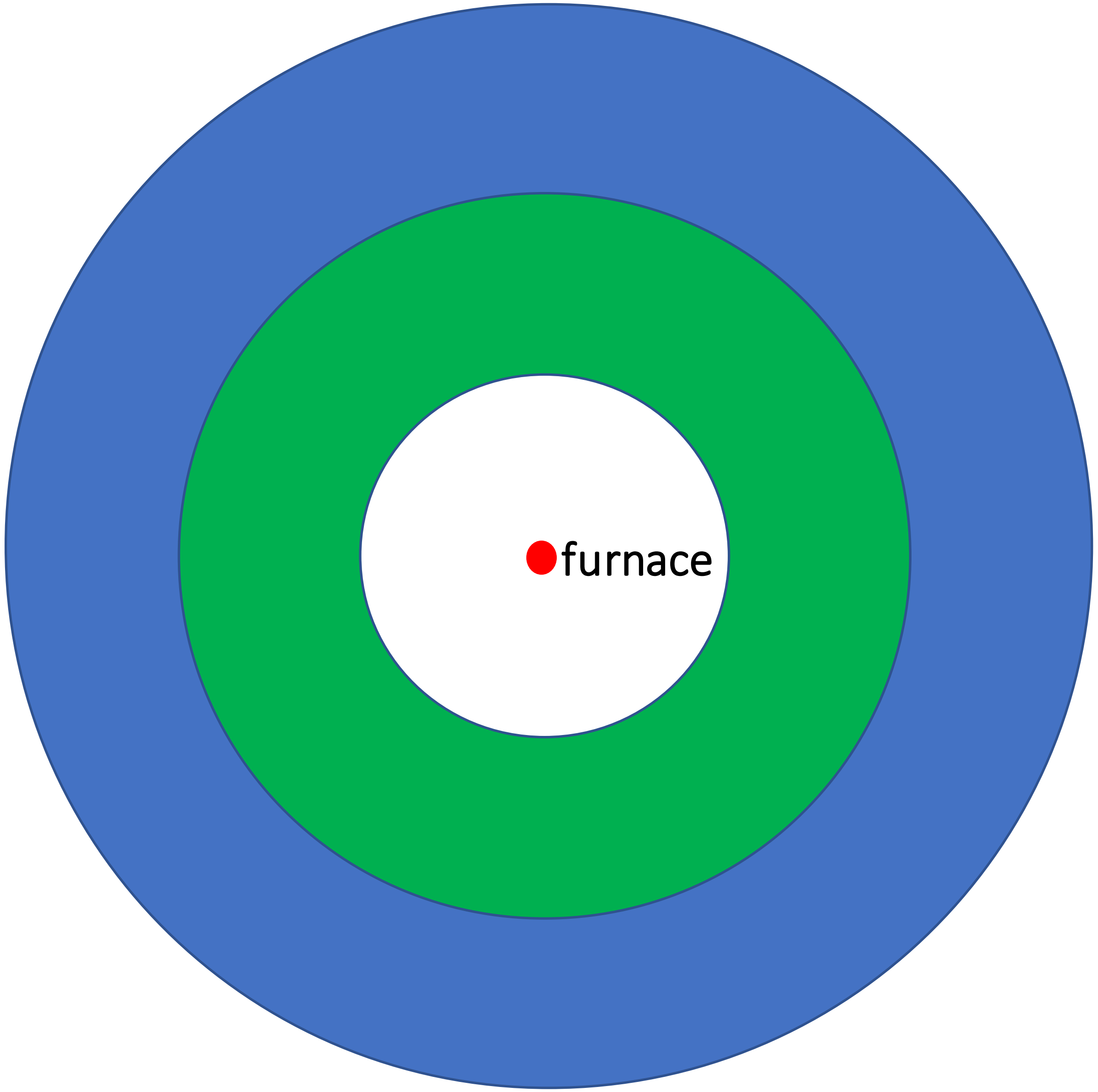
Source: Global Steel Plant Tracker, Global Energy Monitor, March 2023.

Empirical Strategy

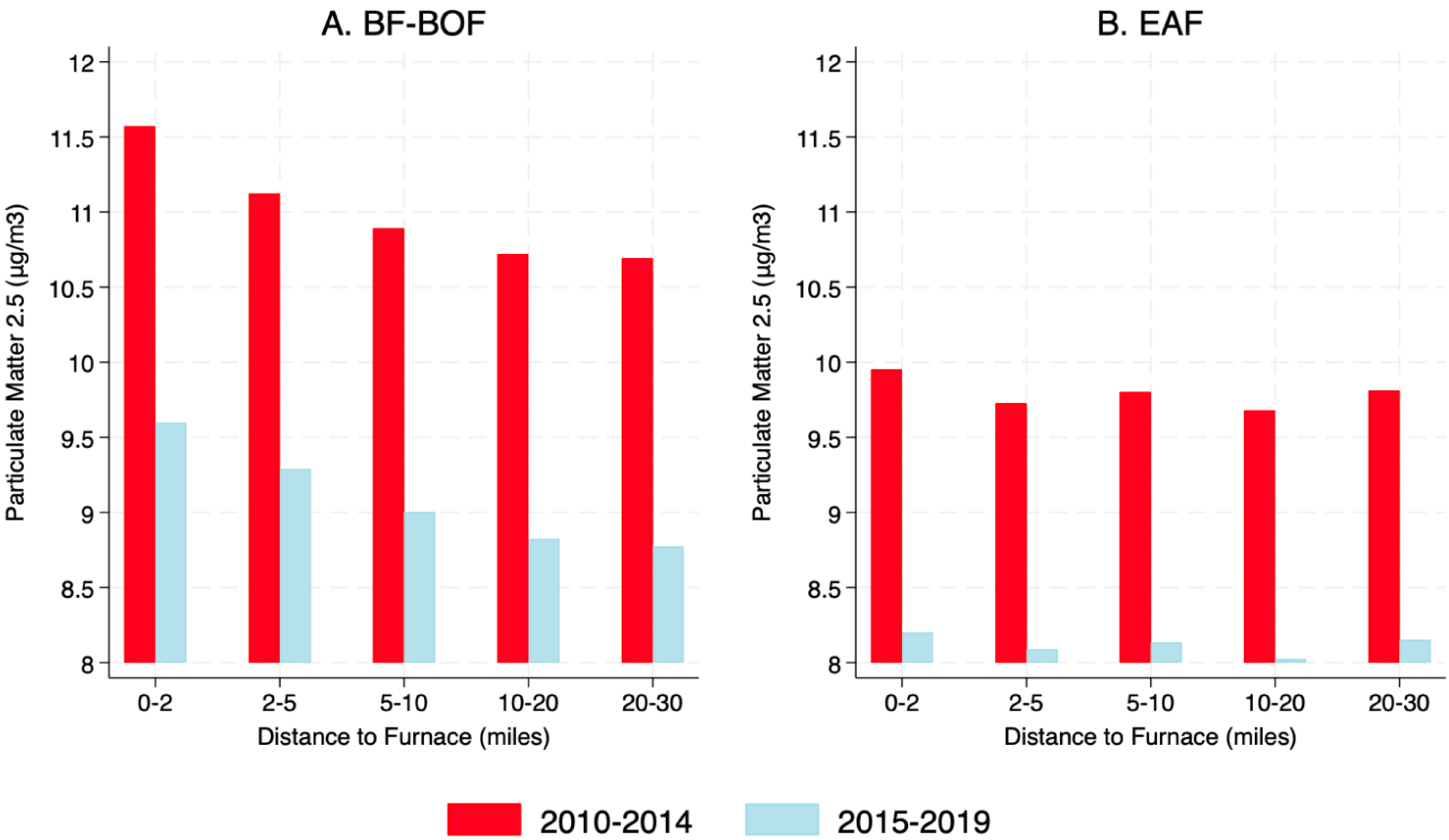
- Descriptive analysis
  - average outcomes across varying distances from steel plants stratified by
  - steelmaking technologies (BF-BOF vs. EAF) & time (2010-2014 vs. 2015-2019)
  - *distance bins*: 0-2 miles, 2-5 miles, 5-10 miles, 10-20 miles, and 20-30 miles

- Difference in differences analysis
  - Δ outcome within BF-BOF & EAF areas relative to 0-2 miles from plants
  - DiD: BF-BOF difference *minus* EAF difference – for each distance bin

Distance Bins

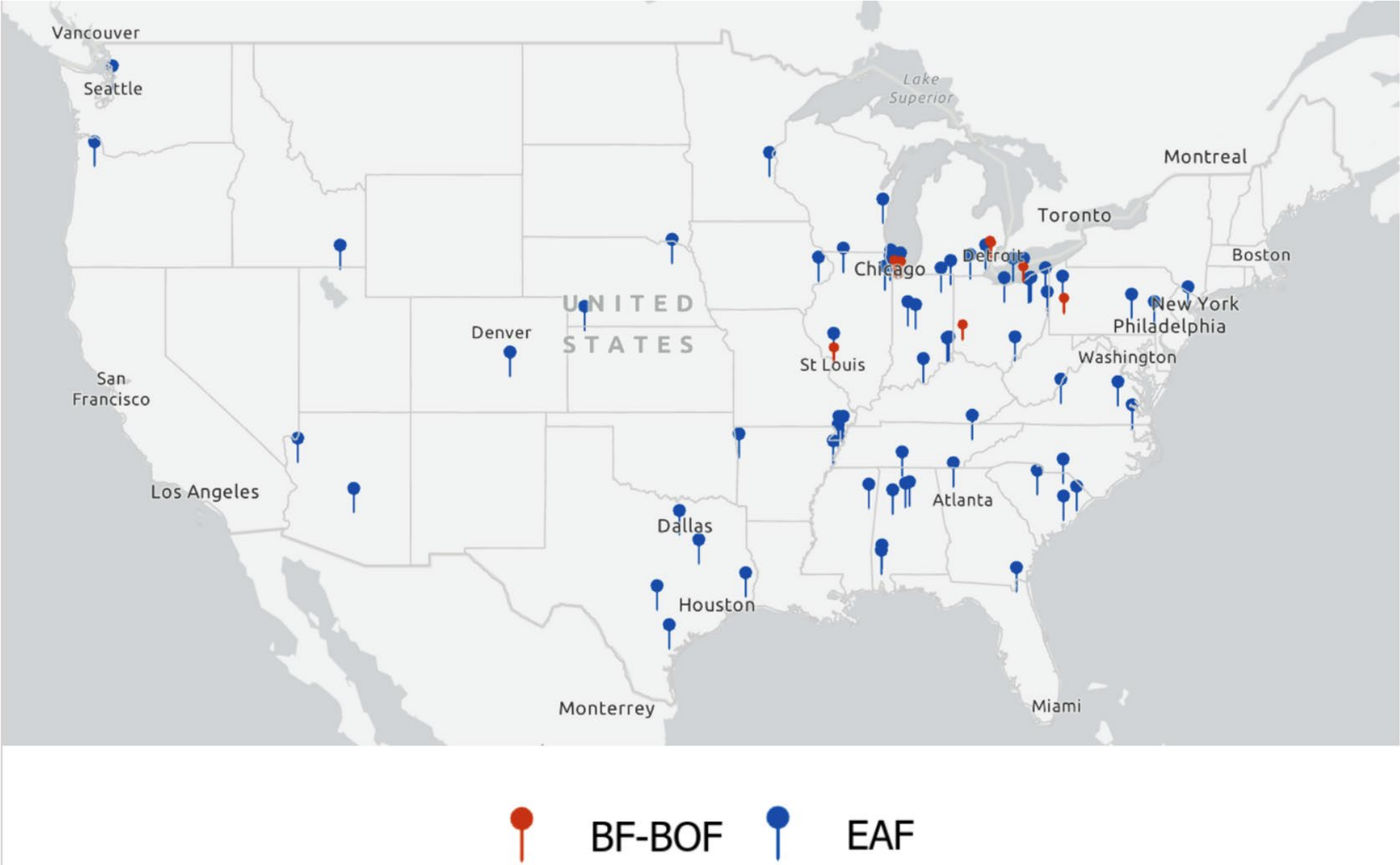


Results: Avg PM2.5 Levels by Distance to Steel Plants

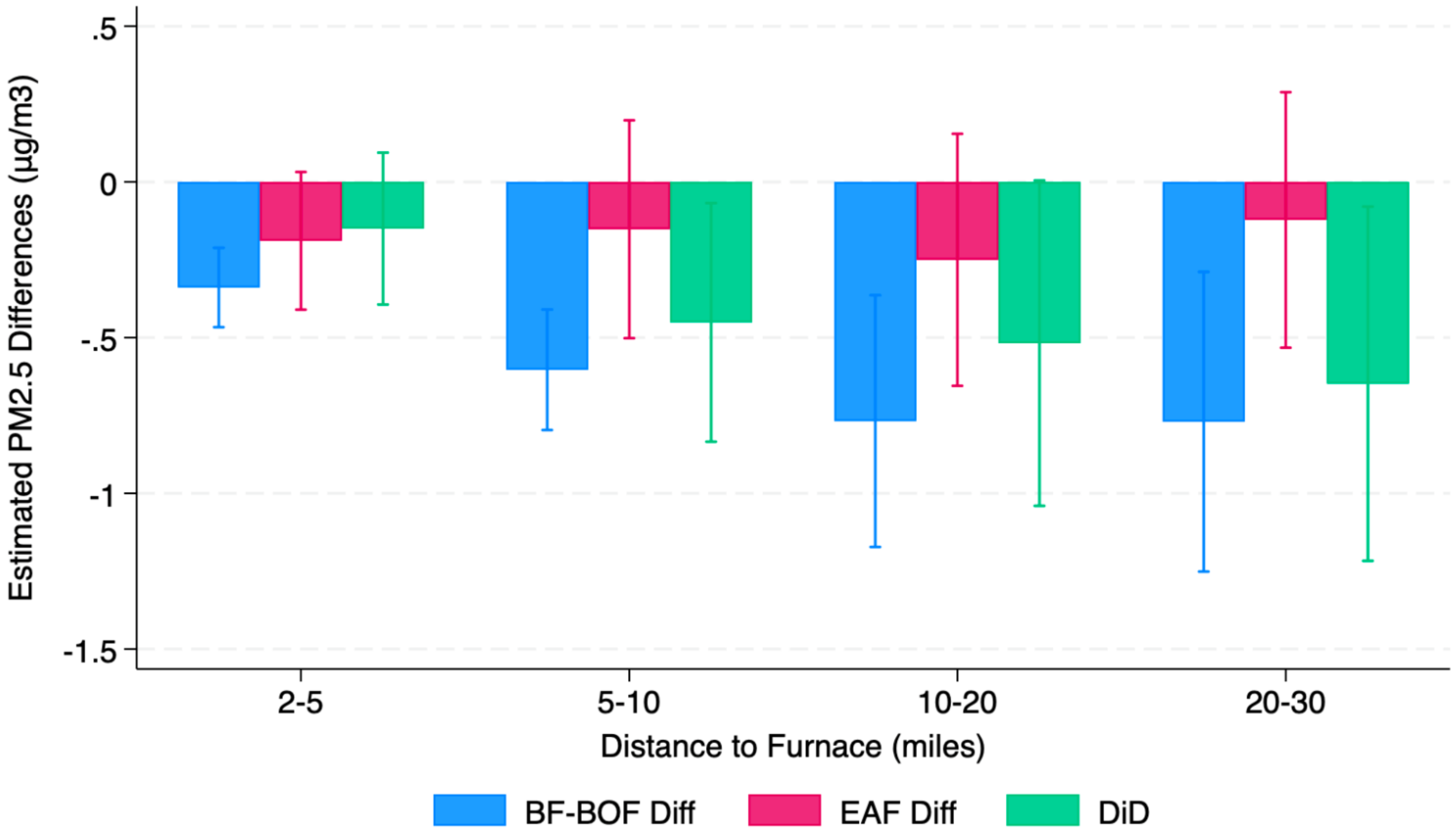


2021 WHO Annual PM2.5 Guidelines: 5µg/m3

Map of Current U.S. BF-BOF and EAF Facilities



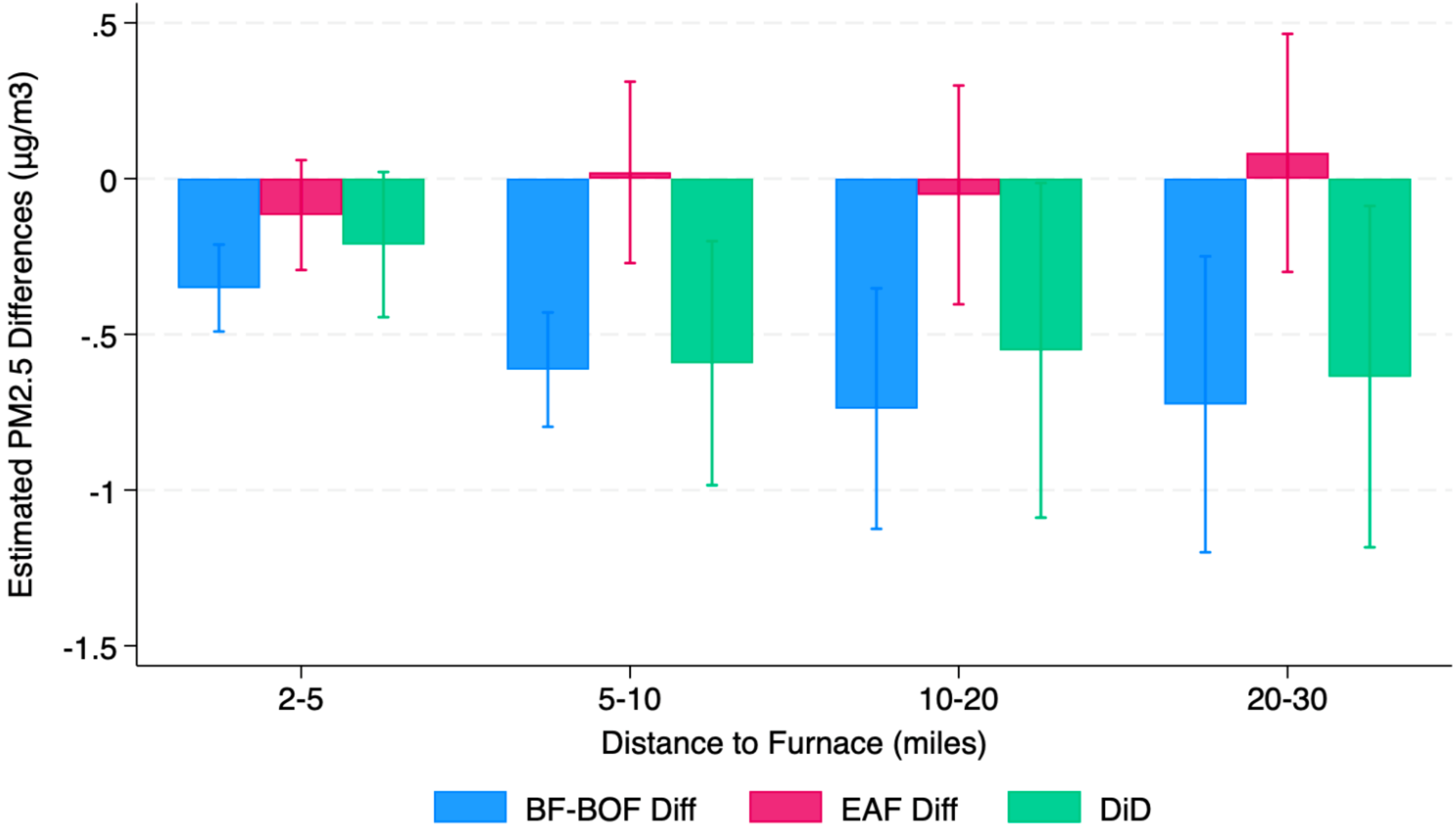
Results: Estimated PM2.5 Differences Relative to 0-2 Miles from Steel Plants



Comparison: Currie et al. (2023)'s estimated effects of "2005" NAAQS for PM2.5:

0.73 μg/m3

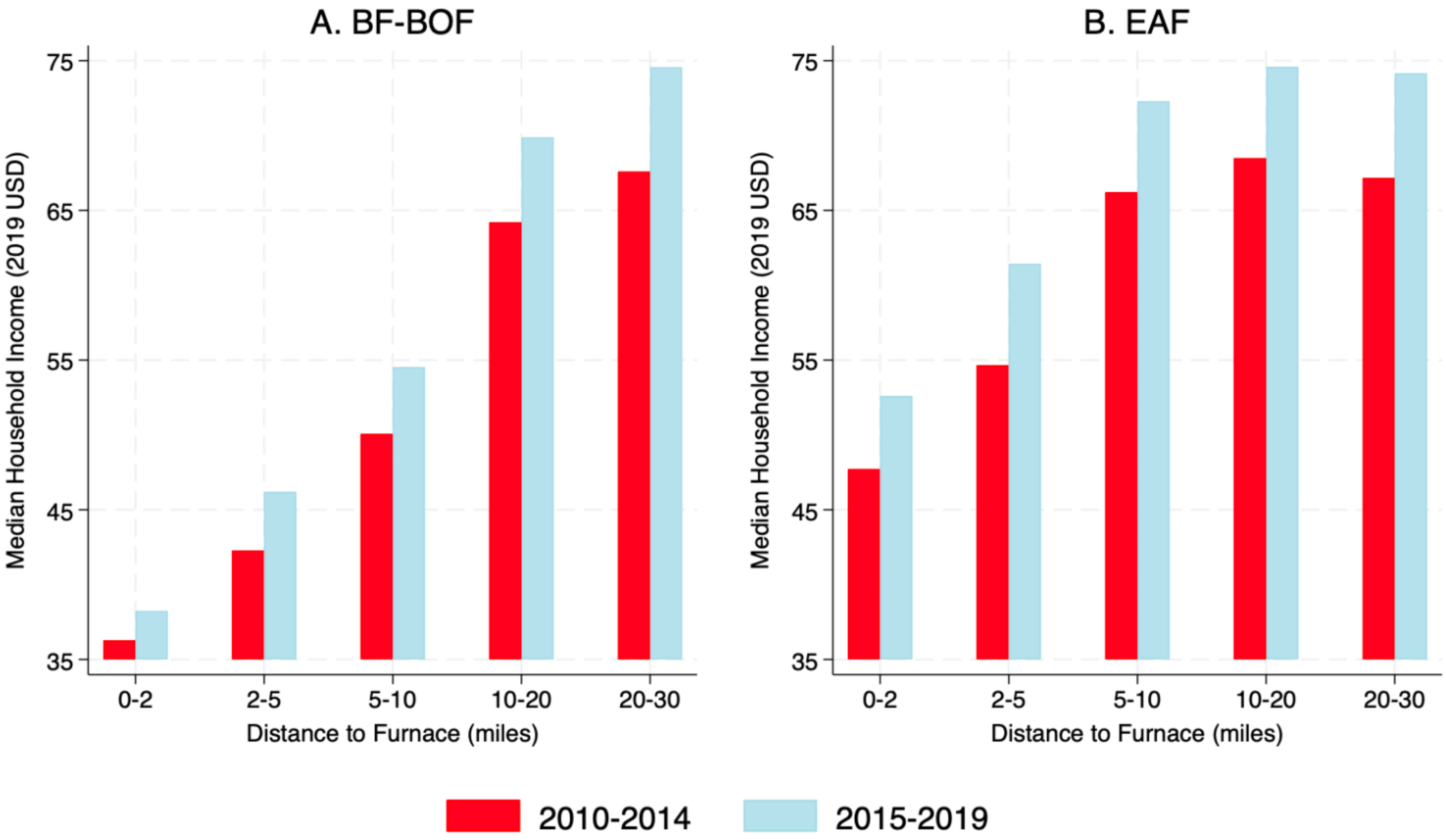
Results: Estimated PM2.5 Differences Relative to 0-2 Miles from Steel Plants *With Additional Controls*



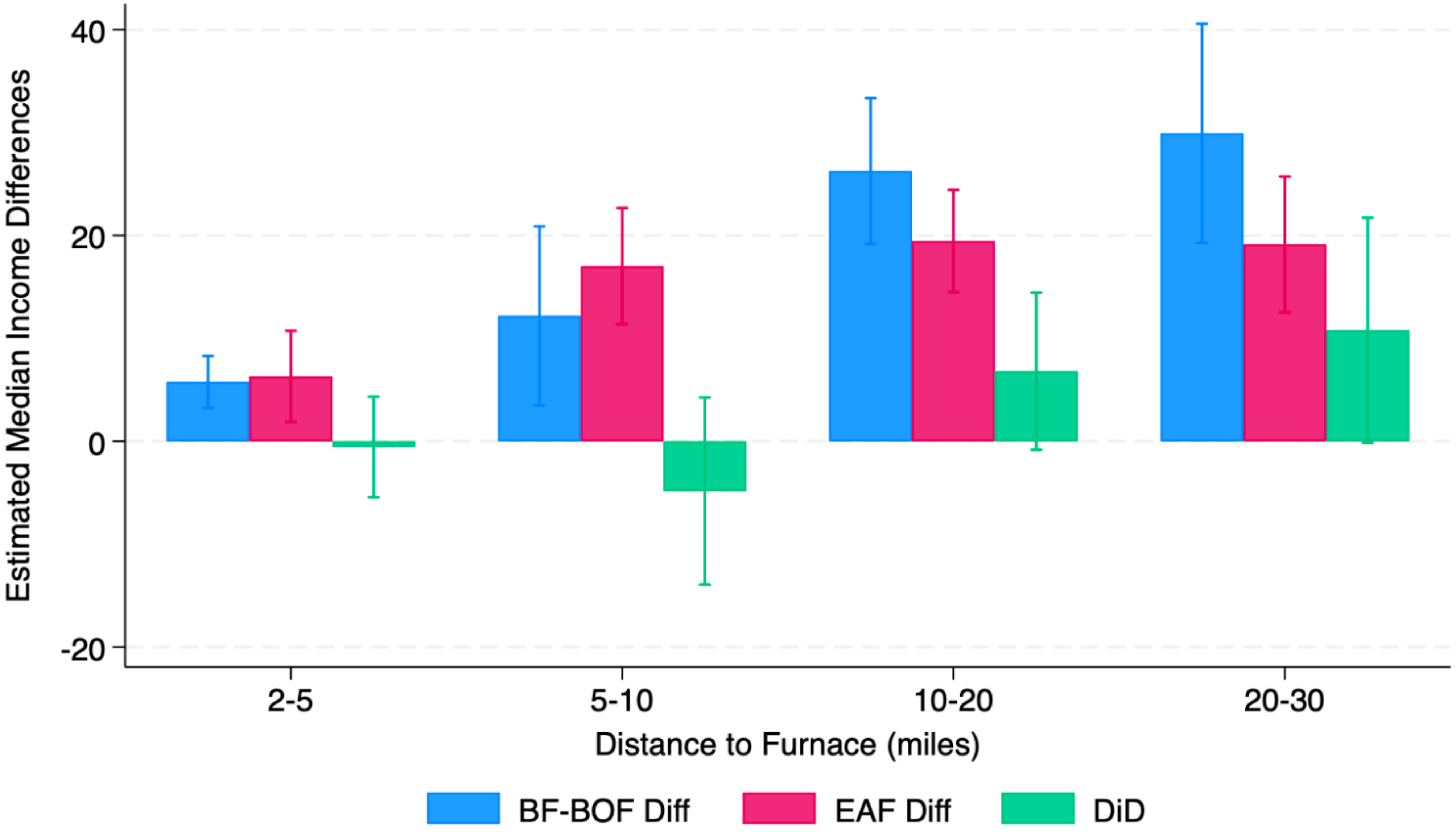
Comparison: Currie et al. (2023)'s estimated effects of "2005" NAAQS for PM2.5:

0.73 µg/m3

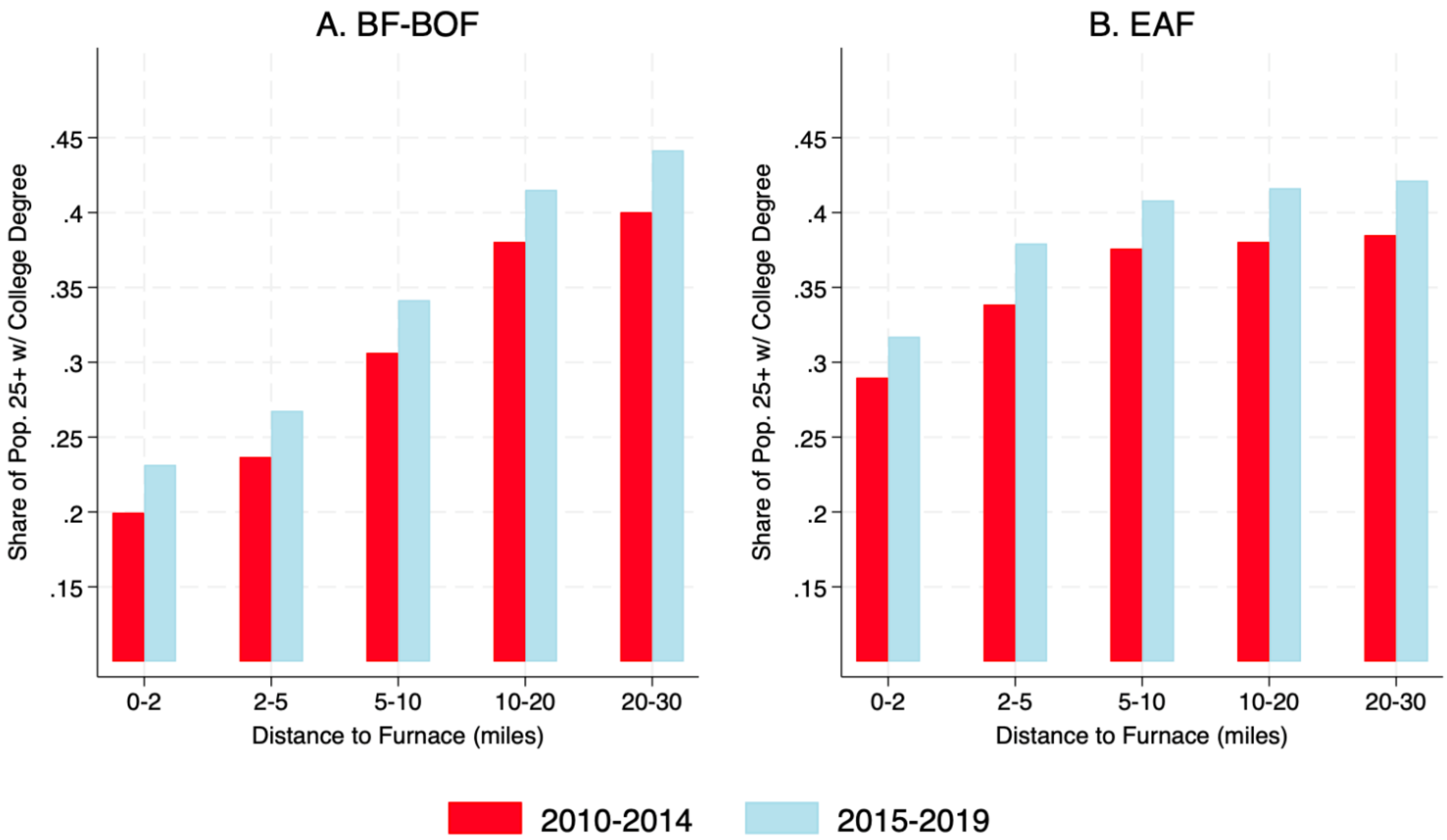
Results: Median Household Income (2019 USD)



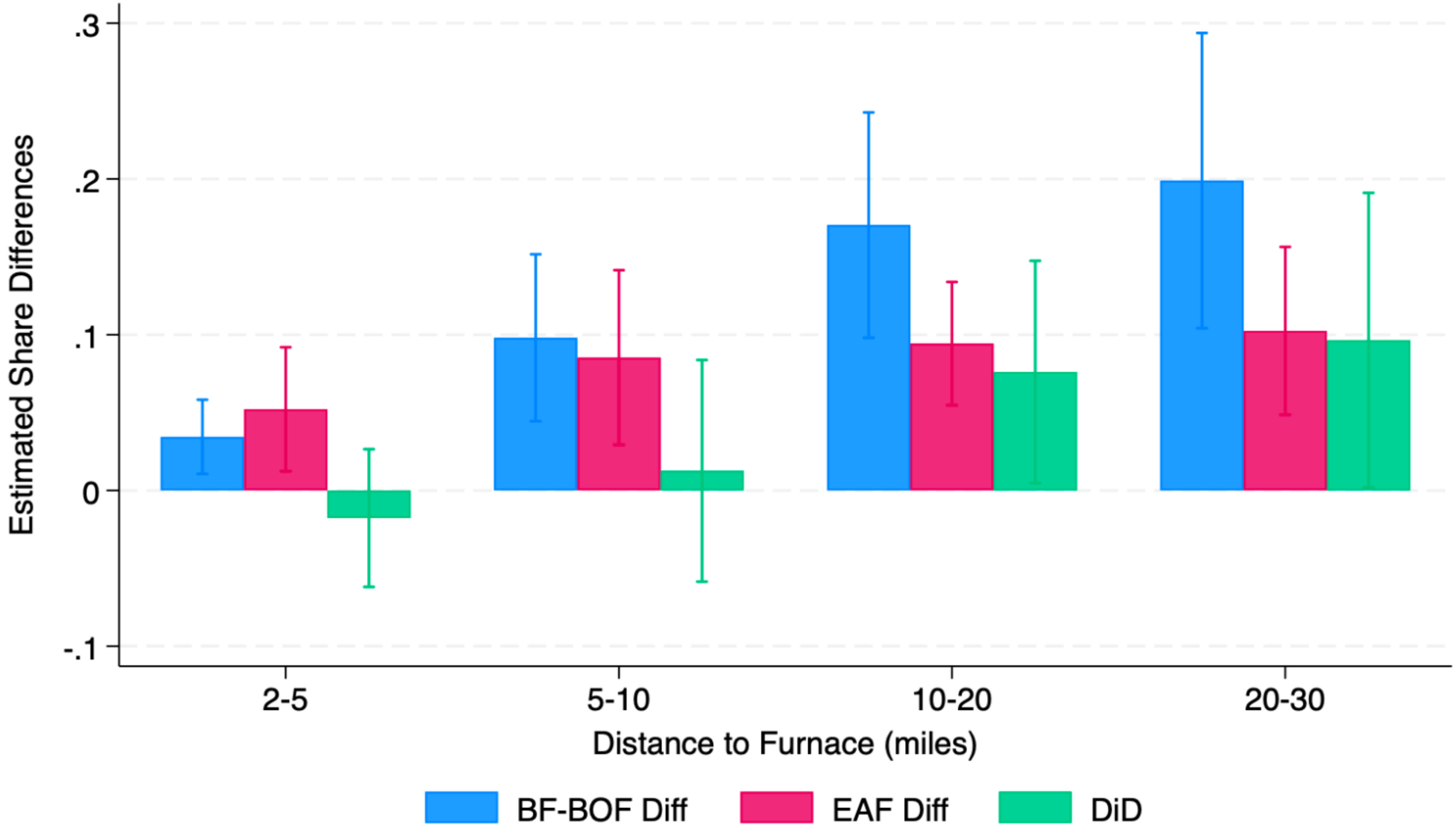
Results: Median Household Income (2019 USD)



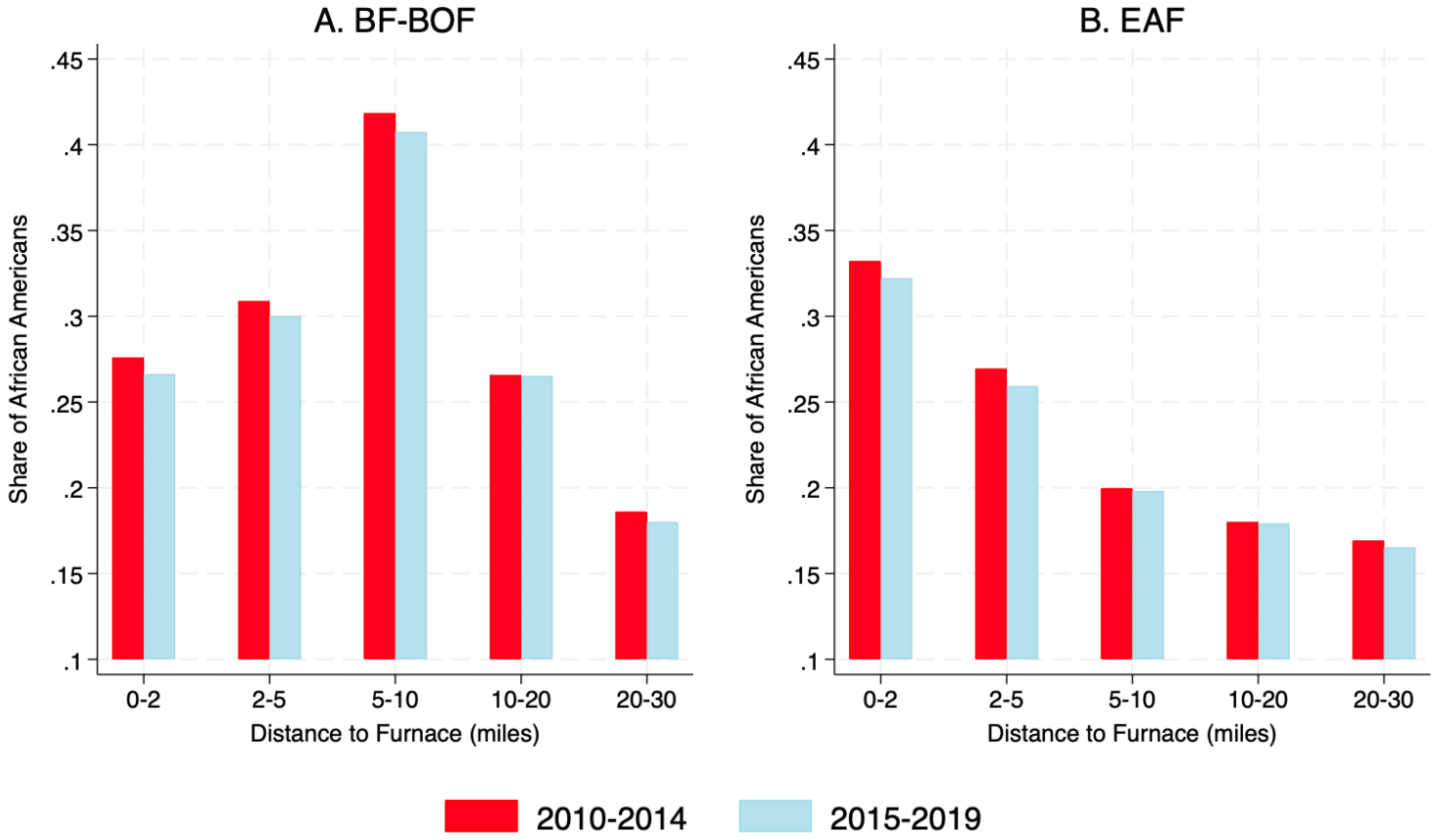
Results: Share of Pop. 25+ with College Degree



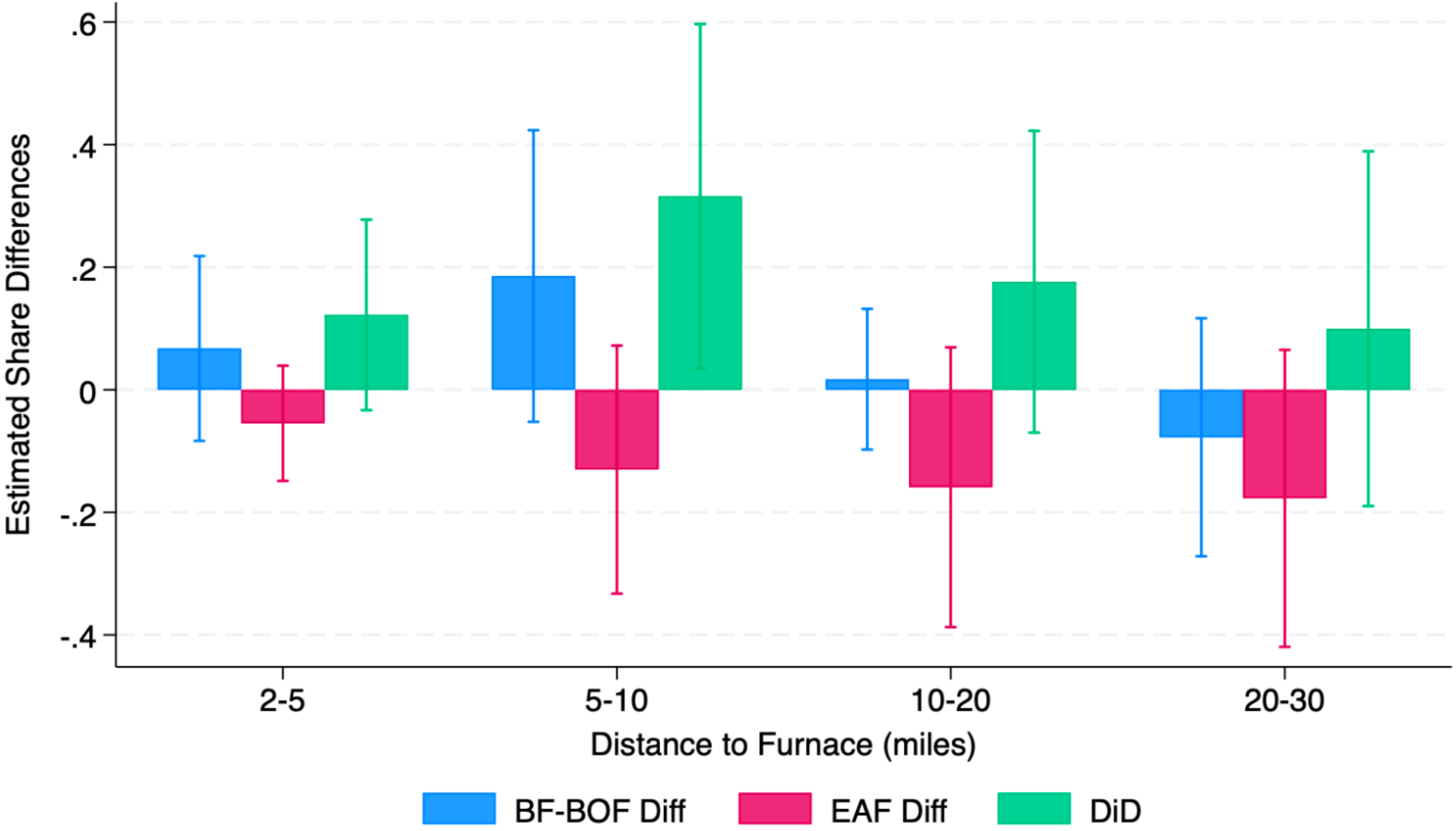
Results: Share of Pop. 25+ with College Degree



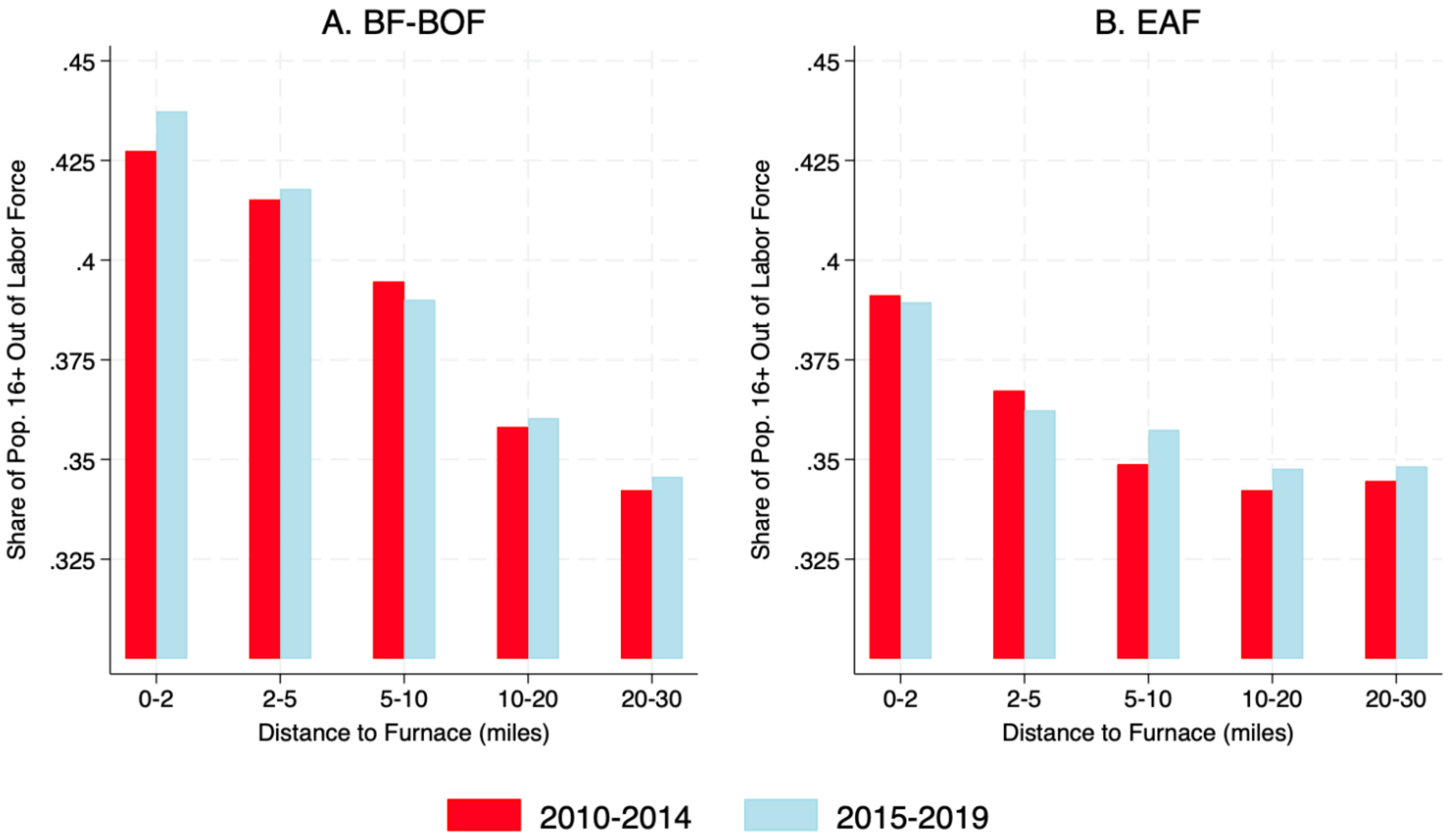
Results: Share of African Americans



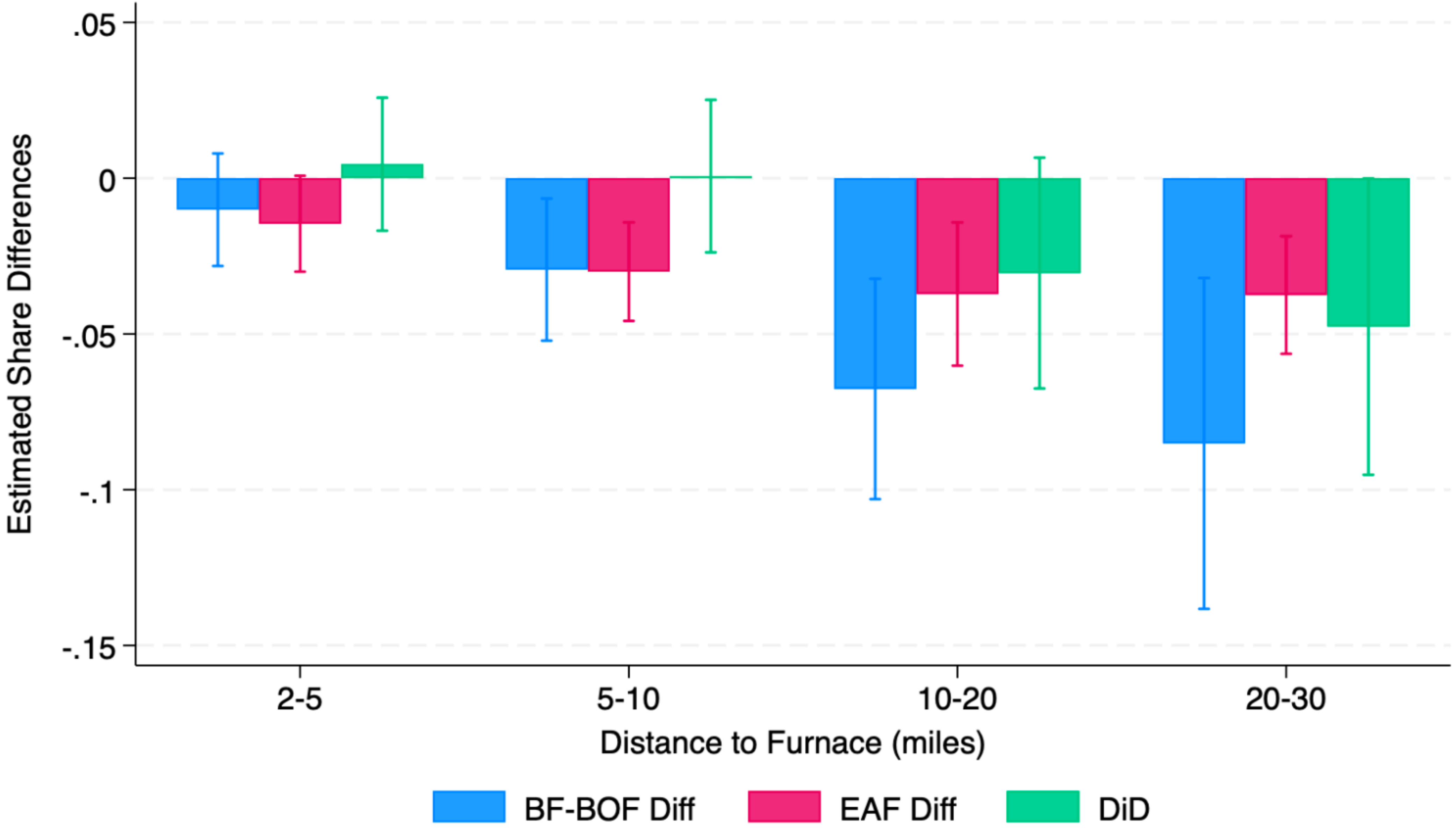
Results: Share of African Americans



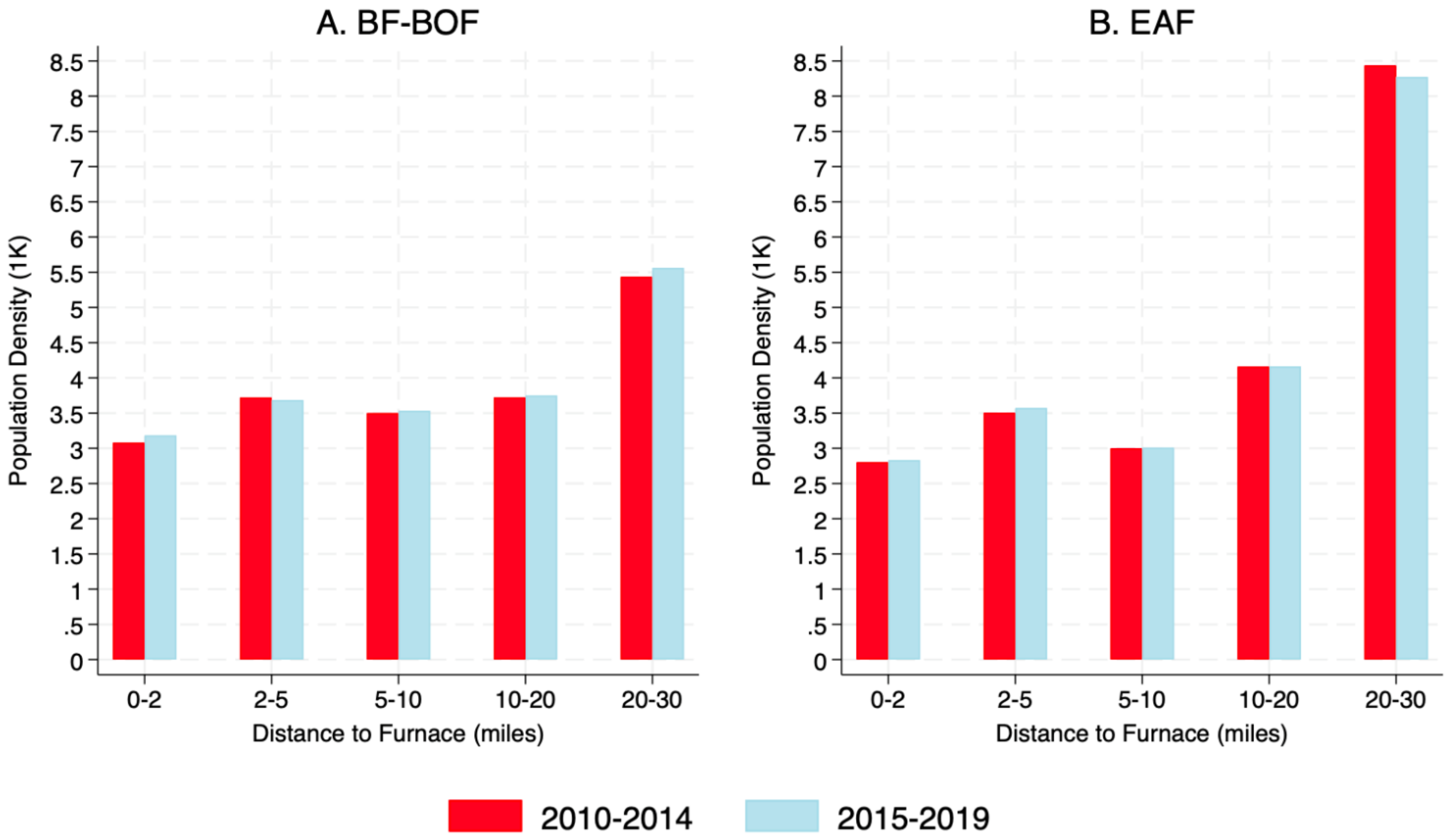
Results: Share of Pop. 16+ Out of Labor Force



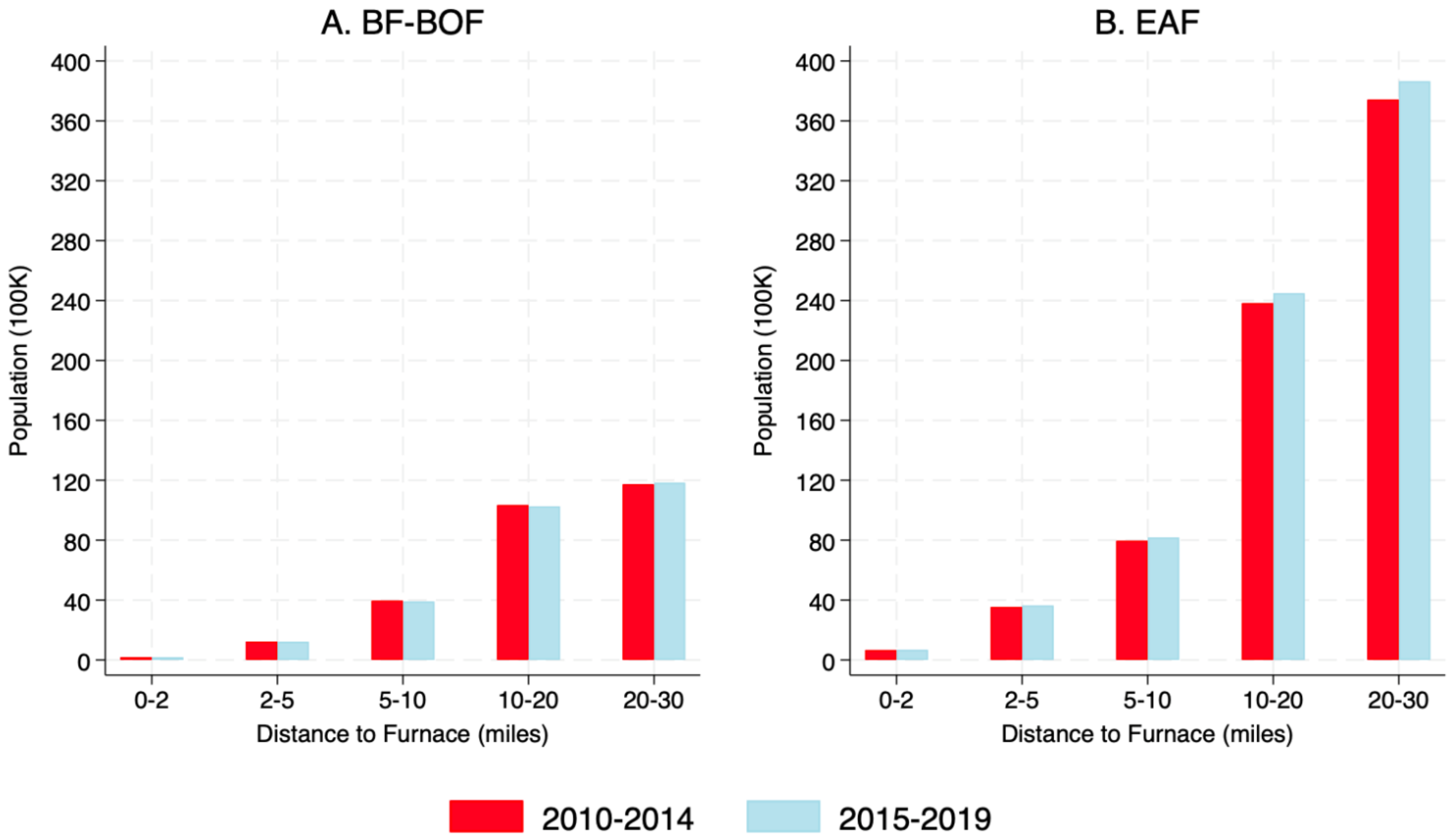
Results: Share of Pop. 16+ Out of Labor Force



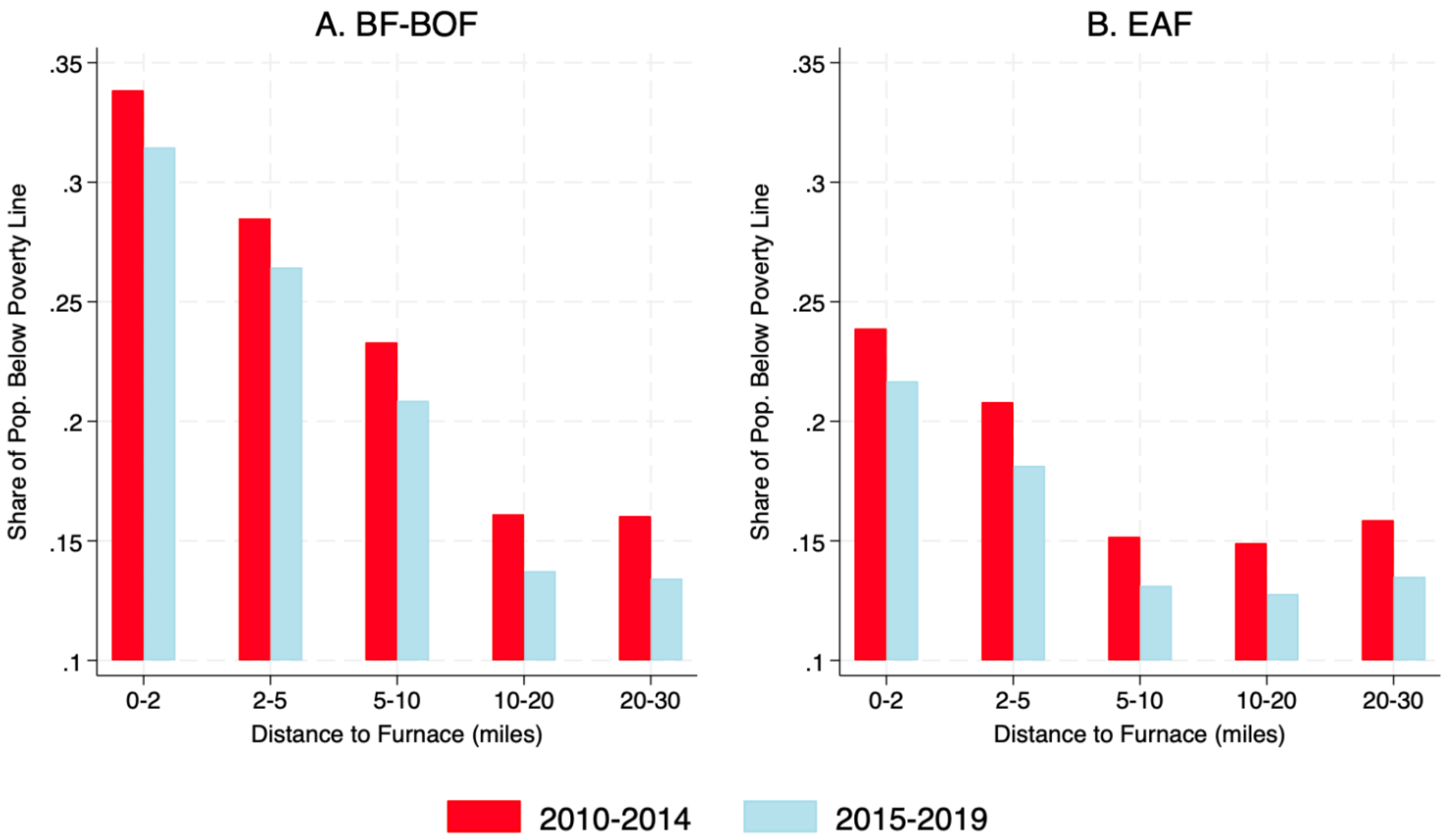
Results: Population Density (1K)



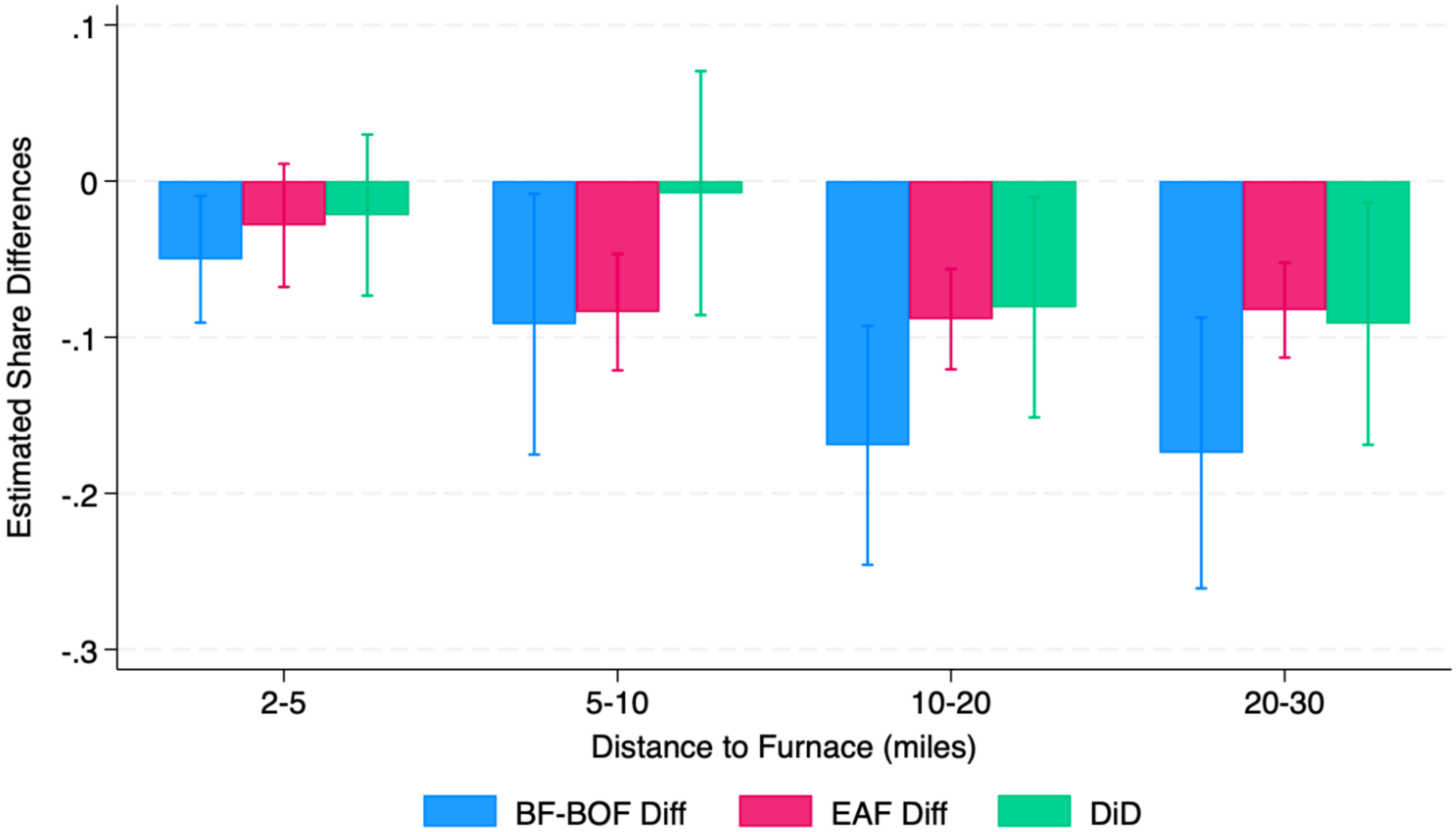
Results: Population (100K)



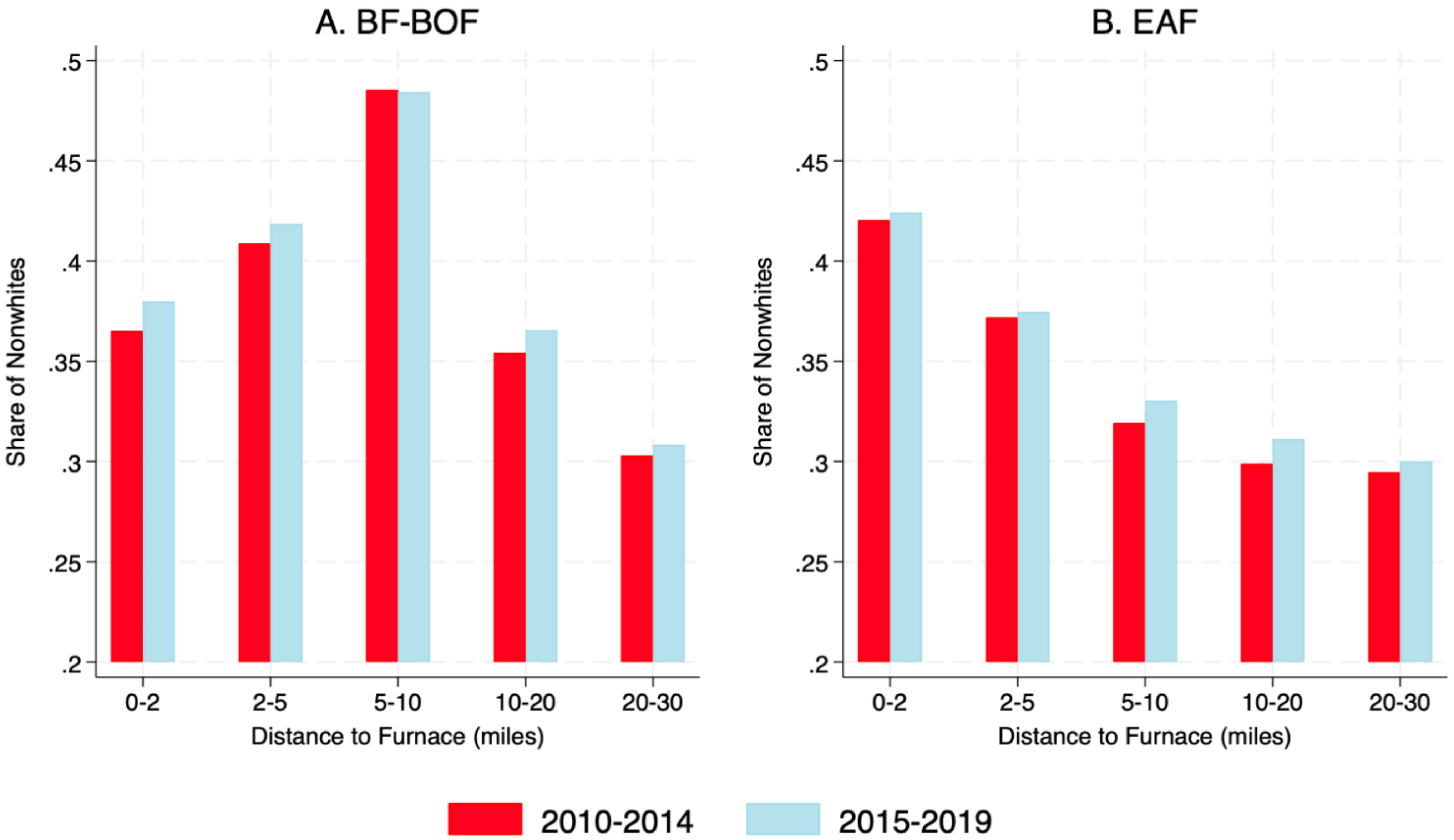
Results: Share of Pop. Below the Poverty Line



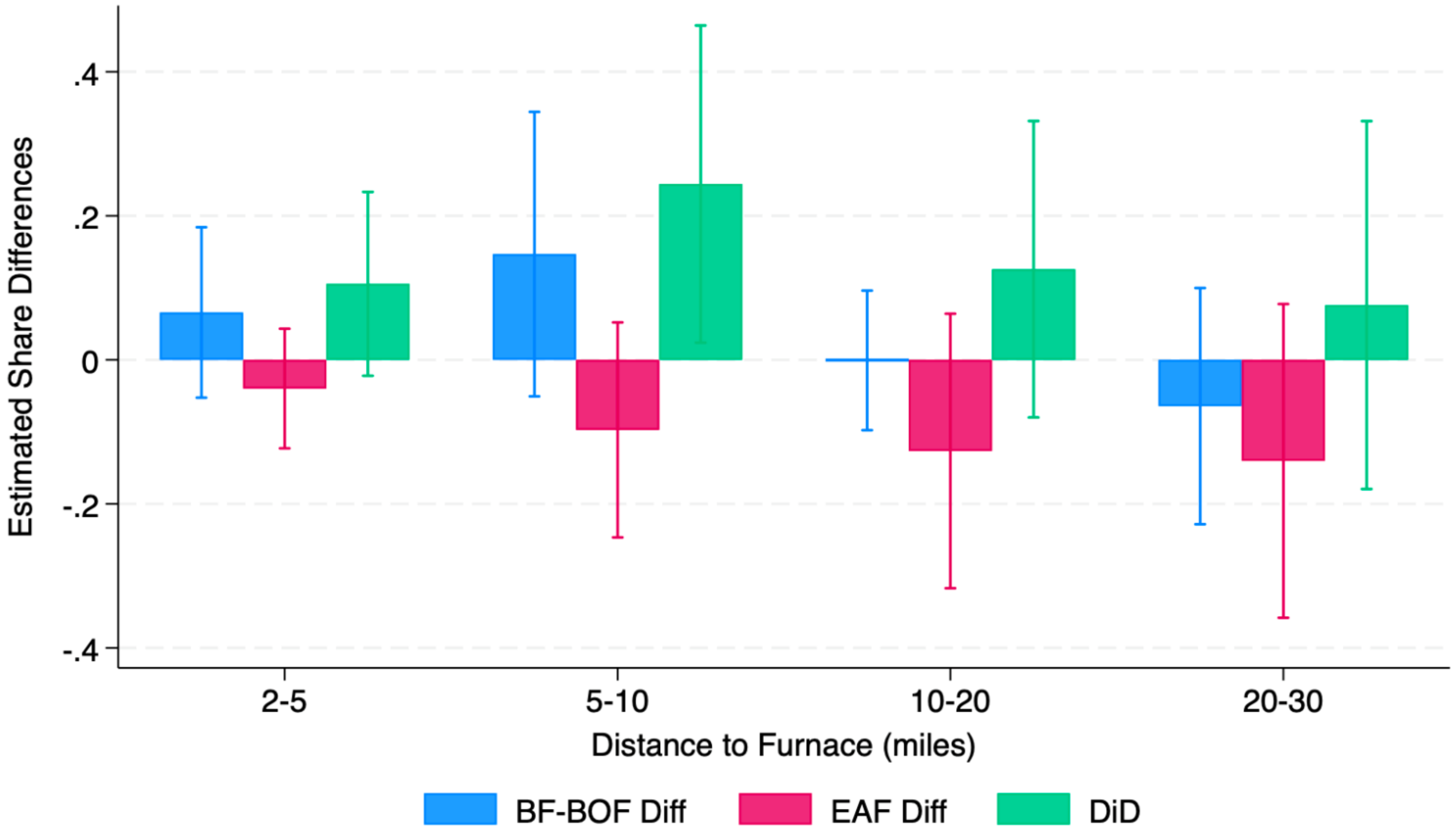
Results: Share of Pop. Below the Poverty Line



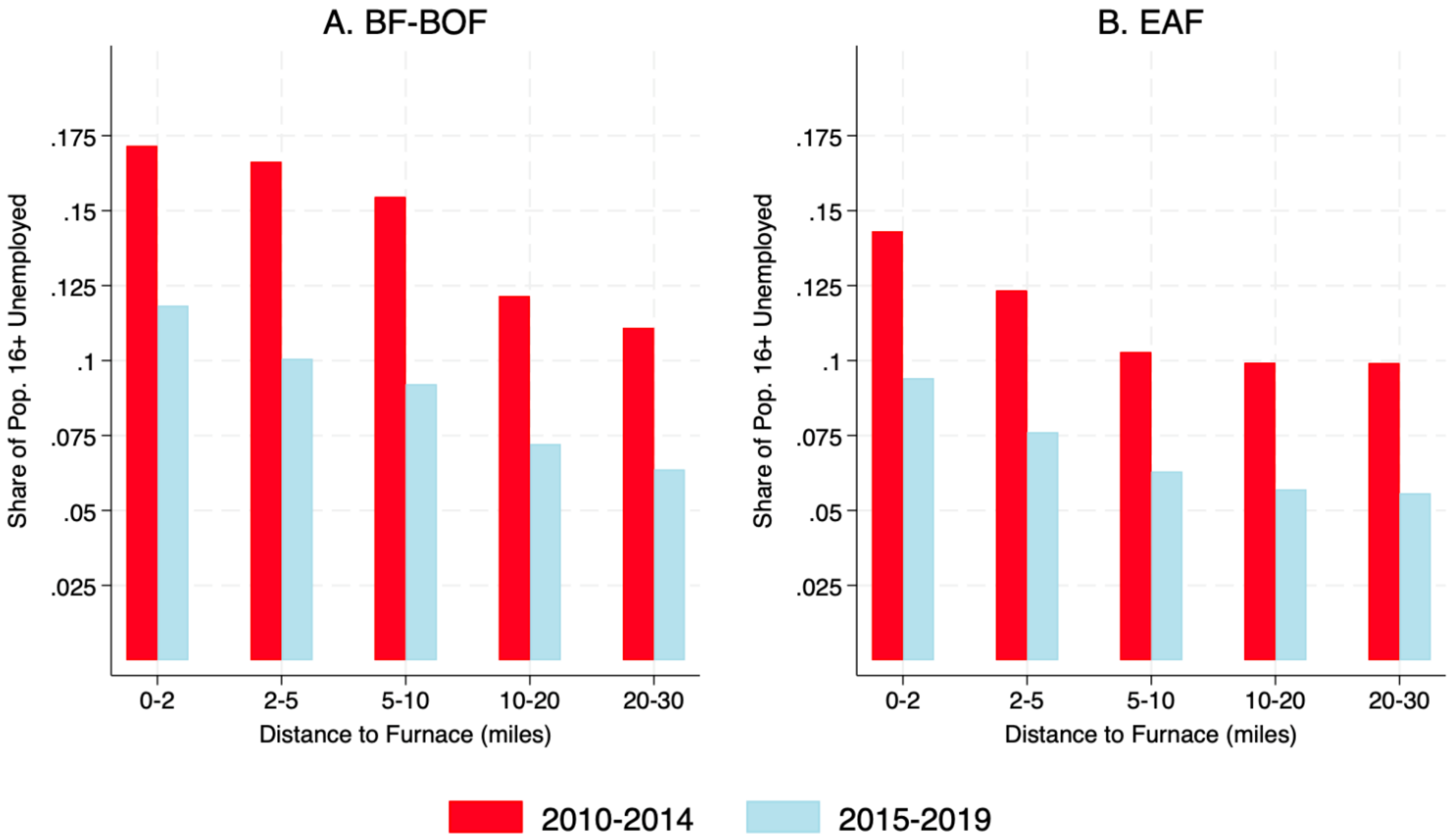
Results: Share of Nonwhites



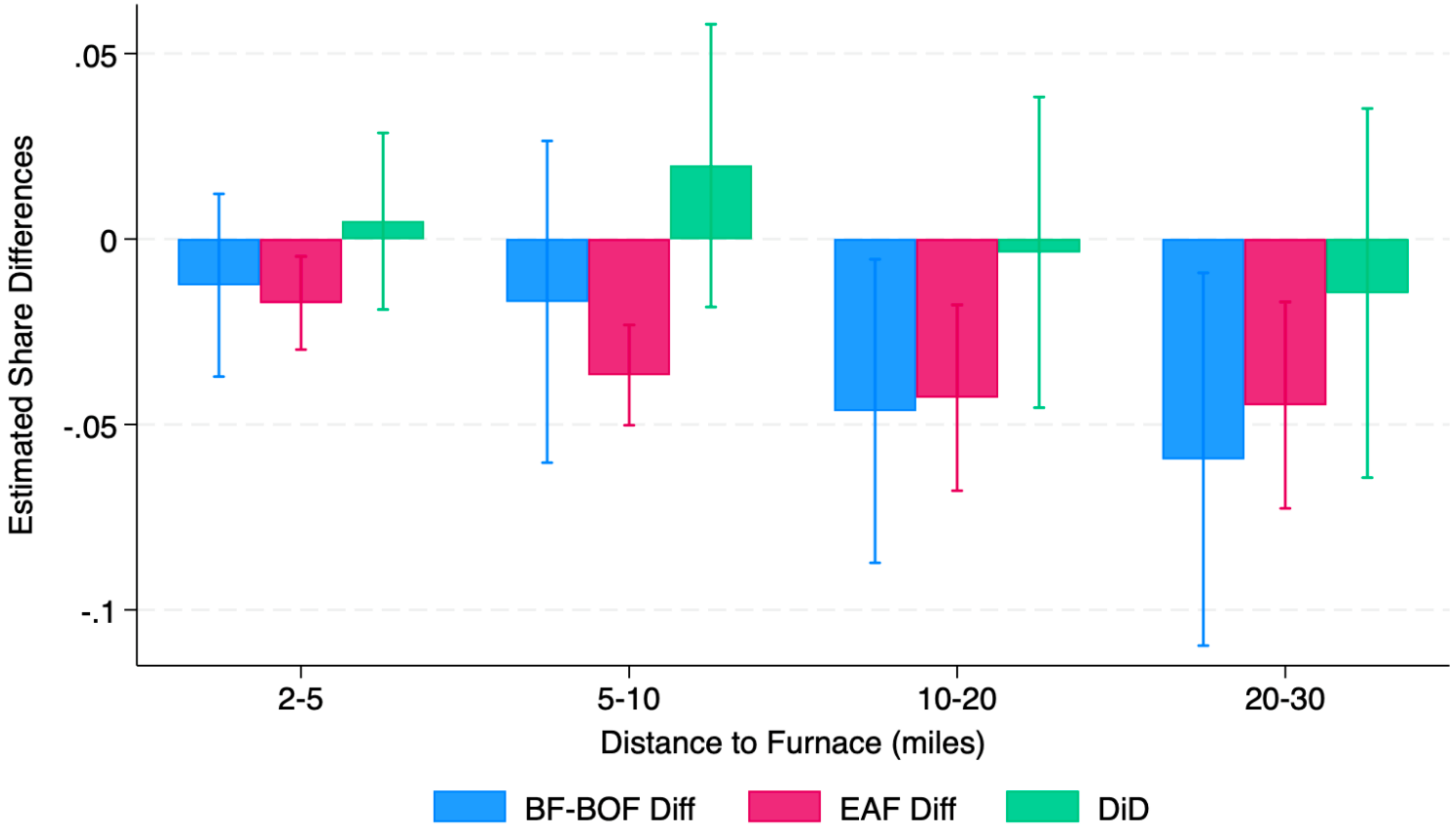
Results: Share of Nonwhites



Results: Share of Pop. 16+ Unemployed



Results: Share of Pop. 16+ Unemployed



Concluding Remarks

- Communities experience worse air quality near BF-BOF vs. EAFs
  - CCS installation may not address local air quality issues
- Transition from BF-BOF to EAF (DRI-EAF, or even DRI-BOF): co-benefits of PM2.5 reductions
  - Hernandez-Cortes and Meng (JPubE, 2023): California's carbon market (2013)
    - lowered GHG, PM2.5, PM10, and NOx emissions by 3-9% annually between 2012-2017
    - EJ gaps in PM2.5, PM10, and NOx from those facilities narrowed by 6-10% annually
  - Counterfactual evidence from Clean Power Plan regulatory impact analysis
  - Currie, Voorheis, and Walker (AER, 2023): >60% of convergence in Black-White PM2.5 exposure since 2000 attributable to Clean Air Act
    - areas with larger Black populations saw greater CAA-related declines in PM2.5

THANK YOU!

Questions? Comments?

vkarplus@andrew.cmu.edu
edsons@andrew.cmu.edu

Comparison of magnitude: Currie et al. (AER, 2023)

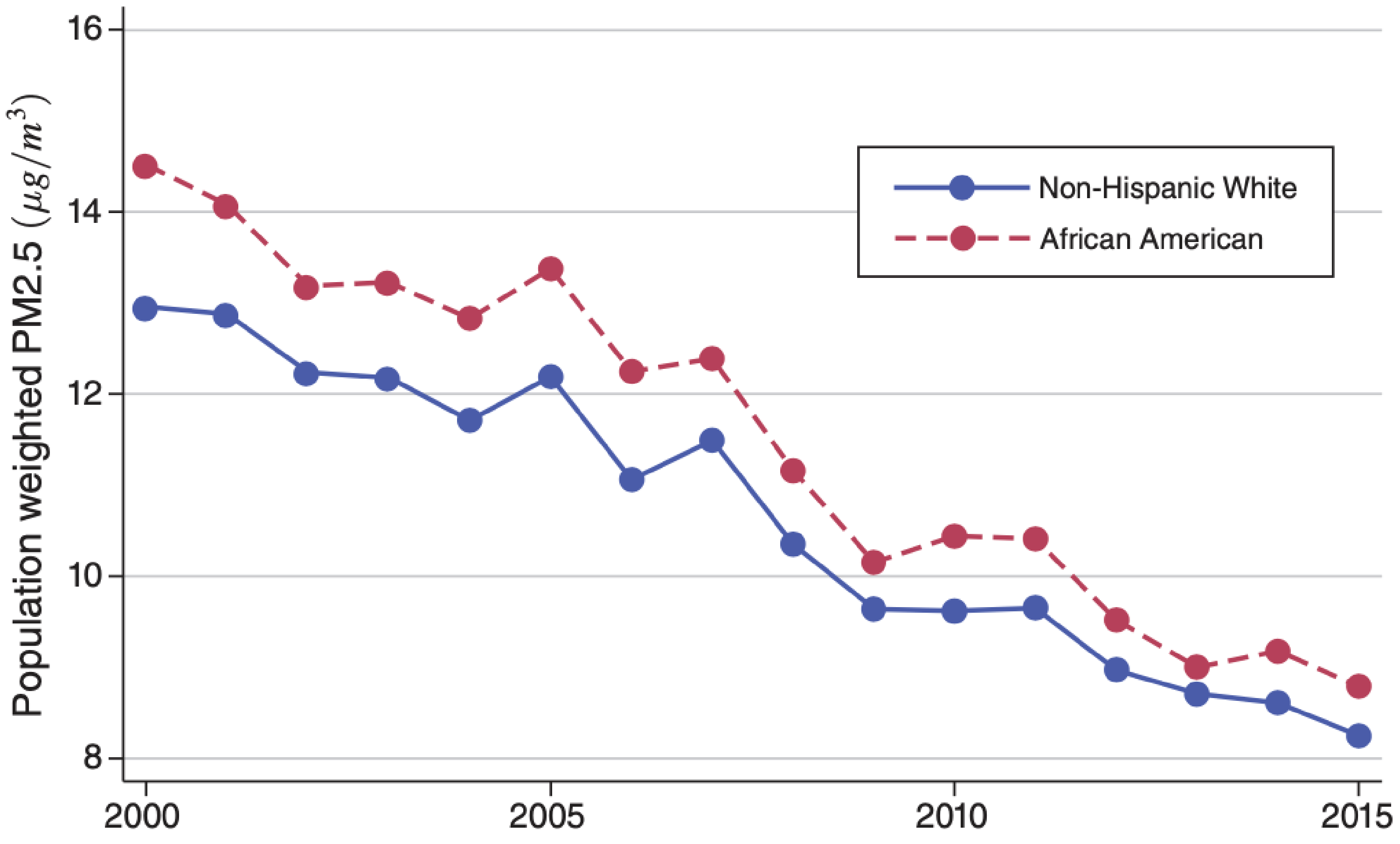


FIGURE 1. TRENDS IN POLLUTION EXPOSURE BY RACE

Comparison of magnitude: Currie et al. (AER, 2023)

TABLE 3—THE IMPACT OF THE 2005 IMPLEMENTATION OF PM2.5 STANDARDS ON PM2.5 LEVELS

	PM2.5 (1)	PM2.5 (2)	ln(PM2.5) (3)	ln(PM2.5) (4)	PM2.5 (5)	PM2.5 (6)	ln(PM2.5) (7)	ln(PM2.5) (8)
PM2.5 *nonattain* × *post*	−1.230 (0.335)	−1.237 (0.334)	−0.075 (0.020)	−0.076 (0.020)	−0.727 (0.080)	−0.726 (0.082)	−0.036 (0.006)	−0.036 (0.006)
PM2.5 *non* × *black* × *post*		0.149 (0.088)		0.008 (0.007)		0.048 (0.091)		0.004 (0.005)
Year FE	X	X	X	X				
State-Year FE					X	X	X	X
County FE	X	X	X	X	X	X	X	X
Observations	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000

Notes: This table presents regression coefficients from 8 separate versions of equation (3), one per column, where the dependent variable consists of PM2.5 or ln(PM2.5) for an individual in a given year. Columns 2, 4, 6, and 8 add an additional interaction for African Americans to test for heterogeneity in regulatory impacts for African Americans. Regressions are weighted by census survey weights and errors are clustered by CZ. FE = fixed effects.

Challenges to keep in mind when evaluating industrial decarbonization pathways

- **Industrial production involves multiple interdependent steps,** with interdependencies in decarbonization decisions across steps.
  - **Important to disaggregate** – within 3312 - Steel Works, Blast Furnaces (Including Coke Ovens), and Rolling Mills, 30-fold difference in CO_2 intensity.
- **Abatement options are not always additive:** efficiency of a given process(low capex, limited reduction potential) versus replacing that process (high capex, greater reduction potential).
- **Multiple margins for innovation:** (1) ability to substitute toward scrap-based (less GHG intensive) pathways over pathways requiring virgin material or (2) innovation across the supply chain to support decarbonization of a particular process step.