The Structural Frictions of Industrial Decarbonization

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Abstract

Restricting clean-investment grants to existing plants avoids paying new plants that would be built anyway, but existing plants may need much larger grants to adopt a cleaner technology. To study this trade-off, I estimate a dynamic structural model of the U.S. steel industry, using a novel plant-level panel constructed from industry directories. Each year, old plants choose whether to keep running, close, or adopt the cleaner technology, and new plants whether to enter. Existing plants face two structural frictions that new plants do not: obligations to workers due at shutdown, and a fixed adoption cost that exceeds the cost of new equipment. At equal abatement, this restriction cuts the share paid for investment that would happen anyway from about half to an eighth but barely changes public spending per tonne of CO_2 avoided, because old plants need larger grants. Paying only plants that replace their old technology nearly doubles that spending: owners would rather add the cleaner technology beside the old one and defer the obligations.

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1 Introduction

A clean technology can spread in two ways: existing plants adopt it, or new plants built around it enter and compete with the incumbents. Supporting cleaner production can therefore preserve existing industrial sites or shift production toward new ones, with different consequences for workers, owners, and taxpayers. In 2024, the U.S. Department of Energy selected projects to reduce industrial emissions at existing and new plants alike, for up to $6 billion in grants (DOE 2024a), while its grants for converting auto plants were only for existing facilities, to retain workers (DOE 2024b). On the one hand, restricting grants to existing plants can raise additionality, the share of payments that changes investment, because some new plants would be built anyway. On the other hand, the restriction can make abatement more expensive, because existing plants may need much larger grants to adopt. In this light, I ask whether clean-investment grants restricted to existing plants cost governments less per tonne of CO_2 avoided than grants open to new plants too.

To study this question, I estimate a dynamic structural model of the U.S. steel industry. Old plants, called integrated works, make steel from iron ore and coal, using blast furnaces, while the cleaner electric arc furnace (EAF) melts scrap with electricity. Each year, an old works decides whether to keep running, close, add an EAF beside its blast furnaces, which keep running (an *add-on*), or build it in their place (a *conversion*), and potential new EAF mills decide whether to enter. The model captures both sides of the trade-off. New mills can enter without a grant, and their output lowers steel prices, which pushes old works to close. An old works that adopts gives up profit from its blast furnaces and bears two *structural frictions* that a new mill does not: obligations to its workers due when the blast furnaces close, and a fixed adoption cost. Both can make the grant it needs much larger. Because owners look ahead and entry moves prices, the policy experiments solve adoption, closure, entry, and steel prices together, for every plant and year.

More broadly, I ask what it costs governments to decarbonize an industry through its old plants rather than through new ones, and why. What does adopting the cleaner technology cost an old plant beyond the new equipment? And what decides whether an old plant adds the new technology beside the old one or replaces it? I study them in steel, but the same questions arise in cement, chemicals, and other heavy industries, where grant programs also fund both existing and new plants.

The paper makes three contributions. First, I provide an assessment of how targeting green subsidies trades off additionality against the cost of inducing adoption. Second, I introduce a channel through which shutdown costs, such as obligations to workers, shape whether firms add a new technology beside the old one or replace it. Third, I estimate from firms' choices the fixed cost incumbents bear in adopting a new technology, beyond the equipment that entrants also buy. Together, they shed light on why old plants are slow to adopt cleaner technologies and on how the eligibility rules of grants shape the public cost of abatement.

Steelmaking accounts for 7% to 8% of human-caused greenhouse gas emissions (World Steel Association 2025), and in the United States the shift to the cleaner technology has

largely happened. The EAF's share of production rose from 34% in 1985 to 71% in 2020, new mills account for 75% of the fall in the CO_2 intensity of steelmaking capacity, and only three old works adopted the EAF. These choices were made without grants of the kind studied here, so they show what owners and entrants do without them. I build a novel year-by-year panel of U.S. steel plants for 1985–2020, mostly from the industry's plant directories (AIST 2004–2022; AISE 1983–2003), which I digitized. The panel records each plant's furnaces with their capacities, openings, closures, and idle years, which shows whether an old works added an EAF beside its blast furnaces or replaced them. It also records each plant's owners with the dates they changed, and I match the owners to the unfunded pension and retiree health obligations they reported in financial data and company filings.

Owners choose the action with the highest expected value, given current profits, the cost of each action, and an unobserved shock to each choice, and forecast steel margins from their past movements. Profits come from observed prices and engineering input requirements, and the building cost of an EAF from industry cost estimates. I estimate five parameters, among them the fixed adoption cost and the scale of the unobserved shocks, from owners' yearly choices by maximum likelihood with a nested fixed point (Rust 1987), and then the costs of setting up new mills from the observed entry. The fixed adoption cost is estimated from how rarely old works adopted, given what adopting would have earned. That return varied across works and years with steel margins, the works' size, and the owner's obligations. Old works passed up adoption in many years, which points to a large cost, and the two adoptions in the estimation period limit how large it can be. How large the fixed cost is in dollars depends on how strongly owners' choices respond to profits. EAF mills, which do not face this cost, help pin this down. How often they close as their margins rise and fall shows how strongly their choices respond.

In the policy experiments, I compare three clean-investment grants per tonne of new EAF capacity, each set to avoid the same CO_2 over 1985–2015: an open grant for new mills and old works alike, an adoption grant for old works only, and a conversion grant for old works that replace their blast furnaces. Restricting grants to existing plants sharply raises additionality but barely changes public spending per tonne of CO_2 avoided. Under the open grant, 54% of the payments go to investment that would happen anyway, mostly to new mills, against 13% under the adoption grant. Yet spending per tonne avoided is about the same, \$28.1 against \$27.5. Counting only the payments for investment the grant causes, the adoption grant spends almost twice as much per tonne as the open grant, because old works need much larger grants to adopt. The open grant loses that advantage by paying for investment that would happen anyway. Restricting saves more when the grants are set to avoid less CO_2. The ranking reverses if the costs of setting up new mills are at the high end of their estimated range or steel demand responds weakly to prices, and near the upper end of the fixed adoption cost's interval the adoption grant cannot avoid that much CO_2. Restricting grants keeps more jobs at existing plants but not more steel jobs in total.

The estimates show why old works need much larger grants. I estimate the fixed adoption cost at \$0.77 billion per adoption, about \$414 per tonne of new EAF capacity,

against a building cost of $260 per tonne. The fixed adoption cost may include stranded ore mines and coke batteries, the time customers take to approve the new steel, and permitting. I decompose the *adoption gap*, the one-time payment that would just make an owner willing to add an EAF, into its parts. Of the part of the gap that is about adoption, about half is the fixed adoption cost, more than the new furnace, which a new mill also pays for, or the profit the blast furnaces give up.

Paying only for conversions makes almost every payment additional, yet nearly doubles spending, to $49.5 per tonne, and costs the most at every level of abatement I study, because owners prefer an add-on. The fixed adoption cost discourages both forms of adoption, but the obligations add $134 per tonne of capacity to the gap to convert and little to the gap to the add-on, which keeps the blast furnaces running. A conversion also leaves the works without steel for the years the new furnace takes to build, and with a smaller furnace, so a grant must be much larger to make owners convert.

The paper speaks to three literatures. First, it contributes to the literature on the targeting of green and industrial subsidies. Much of this literature concerns additionality. Boomhower and Davis (2014), Xing, Leard, and Li (2021), and Calel et al. (2025) find that rebates for efficient appliances, credits for electric vehicles, and carbon offsets mostly pay recipients who would have adopted anyway, and Sallee (2025) ties the revenue cost of green subsidies to that share. I contribute by extending this work to the choice between grants restricted to incumbents and grants open to entrants, when incumbents can adopt the entrants' cleaner technology. The closest paper is Barwick, Kalouptsidi, and Zahur (2025), who find that entry subsidies were the least effective support for Chinese shipbuilders because they drew in high-cost firms. Here, the entrants bring the cleaner technology, and some would enter without support. The grants I study are also restricted by whether a plant already exists, not by firms' costs.

Second, the paper contributes to a large literature on technology diffusion through incumbents and entrants. In steel and cement, Oster (1982) and Macher, Miller, and Osborne (2021) study how new technologies spread through adoption by existing plants, and Collard-Wexler and De Loecker (2015) find that they also spread through the entry of new mills that displaced old plants. Explanations of late adoption by incumbents point to sunk investment in the old technology (Hornbeck et al. 2026) and output lost while switching over (Holmes, Levine, and Schmitz 2012), and costs owed to workers can delay closure (Deily 1987). Igami (2017) finds that the cannibalization of their existing products made incumbent hard-disk makers reluctant to introduce a new generation. In his model, an incumbent that adopts keeps making the old generation beside the new. I contribute by letting old works choose whether to add the new technology or replace the old. I also estimate from owners' choices the fixed cost of adopting at an old works, beyond the new furnace and the profit the old capital gives up, which is the counterpart of cannibalization.

Third, the paper contributes to a growing literature on climate and environmental policy for heavy industry, and in particular on how it treats existing and new plants. Much of this literature studies carbon prices and border adjustments (Clausing et al. 2025; Gorrens 2025; Park, Rausch, and Karplus 2026), and Colmer et al. (2025) find that the EU's

carbon market led manufacturing firms to cut emissions through targeted investments rather than lower output. Rules that treat existing and new plants differently change who produces. Ryan (2012) finds that regulation that raised the cost of entry in U.S. cement benefited incumbents, and Pacelli (2026) that free permits, granted only to operating plants, act as entry subsidies that draw in dirtier entrants. Fowlie, Reguant, and Ryan (2016) compare auctioned permits with free permits for existing capacity, which entrants do not receive, in a dynamic model of U.S. cement in which entrants bring the frontier technology. I contribute by showing that obligations to workers, due when old capital is retired, shape how existing plants respond to such policy. They steer old works toward adding the cleaner technology.

Section 2 describes the industry, its plants and owners, and the panel. Section 3 sets out the facts the model must explain, Section 4 presents the model and the adoption gap, and Section 5 the estimates. Section 6 compares the grants and a carbon price at equal abatement and asks what grant the remaining old works would need to add an EAF. Section 7 concludes.

2 Industry Background and Data

2.1 Steelmaking technologies

Steel is made today mainly in two ways. An integrated works makes steel from iron ore in two steps: in a blast furnace, coke, made from coal in coke ovens on or near the site, reduces the ore to liquid iron, and a basic oxygen furnace (BOF) then blows oxygen through the iron, with some scrap, to make steel. A blast furnace runs continuously for years and, once shut down, cannot easily be restarted (Cleveland-Cliffs 2005–2020; Giarratani, Madhavan, and Gruver 2013), and after a campaign of many years it must be relined, which means rebuilding its worn heat-resistant inner lining, or shut. A works is large and feeds its own rolling and finishing mills, which shape the steel into sheet, bars, and other products. Steel made this way emits about 2.0 tonnes of CO_2 per tonne at a typical U.S. plant (Zang et al. 2023).

An electric arc furnace (EAF) melts steel scrap with electricity. A mill built around one needs no blast furnace, coke, or ore and can be small. Its emissions come mostly from the power plants that supply it, about 0.4 tonnes of CO_2 per tonne of EAF steel on average over 1985–2020 when each mill is charged the emissions of its state's power grid. It is also cheaper to build: in 2005 dollars, the cost estimates of CRU (2024) put the replacement cost of an EAF steelmaking shop, the furnace and the casters that solidify its steel, at $260 per tonne of capacity, and of a whole EAF mill with its rolling mills at $586.

Steel is sold as long products, the bars, rebar, wire rod, and shapes used mostly in construction, or as flat products, the sheet and plate used for cars, appliances, cans, and pipe. Within sheet, the more processed grades, cold-rolled, coated, and tin plate, command higher prices than plain hot-rolled sheet, the sheet as it leaves the hot rolling mill. Before 1989, integrated works made mostly sheet and EAF mills mostly long products (Collard-Wexler and De Loecker 2015). Scrap carries copper and other elements that cannot be

refined out and that the better sheet grades do not tolerate, and the rolling mill needed for sheet cost more than a small mill could afford. Thin-slab casting, which casts slabs thin enough to roll directly into sheet, brought that cost within reach of EAF mills from 1989, and the mills that make the better grades mix in iron made from ore to dilute the scrap's impurities (Peters 1991).

2.2 Capacity and adoption at old works

The shift to the EAF came mostly from new mills. Across the 166 sites of the panel, integrated steelmaking capacity, including that of works that also ran an EAF, fell from 72.7 million tonnes (Mt) in 1985 to 41.6 in 2020, and EAF capacity rose from 64.6 to 80.0. New EAF mills, built elsewhere and usually by other firms, took over the market of works that closed. As Figure 1 shows, the old works sat around the Great Lakes, Pittsburgh, and Ohio, while the new mills spread across the country, most of all into the South (Giarratani, Madhavan, and Gruver 2013), away from the capacity that closed.

Only three old works adopted the EAF between 1985 and 2020, and none of them replaced its blast furnaces in a single step (Figure 2, with the dates in Appendix A.4). Steubenville built an EAF beside blast furnaces that kept running, and Lorain and Fairfield replaced their blast furnaces with one. All three kept using the works' casters and rolling mills. In 1985, 5 works already ran an EAF beside their blast furnaces.

Steubenville, owned by Wheeling-Pittsburgh, added its EAF beside its two running blast furnaces, retired one of them when the EAF started, and kept the other until 2008. After the owner's Chapter 11 filing, a federal loan guarantee of $250 million, approved in 2003, supported financing that included a $110 million EAF, which tapped its first heat, its first batch of steel, in 2004 while steelmaking continued.[1] The blast furnaces closed only in 2008, and the EAF itself stood idle from 2010 to 2017 and ran again from 2018.

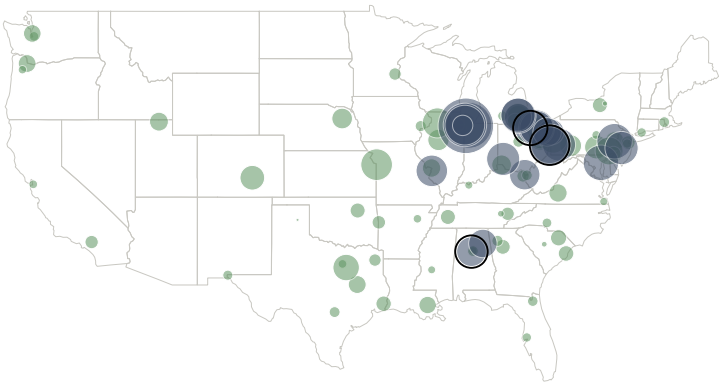
At Lorain and Fairfield, the EAF came after years without steelmaking. Lorain's owner, Republic Technologies, filed for Chapter 11 in 2001, and the Pension Benefit Guaranty Corporation (PBGC), the federal insurer of private pension plans, took over its pension plans in 2003. In 2005, Industrias CH bought the business and kept the blast furnaces running until steelmaking stopped in 2008, after which the works stood idle without closing. The owner decided to convert in 2011, and the EAF started in 2013, made bars, and stood idle from 2016 on. At Fairfield, U.S. Steel, solvent throughout, shut the blast furnaces in 2015, the year it announced the EAF, which started in 2020.

The integrated firms' annual reports agree with this record. In 306 annual reports of 23 integrated firms, fiscal years 1993–2024, no statement weighs adopting the EAF at an integrated works and rejects it, and no such plan predates Wheeling-Pittsburgh's. Integrated firms also built or bought little EAF capacity elsewhere: 14 cases over 1985–2021, most of them purchases (Appendix C.2).

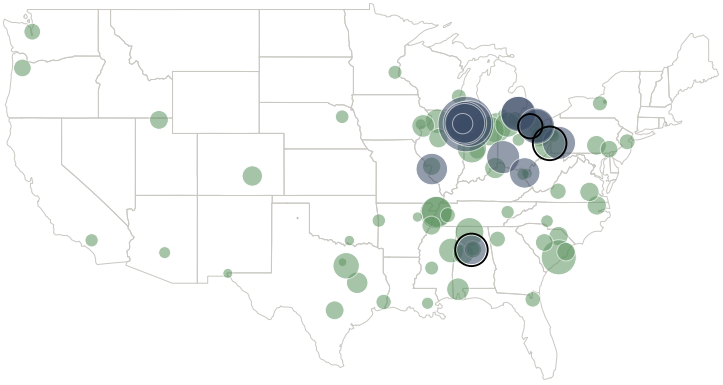
[1] In its annual report for 2004 the firm said the EAF would turn it into "a hybrid steel producer with characteristics of both an integrated producer and a mini-mill" (Wheeling-Pittsburgh Corporation 2005).

Figure 1: U.S. carbon-steel plants in 1985 and 2015

(a) 1985



(b) 2015



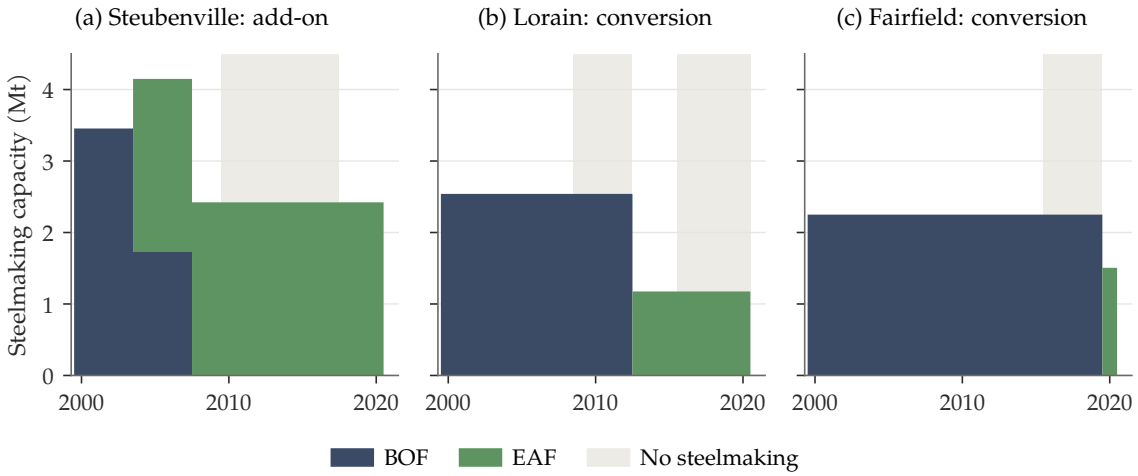
Notes: Carbon-steel sites in the estimation scope (126) in 1985 and 2015. Circle area is capacity, split into the BOF part and the EAF part, so a works with both shows two circles. BOF: basic oxygen furnace, the steelmaking furnace of an integrated works, fed with iron from its blast furnaces. EAF: electric arc furnace, which melts scrap with electricity.

2.3 Owners, obligations, and cleanup

The integrated firms owed their workers and retirees pensions beyond what their plans held, and retiree health care, while the firms that ran EAF mills, with younger workforces, owed little (Cooney 2002). Union plans such as Republic's entitled eligible workers to an immediate, unreduced pension when a facility shut down permanently, the shutdown benefits (United States Court of Appeals, Sixth Circuit 2004). A permanent shutdown could therefore bring part of these pension and retiree health obligations due, together with the shutdown benefits and the cleanup of the site. Closing a works or replacing its blast furnaces with an EAF shuts the blast furnaces for good, while adding an EAF beside running blast furnaces does not.

Over 1985–2014, the works of owners owing at least $50 per tonne of capacity carried on average $206 per tonne in unfunded pension and retiree health obligations, against $260 per tonne to build an EAF steelmaking shop. When the federal pension insurer

Figure 2: Capacity at the three adopting works



Notes: Steelmaking capacity, Mt a year, of the three integrated works that adopted the EAF, by route. (a) EAF built beside running blast furnaces. (b), (c) Blast furnaces replaced by an EAF. BOF: basic oxygen furnace, the steelmaking furnace of an integrated works, fed with iron from its blast furnaces. EAF: electric arc furnace, which melts scrap with electricity. No steelmaking: capacity stayed on the books.

sued to terminate the plan of Wheeling-Pittsburgh's parent, it argued that contingent plant-shutdown liabilities could exceed $378 million, a figure the parent disputed (WHX Corporation 2003), and at Republic, shutdown benefits could add about $95 million to plans already less than half funded (United States Court of Appeals, Sixth Circuit 2004).

The obligations differed across owners and changed with ownership while the same blast furnaces kept running. When an owner went bankrupt, the PBGC could take over its pension plans, though not its retiree health care. In the bankruptcies of 2002–2003 it took over the plans of LTV, Bethlehem, National, and Weirton (Pension Benefit Guaranty Corporation 2026). The International Steel Group, which bought the works of LTV and Bethlehem without the pension plans, carried $11 and $10 per tonne, against $544 and $1,038 before (Appendix C.4). Bankruptcy was also the usual setting for closure: of the 8 closures of integrated works in the sample, 7 came at or near a bankruptcy of the owner. Cleanup accruals were smaller. In the annual reports of 12 owners of integrated works, they average $9 per tonne of integrated capacity over works-years, a lower bound, and Appendix A.3 lists them by owner.

2.4 Plant-level data

I collected 39 editions of the plant directories of the Association for Iron & Steel Technology (AIST 2004–2022) and its predecessor, the Association of Iron and Steel Engineers (AISE 1983–2003), which list the steelmaking shops of U.S. plants with their owners and equipment, and digitized the printed editions. Their entries give one record per site and year, 6,401 site-years from 1984 to 2021, with each site's owner, furnaces, coke ovens, and finishing lines, as Appendix A describes.

The panel joins the directory record with the Steel Plant Capacity Reports of King (2025), which give each iron- and steelmaking furnace's opening, rebuild, and closing

years and its capacity. Where the two disagree, I check company filings, environmental reports, and the equipment roundups of the Iron & Steel Society and of the Association for Iron & Steel Technology (AIST 2007–2023; ISS 1988–2003). The result is 118 dated corrections, 91 of them from the directories or the roundups. Every carbon-steel site in the panel appears in at least two independent sources. The panel has 4,384 site-years at 166 sites, 1985–2020, with capacities in million metric tonnes and a year marked idle when the capacity stays on the books without production.

I then link each works to its owners. For each owner and year, the pension and retiree health obligations come from the notes to its 10-K filings and from Compustat (S&P Global Market Intelligence 2026b), the date on which the PBGC took over its plans from the PBGC's list of trusteed plans (Pension Benefit Guaranty Corporation 2026), the dates of its purchases and sales from completed deals (London Stock Exchange Group 2026; Moody's Analytics 2026), and, from 1993 on, its cleanup costs from the environmental accruals in its annual reports, which firms book only when they judge them probable. A firm's obligations are its pension plans' projected benefit obligation less plan assets, plus its retiree health obligation. Prices by product come from the Census reports on steel mill products, of which I extracted 27 editions from 1983 to 2010 (U.S. Census Bureau 1983–2010). Prices, costs, and obligations in the model and its estimates are in 2005 dollars, and amounts quoted directly from filings and announcements are nominal unless stated otherwise.

I study carbon-steel plants, which could replace an integrated works or be replaced by one, and leave out 40 specialty-steel, stainless, foundry, and forge shops, which sell in other markets. That leaves 126 sites, 26 integrated works and 100 EAF mills, whose plants and owners Appendix A.2 describes.

3 Descriptive Evidence

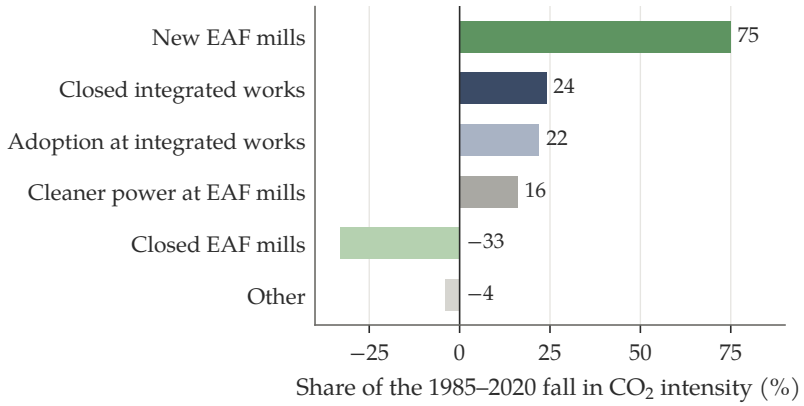
3.1 Sources of the emissions-intensity decline

The EAF share of U.S. crude steel rose from 34% in 1985 to 71% in 2020, while the rest of the world's share was 24% in both years (Appendix C.7). To see which plant decisions lowered emissions, I decompose the change in the capacity-weighted CO_2 intensity of the plants in the panel between 1985 and 2020 into four parts: new plants, closed plants, change at surviving plants, and shifts among them. The decomposition follows Olley and Pakes (1996), extended to entry and exit, and Appendix C.1 gives its formula and variants. A plant's intensity mixes its routes: 2.0 tonnes of CO_2 per tonne for integrated capacity, and for EAF capacity its direct emissions plus its electricity times the CO_2 factor of the state's power sector in that year (EIA 2025c, 2026c).

Intensity fell from 1.28 to 0.89 tonnes of CO_2 per tonne of capacity, by 31%, and Figure 3 decomposes this fall by channel. New plants, all of them EAF mills, account for 75% of the fall. Closures of the old works account for 24%, about a third as much.[2] The three works

[2]Closures of EAF mills have a negative share, −33%, because the mills that closed were cleaner than the 1985 average, not because closing them raised emissions. Together, the closures of both routes raised average

Figure 3: Decomposition of the fall in CO_2 intensity, 1985–2020



Notes: Shares of the 1985–2020 fall in the capacity-weighted CO_2 intensity of all plants in the panel, specialty and stainless shops included. Cleaner power: the fall in the grid factors of surviving EAF capacity. Grid factor: CO_2 per MWh of the power sector of the plant's state. Other: EAF shops closed at surviving works and shifts among surviving plants, rounded so that the shares add to 100. EAF: electric arc furnace, which melts scrap with electricity.

that adopted the EAF account for 22%, and surviving EAF mills on a cleaner grid for 16%. In electricity, new plants likewise account for 68% of the fall in the CO_2 intensity of generating capacity over 2001–2020 (Appendix E.4). Other forces that could have moved the industry, among them demand, imports, energy prices, and environmental regulation, are discussed in Appendix C.6.

3.2 Obligations and closure

Closures are far more frequent than adoptions, so I test whether obligations delayed closure. When a blast furnace needs relining, its owner chooses between relining it and closing it. I take the furnace-years in which a furnace at an integrated works of the estimation sample is due for relining, 1986–2015, and ask whether owners with larger obligations closed less often.

Larger obligations go with fewer closures. Among the furnace-years due for relining, the predicted chance of closing that year falls from about 4.5% at the lower quartile of gross obligations, before plan assets, to about 1.1% at the upper quartile, an odds ratio of 0.73 per $100 per tonne with a 95% interval from 0.59 to 0.88. For unfunded obligations, the odds ratio is 0.67, with a wider interval from 0.38 to 1.09 (Appendix C.4). Because obligations change within an owner mainly through bankruptcies, sales, and pension takeovers, which are themselves signs of distress, the estimates also control for the owner's bankruptcy state, balance sheet, and works, and compare years within the same owner, and the ratio stays below one in each, from 0.70 within owners to 0.82 with the controls. Being in bankruptcy predicts closure more strongly. Chapter 11 multiplies the odds of closing by 4.22 (2.00–8.82). The pattern is consistent with obligations delaying closure.

intensity (−9%).

4 Model

4.1 Plant decisions

A plant is a site i with steelmaking capacity K_i in tonnes a year (the subscript is dropped where clear). Throughout, t indexes years, a choices, y the segment (flat or long), and $r \in \{B, E\}$ the route (BOF or EAF). The site's *configuration* ζ records how its capacity is split between the routes. An integrated works ($\zeta = B$) has only blast furnaces, and an EAF mill ($\zeta = E$) only EAFs. Two hybrid configurations have both: a works that has added an EAF beside its blast furnaces (an *add-on*), and the legacy hybrids that ran an EAF beside their blast furnaces in 1985.

The owner of an integrated works can keep it running, add an EAF beside the running blast furnaces, convert it (shut the blast furnaces and build an EAF in their place), or close it. A hybrid can keep both routes, retire its blast furnaces, or close. An EAF mill keeps running or closes. An idle site holds, restarts, converts if integrated, or closes. Closing is permanent. Table 1 lists the choices and their one-time payoffs.

Three events arrive by chance. A blast furnace's lining wears out: with ν_{it} the campaign age of a works' main blast furnace (years since its last reline), a reline need arrives with probability $h^R(\nu)$ in each operating year. Keeping is then no longer open, and the owner relines (paying C^R per tonne of BOF capacity), adds an EAF, converts, or closes. An operating site is idled with probability h^I a year, paying C^I per tonne, and restarting costs C^S per tonne. An operating EAF configuration replaces a furnace with probability h^F_t a year, at C^F per tonne of its EAF capacity.

At the start of year t the owner observes the state and earns the year's flow payoff. An operating site is then idled, or a reline need arrives, with the probabilities above. The owner observes a shock to each choice open to it and chooses.

An add-on builds EAF capacity of a share κ_{add} of the works' capacity and keeps part of the blast furnaces running, and the EAF and the blast furnaces split the works' output. A conversion leaves a smaller EAF mill, of the share κ_{conv}, and retiring a hybrid's blast furnaces leaves its EAF. A conversion takes T^{conv} years to the first heat, with no steel meanwhile, and an add-on takes T^{add} years while the blast furnaces run. A configuration's capacity is denoted K, its EAF and BOF capacity K^{EAF} and K^{BOF}, and its BOF capacity at the works' effective rate, the smaller of BOF capacity and blast-furnace supply, K^{eff}.

The state of plant i in year t is $\omega_{it} = (n_{it}, z_t, t; x_i)$. The *node* n_{it} is the configuration ζ_{it} with whether the site operates, is idle, or is under construction (and in which year), and the campaign age ν_{it} of a works with a blast furnace. Owners do not know future steel margins: they expect today's margins to drift back toward their long-run means at the rates seen in the data. Formally, the price state z_t collects the deviations of the BOF flat, EAF flat, and EAF long national margin indices from their means and follows a stationary vector autoregression, discretized into a Markov chain (Appendix B.4). Calendar time t indexes the path of mean margins and costs over the years, held fixed after 2015, the last year the estimation uses. Owners know this path and forecast the deviations from it with the chain.

The characteristics x_i are the plant's capacity, its segment, its persistent cost, utilization, and product-mix terms, and the obligation level $L_f \in \{0, 0.5, 1\}$. The obligation level classes the owner f as having no, moderate, or large unfunded obligations per tonne of its capacity, and the owner takes these characteristics as given. When one of these characteristics changes in the data, for example when the PBGC takes over an owner's pension plans, the owner plans anew with the new value as if it were permanent. A run of years with unchanged characteristics is a *spell*.

The flow payoff $\pi_t(n, z)$ of an operating site, in dollars, is output q^r_{it} in tonnes times the net margin m^r_{it} in dollars per tonne of each route present, less three costs of particular configurations:

$$\pi_t(n,z) = q^B_{it}\, m^B_{it}(\zeta, z) + q^E_{it}\, m^E_{it}(\zeta, z) - \alpha\, o^B_t\, q^{\text{idle}}_{it} - C^A \max\{\nu - \bar{\nu}, 0\} K^{\text{BOF}} - h^F_t C^F K^{\text{EAF}}. \quad (1)$$

At an add-on hybrid the blast furnaces were built for the whole works, so the capacity the EAF leaves idle still costs labor and upkeep: a share α of the BOF non-material cost o^B_t on q^{idle}_{it}, the output it would produce. An old campaign costs C^A per tonne of BOF capacity for each year beyond a campaign length $\bar{\nu}$, and an EAF configuration without blast furnaces pays its expected furnace-replacement outlay. Each route runs its capacity at the route's national utilization rate U^r_t that year, scaled by the plant's persistent utilization factor U^{p}_i, so $q^B_{it} = U^B_t U^{\text{p}}_i K^{\text{eff}}$ and $q^E_{it} = U^E_t U^{\text{p}}_i K^{\text{EAF}}$.

The net margin of route r at plant i, what a tonne of its steel sells for less what it costs to make, cast, and roll, built in Appendix B from prices and costs, is

$$m^r_{it}(\zeta, z) = \mu^r_{yt} + z^r + C^{\text{mat},r}_i - o^r_t - C^{\text{down},r}_{yt} + p^{\text{mix},r}_{it}(\zeta), \quad (2)$$

where $\mu^r_{yt} + z^r$ is the national margin index of route r in segment y (its mean on that path plus the route's component of z), $C^{\text{mat},r}_i$ the plant's material-cost term, o^r_t non-material cost, $C^{\text{down},r}_{yt}$ the downstream cost of casting and rolling the steel into the base product (hot-rolled sheet for flat products, rebar for long products), and $p^{\text{mix},r}_{it}$ the price of the plant's own product mix over the base product. After an adoption, the new EAF cannot sell the works' whole mix: none of its output is tin plate, and at most a share $\bar{w}_t$ is cold-rolled or coated, the share of cold-rolled and coated products at EAF sheet mills in that period. The excess above the cap sells as hot-rolled sheet.

4.2 Payoffs and values

An add-on or a conversion pays the building cost I^C per tonne of new EAF capacity, in installments over construction. The works' casters, rolling mills, and site are reused.

As in Ryan (2012), shutting down capacity can carry a one-time cost. Here, shutting a works' blast furnaces brings two bills, its *shutdown costs*. The first is the owner's obligations to its workers and retirees, D^C on conversion and on retiring a hybrid's blast furnaces and D^X on closure:

$$D^C_{it}(\zeta) = \bar{\lambda}\, L_f\, K^{\text{BOF}}(\zeta), \qquad D^X_{it}(\zeta) = d_X\, D^C_{it}(\zeta), \quad (3)$$

where $K^{\text{BOF}}(\zeta)$ is the BOF capacity of the configuration and $\bar{\lambda}$ is the mean unfunded obligation per tonne of owners at $L_f = 1$. Closure pays D^X with $d_X = 1$, because the same obligations fall due whichever way the blast furnaces shut. An add-on pays nothing at the time, but its hybrid owes D^C on its remaining BOF capacity if it later retires the blast furnaces or closes. The second bill is site cleanup, $\mathcal{R}_{it}(\zeta) = C_{it}^{\text{rem}} K^{\text{BOF}}(\zeta)$, with C_{it}^{rem} the cleanup accrual per tonne. The obligations are transfers for the economy but costs to the owner, while the cleanup uses real resources. Only closing, converting, and retiring the blast furnaces pay them.

Converting brings the whole of D^C due, as closing does, because both shut the blast furnaces for good, the event that triggers the shutdown benefits (Section 2.3). Ownership and the owners' obligation levels follow the data, so an owner in Chapter 11 carries its obligation until the PBGC takes over its plans.

Closing pays S_{EAF}^X per tonne of EAF capacity and S_{BOF}^X per tonne of effective BOF capacity, before shutdown costs. A closure value is what closing is worth relative to running on, including scrap, land, and whatever the margins leave out, such as fixed operating costs. Every add-on and conversion also pays a fixed adoption cost ϕ_C, in dollars per adoption. It is what adopting the EAF costs or saves a works beyond the building cost, the forgone profit, and the shutdown costs, so its sign is not restricted. One ϕ_C applies to add-ons and conversions and to all works.

Each choice a also receives a shock $\sigma_i \varepsilon_{ait}$, with ε_{ait} independent type-I extreme value and σ_i, in dollars, the shock scale of the spell,

$$\sigma_i = \sigma K^{\text{med}} \left(\frac{\bar{K}_i}{K^{\text{med}}} \right)^{\rho}. \tag{4}$$

Here $\bar{K}_i$ is the capacity of the configuration in which the spell starts, its BOF part at the effective rate, and K^{med} is the median of $\bar{K}_i$ over the spells of the sample. The shock scale σ is in dollars per tonne at the median capacity, and ρ is the elasticity of σ_i with respect to capacity. When $\rho = 1$ the shock per tonne is the same at every size, and when $\rho < 1$ it falls with capacity. The shocks capture reasons for a choice that the data do not record, such as an offer from a buyer for the site or a manager's view of a project. They explain why the same plant in the same state can make different choices.

Let $V_t(n, z)$ be the value of a site at node n and price state z at the start of year t. A choice is worth its one-time payoff plus the discounted value of the node it leads to,

$$\begin{aligned} v_t(a \mid n, z) &= u_a(n) + \beta \, \mathbb{E}\left[V_{t+1}(n'(a), z') \mid z \right] \quad \text{for } a \neq \text{close}, \\ v_t(\text{close} \mid n, z) &= u_{\text{close}}(n), \end{aligned} \tag{5}$$

where $u_a(n)$ is the one-time payoff of Table 1, $n'(a)$ the node that follows a, z' next year's price state, and β the annual discount factor. Closing is worth its payoff alone, because a closed site has no future.

The value of facing the menu $\mathcal{A}$ of choices open at node n, before the shocks are seen,

Table 1: Choices, one-time payoffs, and the configuration that follows

Configuration	Choice	One-time payoff $u_a(n)$	Next year
Integrated works	Keep	0	Integrated works
	Reline	$-C^R K^{\mathrm{BOF}}$	Integrated works, $\nu = 0$
	Add-on	$-I^C \kappa_{\mathrm{add}} K - \phi_C$	Add-on hybrid
	Convert	$-I^C \kappa_{\mathrm{conv}} K - D^C - \mathcal{R} - \phi_C$	EAF mill after T^{conv} years
	Close	$S^X_{\mathrm{BOF}} K^{\mathrm{eff}} - D^X - \mathcal{R}$	Closed
Hybrid	Keep	0	Hybrid
	Retire	$-D^C - \mathcal{R}$	EAF mill
	Close	$S^X_{\mathrm{EAF}} K^{\mathrm{EAF}} + S^X_{\mathrm{BOF}} K^{\mathrm{eff}} - D^X - \mathcal{R}$	Closed
EAF mill	Keep	0	EAF mill
	Close	$S^X_{\mathrm{EAF}} K^{\mathrm{EAF}}$	Closed
Idle site	Hold	0	Idle site
	Restart	$-C^S K$	Operating
	Convert	As convert above	EAF mill after T^{conv} years
	Close	As close above	Closed

Notes: One-time payoff $u_a(n)$ of choice a at a node n of configuration ζ, in dollars, and the next year's configuration. A reline is open only when a reline need arrives. Retire: a hybrid shuts its blast furnaces and keeps its EAF. A conversion leaves an EAF mill of capacity $\kappa_{\mathrm{conv}} K$. Among idle sites, only an integrated works can convert, and a restart returns an idle site to its operating configuration. K, K^{EAF}, K^{BOF}: site, EAF and BOF capacity, and K^{eff} the effective BOF capacity. C^R, C^S: reline and restart cost per tonne. ν: years since the last reline. I^C: building cost per tonne of new EAF capacity. κ_{add}, κ_{conv}: EAF capacity of an add-on and of a conversion, as shares of K. T^{conv}: years to a conversion's first heat. ϕ_C: fixed adoption cost. D^C, D^X: obligations due on shutting the blast furnaces and on closure. $\mathcal{R}$: site cleanup. S^X_{EAF}, S^X_{BOF}: closure values per tonne. BOF: basic oxygen furnace, the steelmaking furnace of an integrated works, fed with iron from its blast furnaces. EAF: electric arc furnace, which melts scrap with electricity.

is the expected value of the best choice, shock included. With logit shocks, this value is

$$\bar{v}_t(\mathcal{A} \mid n, z) = \sigma_i \Big(\gamma + \log \sum_{a \in \mathcal{A}} \exp\big(v_t(a \mid n, z)/\sigma_i\big) \Big), \tag{6}$$

where γ is Euler's constant.

Let $\mathcal{A}^{\mathrm{reg}}(n)$ be the regular choices of an operating node and $\mathcal{A}^{\mathrm{arr}}(n)$ the choices at a reline arrival. The value of an operating site at the start of year t is

$$\begin{aligned} V_t(n, z) = \pi_t(n, z) &+ h^I \big(-C^I K + \beta\, \mathbb{E}[V_{t+1}(n^{\mathrm{idle}}, z') \mid z] \big) \\ &+ (1 - h^I) \Big(h^R(\nu)\, \bar{v}_t\big(\mathcal{A}^{\mathrm{arr}}(n) \mid n, z\big) + \big(1 - h^R(\nu)\big)\, \bar{v}_t\big(\mathcal{A}^{\mathrm{reg}}(n) \mid n, z\big) \Big), \end{aligned} \tag{7}$$

where n^{idle} is the idle node of the same configuration and $h^R = 0$ without a campaign clock. In words, a running site earns this year's profit. It is then idled by chance with probability h^I. Otherwise the owner chooses from the menu open that year: the reline menu if a reline need has arrived, the regular menu if not. Within a menu $\mathcal{A}$, the probability that the owner chooses a is the logit

$$\Pr_t(a \mid \mathcal{A}, n, z) = \frac{\exp\big(v_t(a \mid n, z)/\sigma_i\big)}{\sum_{a' \in \mathcal{A}} \exp\big(v_t(a' \mid n, z)/\sigma_i\big)}. \tag{8}$$

The full state, the chance events, the values of idle and construction nodes, the solution, the likelihood, and the parameter values with their sources are in Appendix D.

4.3 Entry and prices

In each decision year $t = 1985, \ldots, 2013$ and segment y, a pool of $\bar{N}$ potential entrants each consider one EAF mill, which produces after T^{ent} years. A project's capacity is $K = K_y^{\text{ent}}$, the mean capacity of the observed entrants of its segment. The value of entry per tonne, before the entry cost, is

$$V_y^{\text{ent}}(t, K) = -I^C + \frac{\beta^{T^{\text{ent}}}}{K} \mathbb{E}_t \mathbb{E}_{U^{\text{P}}} \left[V_{t+T^{\text{ent}}}(n^E, z') \right], \tag{9}$$

where V is the value in Equation (7) of an operating EAF mill n^E of the segment, with no obligations, the entrants' product mix, and the furnace-replacement outlay, and $\mathbb{E}_t$ averages over the price state. The expectation $\mathbb{E}_{U^{\text{P}}}$ averages over utilization factors drawn from observed entrants in the joint estimate, while the baseline entry estimate and the policy experiments set this factor to one.

A potential entrant builds if this value exceeds its entry cost, F_y^{ent} in 2000, the middle of the period studied, with a trend of τ a year, $F_y^{\text{ent}} + \tau(t - 2000)$, plus a logistic shock of scale $\sigma_{\text{ent},y}$ per tonne. The entry cost covers what a new mill needs beyond the steelmaking shop and other barriers to entry. The trend τ absorbs the diffusion of thin-slab casting and the falling number of good sites. With Λ the logistic distribution function, the probability $\Pr_y^{\text{ent}}(t)$ that a project enters is

$$\Pr_y^{\text{ent}}(t) = \Lambda\Big(\frac{V_y^{\text{ent}}(t, K_y^{\text{ent}}) - F_y^{\text{ent}} - \tau(t - 2000)}{\sigma_{\text{ent},y}} \Big). \tag{10}$$

Per tonne, the entrants' shock has the scale of a plant's at that size. The logit entry probability follows Collard-Wexler (2013) and the construction lag Kalouptsidi (2014).

When a policy changes domestic output by ΔX_{yt}, the price of segment y moves along the net demand facing U.S. producers, with slope the denominator of

$$\Delta p_{yt} = -\frac{\Delta X_{yt}}{\left(\eta_y^d Q_{yt} + \eta_y^m M_{yt}\right) / p_{yt}}, \tag{11}$$

where p_{yt} is the segment's price, Q_{yt} apparent consumption (domestic shipments plus imports less exports), M_{yt} imports, η_y^d the demand elasticity, and η_y^m the import-supply elasticity (Appendix C.5). Extra domestic steel has to be absorbed by buyers buying more and by imports falling, so the price falls less when demand and imports respond more to price.

In the policy experiments, prices respond to the plants' and entrants' choices. A grant changes how much steel is made, and the resulting prices change who adopts, closes, and enters. Plants and entrants foresee this price path, which shifts every margin one for one, but not the random swings in margins around it. The experiment finds the price path

that is consistent with the output it produces. Estimation needs no such step, because the observed prices already reflect every plant's and entrant's choices. Owners therefore take them as given and expect them to follow the estimated chain.

4.4 The adoption gap

For an operating integrated works i at node n in year t and price state z, and for $a \in \{\text{add-on}, \text{convert}\}$, the *adoption gap* is

$$\Gamma_{it}(a) \equiv \max\{v_t(\text{keep} \mid n, z),\, v_t(\text{close} \mid n, z)\} - v_t(a \mid n, z), \tag{12}$$

the one-time payment, in dollars, that would make choice a worth as much to the owner as the better of keeping and closing the works, before shocks. I report it per tonne of site capacity. The adoption gap compares the whole future of each choice. Keeping includes the blast furnaces' remaining profits and the option to close later. Converting includes the years without steel, the smaller shop, and the cap on its high-end products.

I group the parts of the adoption gap into three categories. I report their shares with the estimates, net of two pieces unrelated to adoption. The *price of the technology* is what the new furnace costs and can make: the building cost, the size of the shop, and the cap on its high-end products, which a new mill faces too. The *forgone profit* is what the running blast furnaces still earn, which only an old works gives up by adopting. The *structural frictions* are specific to adopting at an old works: the shutdown obligations and the fixed adoption cost.

5 Estimation and Results

5.1 Identification and estimation

Of the 126 carbon-steel sites, 122 operate in at least one year of 1985–2014, which gives 2,763 decision years, each with its outcome read from the following year (through 2015), and the decisions of 2015 to 2019 are held out. Table 2 counts the events: 36 closures, 1 add-on (Steubenville, decided in 2003), 1 conversion (Lorain, decided in 2011), and the entry of 24 new EAF mills.

I estimate the plant model by maximum likelihood with a nested fixed point (Rust 1987). For each candidate $\theta = (\phi_C, \sigma, \rho, S^X_{\text{EAF}}, S^X_{\text{BOF}})$, the model is solved for every plant, and each decision contributes the probability of the observed choice, which mixes the logit of Equation (8) over the menus because relines and idling are chance events. The plant log likelihood sums over the 2,760 decisions at 122 sites,

$$\ell^P(\theta) = \sum_i \sum_t \log \Pr\big(a_{it} \mid n_{it}, z_t, t; \theta\big). \tag{13}$$

A new mill is the plant model's EAF mill, so entry and the plants' choices share the shock scale, the discount factor, the price process, and the value of a mill. Each of the $\bar{N}$ potential entrants of a segment and year enters with probability $\Pr^{\text{ent}}_y(t)$, so with N_{yt} the

Table 2: Estimation sample and events, decisions 1985–2014

	Sample			Events				
Configuration	Years	Sites	Idle	Closed	Added	Converted	Retired	Entered
Integrated works	518	21	11	6	1	1	–	–
Legacy hybrids	81	5	0	2	–	–	0	–
Add-on hybrids	4	1	0	0	–	–	1	–
EAF mills	2,160	100	19	28	–	–	–	24
All	2,763	122	30	36	1	1	1	24

Notes: Carbon-steel sites in the estimation scope. Years: plant-years, decisions 1985–2014, each with its outcome in the next year. Idle: years with capacity on the books and no output, counted as decisions to keep. Closed, Added, Converted: closures, add-ons, and conversions. Retired: a hybrid retires its blast furnaces. Entered: new EAF mills that began operating in 1987–2015, 13 flat-product and 11 long-product, the observations of the entry model. Add-on hybrids: works after an add-on. Sites: a site that changes configuration counts in each row it passes through, so the rows sum to more than the last row, which counts distinct sites. –: not open to the configuration. EAF: electric arc furnace, which melts scrap with electricity.

observed entries in segment y and year t, the entry log likelihood is the binomial

$$\ell^{\text{ent}}(\theta, F^{\text{ent}}, \tau) = \sum_{y} \sum_{t} \log\Big[\binom{\bar{N}}{N_{yt}} \Pr_{y}^{\text{ent}}(t)^{N_{yt}} \big(1 - \Pr_{y}^{\text{ent}}(t)\big)^{\bar{N} - N_{yt}} \Big], \tag{14}$$

over the 24 entries of new mills into the sample's scope (13 flat, 11 long), and the joint log likelihood ℓ is

$$\ell(\theta, F^{\text{ent}}, \tau) = \ell^{P}(\theta) + \ell^{\text{ent}}(\theta, F^{\text{ent}}, \tau), \qquad \sigma_{\text{ent},y} = \sigma \Big(\frac{K_{y}^{\text{ent}}}{K^{\text{med}}} \Big)^{\rho - 1}. \tag{15}$$

The entrants' decisions after entry are already plant decisions in ℓ^{P}, so nothing is counted twice. The entrant's shock per tonne is the plant model's at the entrant's capacity K_{y}^{ent}, the mean capacity of the observed entrants of segment y, and ρ is held at the plant model's estimate. The baseline estimate maximizes ℓ^{P} over θ, so that the plant parameters rest on what owners did, and then ℓ^{ent} over the entry costs given those parameters. The joint estimate maximizes ℓ. The entry costs rest on how many mills entered in each segment and year, given what a new mill was then worth. How often mills entered fixes each segment's level, and whether entry at a given worth rose or fell over the years fixes the trend.

The entries say little about the size of the pool apart from the entry cost, because a larger pool facing a higher entry cost predicts nearly the same entries. When each project's chance of entering is small, predicted entries depend, to a close approximation, only on $F_{y}^{\text{ent}} - \sigma_{\text{ent},y} \log \bar{N}$. As in Igami (2017), the pool must be at least as large as the most entries in a segment and year, 3 in the data. I fix it at $\bar{N} = 10$ and state the entry costs for this pool.

The 29 closures of EAF mills inform σ and S_{EAF}^{X}, because their margins vary across years and segments. How strongly closures respond to margins shows the scale of the shocks, and how often mills close at given margins shows what closing is worth. The

8 closures of integrated works and hybrids inform S^X_{BOF} in the same way, given the shutdown obligations. Closures by size inform ρ: most integrated works are above the median capacity and most EAF mills below it.

The fixed adoption cost rests on the choices to adopt, given the shock scale that the closures pin down. What adopting would have earned varied across works and years with steel margins, the works' size, and the owner's obligations. At that scale, the many years in which works could have adopted and did not bound ϕ_C from below, and the 2 adoptions bound it from above, less tightly. With 2 adoptions, I estimate one ϕ_C for both forms of adoption, which still differ in their building costs, forgone profits, and obligations.

Choice data alone do not identify the discount factor without further restrictions on payoffs (Magnac and Thesmar 2002; Rust 1994). A higher β raises the value of keeping a works running, and the model answers with larger closure values and a larger ϕ_C. I chose β by a rule fixed before estimation. On a grid of values, a value counts as plausible if both closure values (for integrated works, net of the obligation scale) lie within a factor of 3 of the median price buyers paid for going plants of that kind, which Appendix C.3 reports. Only $\beta = 0.85$ passes. Below it the closure value of EAF mills is negative, above it that of integrated works net of the obligations exceeds three times the median price. Dynamic models of industries fix values from 0.8 a year (Igami 2017) to about 0.95 (Collard-Wexler 2013; Kalouptsidi 2014), and the cost estimates of Igami (2017) also rise with the discount factor (Appendix D.4.1).

5.2 Parameter estimates

Two adoptions in three decades require a large fixed adoption cost. The owners' choices put it at $\phi_C = \$0.77$ billion per adoption, about \$414 per tonne of new EAF capacity, on top of the \$260 per tonne building cost of the EAF shop, the forgone profit, and the obligations. As the cost that rationalizes the observed choices, it is the average net cost of adopting beyond what the model prices.

A likelihood-ratio test rejects a model without a fixed adoption cost (p-value 0.002), so the priced costs alone do not explain why so few works adopted. The two adoptions bound its size only loosely. The profile interval in Table 3 runs from \$0.19 to \$1.97 billion (\$101 to \$1063 per tonne). Because the plants of one firm may share shocks, I also resample whole firms with their plants, a pairs cluster bootstrap (Cameron and Miller 2015), and re-estimate the model in each draw. Over all draws, the percentile interval runs from \$0.42 to \$12.3 billion, wide at the top because the 11 draws without an adoption yield very large cost estimates. Among the 89 draws with an adoption, it runs from \$0.40 to \$1.83 billion. In both, its lower end stays above zero (Appendix D.4.3).

Two further checks ask how much two adoptions can tell. A Monte Carlo experiment simulates 200 panels from known parameters, at a design point calibrated to the observed numbers of closures and adoptions, and re-estimates the model on each. The median estimate is \$0.049 billion above the true value of \$0.67 billion. The 95% interval contains the true value in 91.5% of the panels and in 96% of the 50 panels with two adoptions, as in

Table 3: Estimates of the plant model and of entry

	Baseline estimate	Joint estimate with entry
Plant model		
Fixed adoption cost ϕ_C, \$ billion per adoption	0.77 [0.19, 1.97]	0.72 [0.19, 1.77]
per tonne of new EAF capacity, \$	414 [101, 1063]	391 [101, 959]
Shock scale σ, \$ per tonne at median capacity	158 (49)	154 [109, 229]
Elasticity of σ_i to capacity ρ	0.59 (0.20)	0.59[a]
Closure value, EAF mill S^X_{EAF}, \$ per tonne	96 (84)	100 (53)
Closure value, integrated works S^X_{BOF}, \$ per tonne	475 (47)	476 (46)
Entry		
Entry cost, flat-product mill $F^{\text{ent}}_{\text{flat}}$, \$ per tonne	–	805 [570, 1204]
Entry cost, long-product mill $F^{\text{ent}}_{\text{long}}$, \$ per tonne	–	1059 [765, 1556]
Trend in entry costs τ, \$ per tonne a year	–	13.7 [6.3, 23.5]

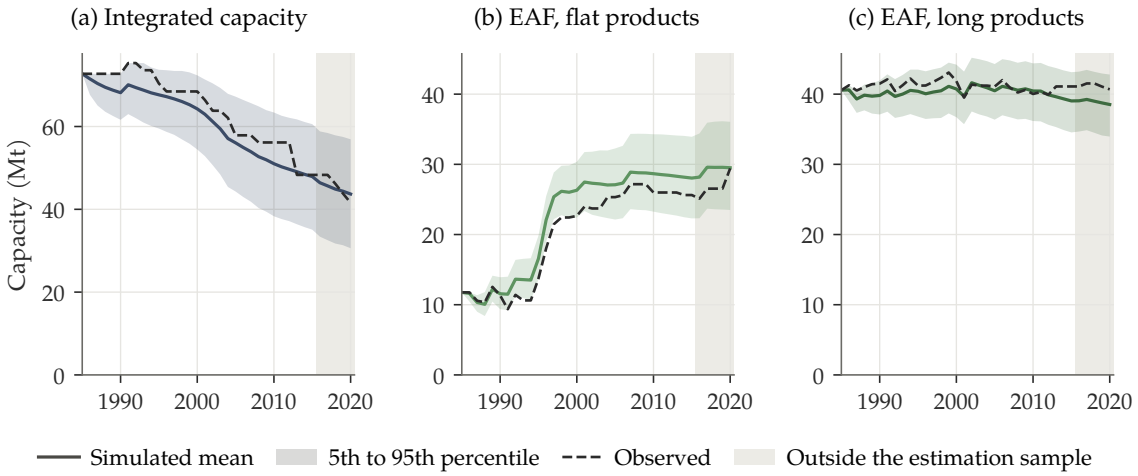
Notes: Maximum-likelihood estimates at the annual discount factor $\beta = 0.85$, in 2005 dollars. Baseline estimate: the plant model estimated on the plant decisions alone, and entry given its parameters. Brackets: 95% profile-likelihood intervals, reported for ϕ_C, whose likelihood is asymmetric with two adoptions, and for the joint estimate's shock scale and entry parameters. Parentheses: standard errors. σ_i: shock scale of plant i, with σ at the median capacity of 1.06 million tonnes. Fixed adoption cost per tonne: over the new EAF capacity of an adoption, 1.85 Mt on average. S^X_{BOF}: per tonne of effective BOF capacity. τ: trend from 2000. The joint estimate fits entry and the plant model together, with the entrants' shock scale σ_{ent} tied to σ. [a]Held at the baseline estimate: the entrants' shock scale is the plant model's at the entrants' mean capacity. Log likelihood of the plant decisions: -398.90 at the baseline. The joint estimate lowers it by less than 0.01 and adds an entry log likelihood of -46.41. Observations: 2,760 plant decisions and 24 entries. –: not in the model or not estimated. BOF: basic oxygen furnace, the steelmaking furnace of an integrated works, fed with iron from its blast furnaces. EAF: electric arc furnace, which melts scrap with electricity.

the data. In panels simulated from the model estimated with $\phi_C = 0$, the likelihood-ratio test of $\phi_C = 0$ rejects in 6.5% of 200 at the 5% level, and none yields a statistic as large as the observed 9.27. In panels simulated at the estimate itself, the 95% interval contains the true value in 94% of them and in all 54 with two adoptions (Appendix D.4.2). Leaving out one of the two adoptions raises the estimate and above all the upper end of the interval, to \$0.98 and \$2.52 billion without Lorain's conversion, because a single adoption limits the cost less from above (Appendix D.4.5).

At the median capacity, the shock scale is $\sigma =$ \$158 per tonne, so a \$100 per tonne rise in the value of a choice multiplies its odds by about 1.9 there, and the shock per tonne falls with capacity ($\rho = 0.59$, and a likelihood-ratio test rejects $\rho = 1$ with p-value 0.027). The choices of large integrated works therefore follow their payoffs more closely than those of small EAF mills. Closing is worth \$96 per tonne of an EAF mill and \$475 per tonne of effective BOF capacity at an integrated works, before shutdown costs. Besides scrap and land, the larger value can reflect fixed operating costs that closing an integrated works avoids and the margins leave out.

Beyond the steelmaking shop, entry cost \$805 per tonne for a new flat-product mill and \$1059 for a long-product mill in 2000, rising by \$13.7 per tonne a year (a likelihood-ratio test rejects a constant entry cost, p-value <0.001). A new flat-product mill therefore costs about four times its steelmaking shop. Freeing the entrants' shock scale gives 0.43 times the plant model's, and a likelihood-ratio test does not reject the tie (p-value 0.35), which

Figure 4: Observed and simulated capacity



Notes: Installed steelmaking capacity, idle capacity included, Mt, at the carbon-steel sites of the estimation scope. EAF capacity at integrated works counts with the works' product. Simulated: mean and 5th to 95th percentiles over 4,000 histories of the plant model without policy, from the 1985 state, with new mills entering when they did. Outside the estimation sample: 2016–2020, with inputs extended to 2020. EAF: electric arc furnace, which melts scrap with electricity.

anchors the entrants' response to profits in the plants' many choices rather than in 24 entries. The joint estimate leaves the plant parameters nearly unchanged, and the policy experiments use the entry costs estimated given the plant model, \$830 and \$1089 per tonne with a trend of \$14.0 a year, inside the joint intervals of Table 3.

On the observed state paths the model replicates the closures (Appendix D.4.6), 27.0 of EAF mills against 29 observed and 7.1 of integrated works and hybrids against 8, and the number of adoptions, 1.8 against 2, most of them as add-ons, the cheaper form at the estimate (1.7 add-ons and 0.1 conversions against one each). In the held-out decisions of 2016–2019 it expects 2.3 closures of EAF mills against 2 and 0.3 conversions against 1. The model matches the total number of entries, and Figure 4 compares the capacity it simulates from 1985 with the observed capacity.

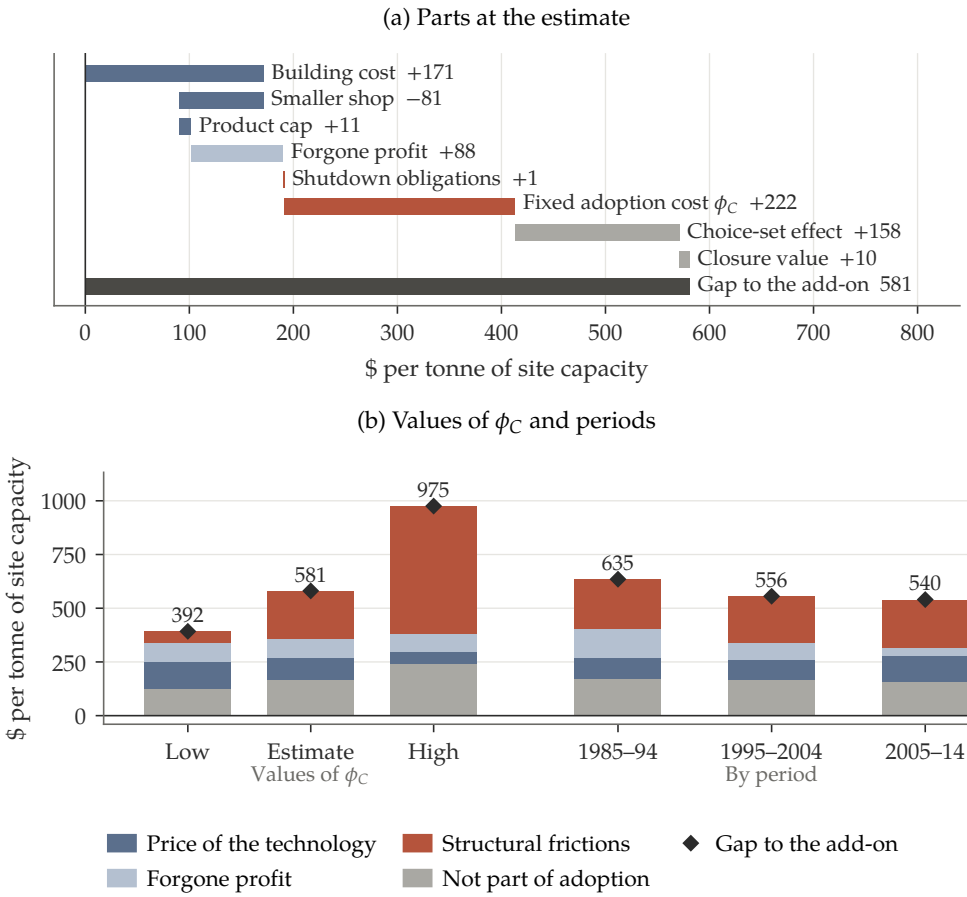
5.3 Decomposition of the adoption gap

The adoption gap of Section 4.4 has seven parts that can be switched off: the building cost, the forgone profit, the shutdown obligations, the smaller shop, the product cap, the fixed adoption cost, and the closure value. Because the parts interact, I use a Shapley decomposition. The part $c_{it}^{k}(a)$ is the effect on the adoption gap of switching part k on, with the model solved again at the estimated parameters, averaged over all orders (Shorrocks 2013). With $b_{it}(a)$ the adoption gap with every part switched off, the parts add up exactly:

$$\Gamma_{it}(a) = b_{it}(a) + \sum_{k=1}^{7} c_{it}^{k}(a). \tag{16}$$

Two pieces are not part of adoption and are netted out. For the add-on, the first piece, $b_{it}(a)$, comes only from the logit. Each choice carries its own shock, so a works that keeps

Figure 5: Decomposition of the adoption gap



Notes: Shapley decomposition of the add-on's adoption gap, the one-time payment that would make building an EAF beside the running blast furnaces as good to the owner as the better of keeping and closing, dollars per tonne of site capacity, mean over the 507 works-years of running integrated works with an observed decision, 1985–2014. Choice-set effect: the value of keeping more choices open, each with its own shock. (a) Parts at the estimate, among them the fixed adoption cost ϕ_C. (b) Parts at the low end, at the estimate, and near the high end of the 95% interval for ϕ_C, and at the estimate by decision period. EAF: electric arc furnace, which melts scrap with electricity.

more choices open each year is worth more for that reason alone. The second, the closure value, belongs to closing. I report the remaining parts as shares of this *net gap*, in the model's three categories: the price of the technology, the forgone profit, and the structural frictions. The shares are means over the 507 works-years in which a running integrated works made an observed decision in 1985–2014.

Figure 5(a) decomposes the mean gap to the add-on, $581 per tonne of site capacity. Netting out the $168 that is not part of adoption leaves $413. At the estimate, the priced costs explain less than half of it. The price of the technology is $102 per tonne (25%): the building cost of $171, less $81 because the add-on shop is smaller than the works, plus the product cap. The forgone profit is $88 (21%). The structural frictions are the rest, $223 or 54%, almost all of it the fixed adoption cost. The frictions are 20% of the net gap at the lower end of the interval for ϕ_C and 81% near the upper end, and at the lower end the gap is still $392 per tonne, more than twice the building cost. The building cost is supplied from outside, but its part of the adoption gap is computed in the model and depends on

the estimated parameters too.

The gap to the add-on is smaller than the gap to convert in every works-year. The means and shares at the lower end and near the upper end of the interval and by period are in Appendix D.4.4. Under the model's assumption that converting brings the shutdown obligations due, they add $134 per tonne to the gap to convert, 20% of its net gap. They add little to the gap to the add-on, which leaves the blast furnaces running and pays nothing when it is built. The obligations therefore steer owners to the add-on rather than away from the EAF.

The forgone profit fell from $131 per tonne in 1985–94 to $81 in 1995–2004 and $41 in 2005–14, as the flat-product margins of integrated works fell toward those of EAF mills. The gap to the add-on fell by about as much, from $635 to $540. Both observed adoptions came after the first period.

The fixed adoption cost ϕ_C is an average across works. Candidates for what it covers are the stranding of the works' own ore mines and coke batteries when the blast furnaces stop, the time customers take to approve steel from the new shop, and permitting, if adding an EAF counts as a major modification that brings an old works under the stricter rules for new sources, which deter such changes at old plants (Stavins 2006). It is also net of the benefits of keeping an old site's customers and permits.

5.4 Robustness

Across modeling choices, the fixed adoption cost moves mainly with the assumptions about EAF margins, and upward. A better margin for an EAF at an old works makes adopting more attractive, so a larger cost is needed to explain why so few works adopted. I re-estimate the model with one setting changed at a time (Appendix D.4.5). Settings that raise that margin, pricing what the EAF melts at the prices of scrap and pig iron (solid blast-furnace iron) or adding $40 or $80 per tonne to the EAF flat margin, put ϕ_C between $1.25 and $2.02 billion. Higher finishing costs for long products, alone or with plate, and counting the obligations before plan assets raise it to between $1.21 and $1.43 billion, because they imply larger shocks. Larger shocks make choices respond less to costs, so the same reluctance to adopt takes a larger cost to explain. The margin and finishing-cost settings fit the choices worse than the baseline, and only the $80 shift takes ϕ_C outside the baseline's interval. Every other setting and assumed value keeps it between $0.51 and $0.99 billion.

The decomposition of Section 5.3 holds in each of the nine re-estimates for which I recompute it. The fixed adoption cost remains more than half of the net gap, so the priced costs explain less than half, and the gap to the add-on stays below the gap to convert. Where the obligations are counted net of plan assets, they add $132 to $136 per tonne to the gap to convert and little to the gap to the add-on.

6 Policy Counterfactuals

6.1 Instruments at equal abatement

I compare grants that pay for new EAF capacity under different eligibility rules, and use a carbon price as the benchmark. Beyond the CO_2 externality, which a carbon price corrects directly, a grant for adoption needs a market failure in investment itself to be the better instrument (Allcott and Greenstone 2012).[3]

Every policy starts in 1985, is expected to be permanent, and is foreseen by plants and entrants. It is compared with the model's path without policy, the *baseline*, which gives 1.56 adoptions in 1985–2014 against 2 observed.[4] I count CO_2 avoided over 1985–2015 as the fall in domestic emissions plus the emissions of the imports a policy displaces, at 1.2 tonnes per tonne of imported steel, midway between the two routes. I compare all policies at one abatement target, 311 Mt of CO_2, the abatement that a carbon price of $21.3 per tonne would have bought in the baseline, whose plants emit 3,374 Mt over 1985–2015. That is the carbon price that, with EAF technology and input prices held at their 1985 levels as in Appendix E.1, would have kept emissions at the level of the baseline, and I use it to set one common target.

The *open grant* pays a level per tonne of new EAF capacity to every new mill and every old works that builds it. The *adoption grant* pays only old works that add an EAF or convert, and the *conversion grant* pays only old works that convert, building the EAF and retiring the blast furnaces in one decision.[5] Four other instruments complete the comparison: a *conditional grant*, paid once per tonne of EAF capacity at an old works, but only when the works retires its blast furnaces, at once or later; a *site-retention grant*, paid each year per tonne of EAF capacity running at an old works; an *obligation takeover*, in which a public fund pays a share of the shutdown obligations when they fall due; and the *carbon price*, on both routes. Each grant pays on every qualifying tonne, including those that would have been built without it.

For a grant of level G per tonne, let K^0 be the qualifying capacity in the baseline, ΔK the capacity the grant adds, and ΔCO_2 the CO_2 it avoids. Public spending per tonne of CO_2 avoided is

$$C^G = \frac{G\,(K^0 + \Delta K)}{\Delta CO_2} = \frac{G\,\Delta K}{\Delta CO_2} \cdot \frac{1}{1-\iota}, \qquad \iota = \frac{K^0}{K^0 + \Delta K}. \tag{17}$$

Here ι is the *non-additional share*, the share of the payments made for investment that would have happened anyway, and $G\,\Delta K/\Delta CO_2$ is the payment per tonne of CO_2 for the investment the grant adds. Spending per tonne is low when the qualifying plants respond strongly to the grant, when each added tonne of capacity avoids much CO_2, and when the

[3] Comparisons of instruments at a given emissions target find that an emissions price reaches it at a lower welfare cost than subsidies for clean electricity (Abrell, Rausch, and Streitberger 2019; Fischer and Newell 2008).

[4] The baseline's counts are means over 2,000 simulated histories, the same draws as for each policy.

[5] Like the grants here, the up-front subsidies that Butters, Dorsey, and Gowrisankaran (2025) evaluate for battery storage pay for new capacity when it is built, as a share of its capital cost. In their equilibrium model of the California electricity market, the option value of waiting for cheaper capital delays adoption.

Table 4: Cost-effectiveness at equal abatement

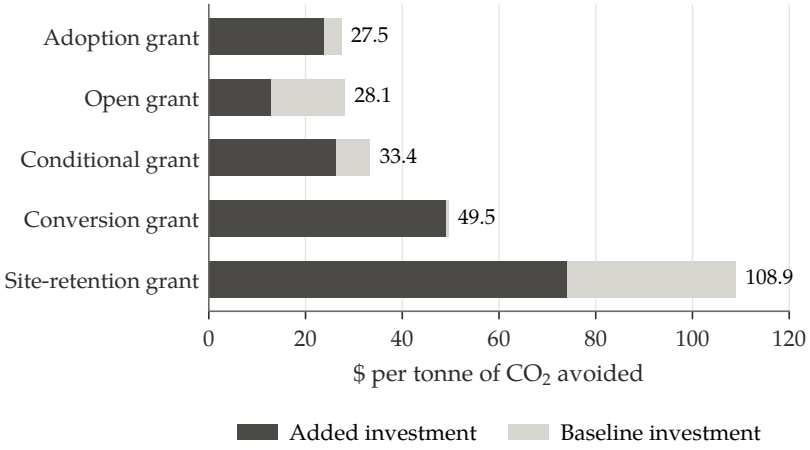
	Grants						
	Open	Adoption	Conversion	Conditional	Retention	Takeover	Carbon price
A. Abatement and response							
CO_2 avoided (Mt)	311	311	311	311	311	(188)	311
Policy rate	137	351	1,098	416	64	(100)	21
Unit	\$/t	\$/t	\$/t	\$/t	\$/t a year	%	\$/t CO_2
CO_2 per added tonne (t)	11	15	22	16	–	–	–
Extra adoptions	+1.9	+8.9	+8.0	+4.7	+8.8	(0.0)	+1.2
Extra entries	+18.3	+0.6	+2.8	+3.3	−0.5	(+4.6)	+5.9
B. Public spending (\$ per tonne of CO_2)							
Budget per tonne	28.1	27.5	49.5	33.4	108.9	(22.5)	–
Share ι (%)	54	13	1	21	32	–	–
Added investment	12.8	23.8	49.0	26.4	74.1	–	–
C. Welfare (\$ per tonne of CO_2)							
Welfare cost	−29.0	21.4	15.3	−7.4	24.6	(−5.7)	5.6
Without shocks	98.8	89.1	87.2	77.2	86.5	(41.6)	49.0
Break-even value	−29.3	22.6	19.8	−5.2	26.0	(−5.9)	6.2
Without shocks	114.8	98.5	97.7	85.7	95.2	(46.6)	54.7

Notes: Each instrument at the level that avoids 311 Mt of CO_2 over 1985–2015. Open grant: paid for new EAF capacity at new mills and old works. Adoption grant: paid to old works that add an EAF or convert. Conversion grant: paid to old works that convert. Conditional grant: paid once per tonne of EAF capacity at an old works, when the works retires its blast furnaces. Site-retention grant: paid each year per tonne of EAF capacity running at an old works. Obligation takeover: a public fund pays a share of the shutdown obligations when they fall due. Carbon price: per tonne of CO_2 on both routes. Policy rate: in the unit below it, \$/t per tonne of new EAF capacity, \$/t a year per tonne of EAF capacity a year, % of the obligations, \$/t CO_2 per tonne of CO_2. Parentheses: the takeover at its largest level, short of the target. CO_2 per added tonne: tonnes of CO_2 avoided over 1985–2015 per tonne of qualifying EAF capacity the grant adds, not defined for the site-retention grant, which pays per year. Extra adoptions and entries: changes from the baseline without policy. Budget per tonne: grants paid over CO_2 avoided, undiscounted. Share ι: the non-additional share, the share of the payments made for investment that would happen without the grant. Added investment: the budget times $(1 - \iota)$. Welfare cost: the loss of steel buyers, U.S. plants and entrants, and the government per tonne of CO_2 avoided, before the value of CO_2, undiscounted, with and without the choice shocks in producer surplus. Break-even value: the social cost of carbon at which net welfare, discounted at 2%, is zero. –: not defined (the carbon price pays no grants, and the takeover pays obligations, not investment). EAF: electric arc furnace, which melts scrap with electricity.

non-additional share is small. For an agency with a fixed budget, it is the relevant cost: the cheaper each tonne, the more abatement the budget buys. It is the government cost per ton of Hahn et al. (2026), counting grants only, and likewise separates the payments to recipients who would have acted anyway.

Table 4 compares the instruments at the abatement target, and Figure 6 splits the grants' spending. Restricting eligibility cuts the non-additional share from 54% under the open grant to 13% under the adoption grant and 1% under the conversion grant. The open grant's share is of the size found in observed programs: about half of the participants in a large program of appliance subsidies, more than half of the carbon offsets for wind farms in India, and most U.S. tax credits for electric vehicles went to adoption that would have happened anyway (Boomhower and Davis 2014; Calel et al. 2025; Xing, Leard, and

Figure 6: Public spending per tonne of CO_2 avoided, by component



Notes: Each grant at the level that avoids 311 Mt of CO_2 over 1985–2015, 2005 dollars per tonne of CO_2 avoided, undiscounted. Bar length: the budget per tonne. Baseline investment: investment the grant pays for that also happens without it. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works. Conditional grant: paid once per tonne of EAF capacity at an old works, when the works retires its blast furnaces. Conversion grant: paid to old works that convert. Site-retention grant: paid each year per tonne of EAF capacity running at an old works. EAF: electric arc furnace, which melts scrap with electricity.

Li 2021). Spending per tonne of CO_2 is nearly the same for the open and the adoption grant, \$28.1 and \$27.5, and \$49.5 for the conversion grant. Restricting eligibility to old works thus removes most of the non-additional payments but saves little spending. The obligation takeover cannot reach the target, and the carbon price pays nothing and raises \$64.0 billion.

6.2 Payments, investment, and emissions

The adoption and open grants cost nearly the same per tonne of CO_2 for opposite reasons. Spending per tonne depends on three factors, as equation (17) shows. They are the grant needed per tonne of new capacity, the CO_2 each added tonne of capacity avoids, and the non-additional share, and Table 4 reports all three. First, old works respond weakly to grants, so the adoption grant must pay \$351 per tonne of new EAF capacity to reach the target, against \$137 for the open grant. Because an add-on builds EAF capacity of a share $\kappa_{\text{add}} = 0.70$ of the works' capacity, \$351 is about \$246 per tonne of the works, less than half of the \$581 that on average would make an owner willing to add an EAF (Section 5.3). Second, each tonne of capacity the adoption grant adds avoids about 15 tonnes of CO_2 over 1985–2015, against 11 under the open grant. This count includes every change the policy brings about, in closures, in the output of other plants, in imports, and in consumption, and depends on when the capacity is built and how long it runs. Together, the first two factors put spending on added investment at \$23.8 per tonne of CO_2 under the adoption grant and \$12.8 under the open grant. Third, 54% of the open grant's payments are non-additional, against 13% of the adoption grant's. The open grant thus pays about half as much per tonne of CO_2 for the investment it adds but pays for far more investment that would happen anyway, and the two nearly cancel, at \$28.1 against \$27.5.

Almost all the adoptions the adoption grant adds are add-ons, the form owners prefer because it leaves the blast furnaces running and does not bring the shutdown obligations due. The open grant draws in 18.3 new mills. They lower the flat price (Appendix E.2) and push out other domestic output. Of their extra flat output, 0.87 replaces other domestic output, and 6.7 more EAF mills close. Most of the displaced output is from blast furnaces, but the part from other EAF mills saves almost no CO_2.

Full conversions are rare in the baseline, so the conversion grant's non-additional share is almost zero. But converting gives up the running blast furnaces and brings the obligations due, so owners respond little. The grant must reach $1098 per tonne of new capacity, well above the building cost, before it buys the target. It then pays about twice as much per tonne of CO_2 for added investment as the adoption grant.

The conditional grant moves owners from adding an EAF and keeping the blast furnaces to adding one and later retiring them, and it pays every retirement of a hybrid that exists in 1985, including those that would happen anyway. The site-retention grant pays every tonne of EAF capacity at an old works in every year, and its non-additional share is about a third.

The carbon price and the obligation takeover act mainly through closure. At the target, the carbon price closes 3.4 more integrated works and adds 1.2 adoptions. The flat price rises by $24.2 per tonne, which draws in 5.9 new mills. Under the model's assigned obligation levels, the full obligation takeover closes 3 more integrated works and pays mainly the owners of works that close, with little change in adoptions.

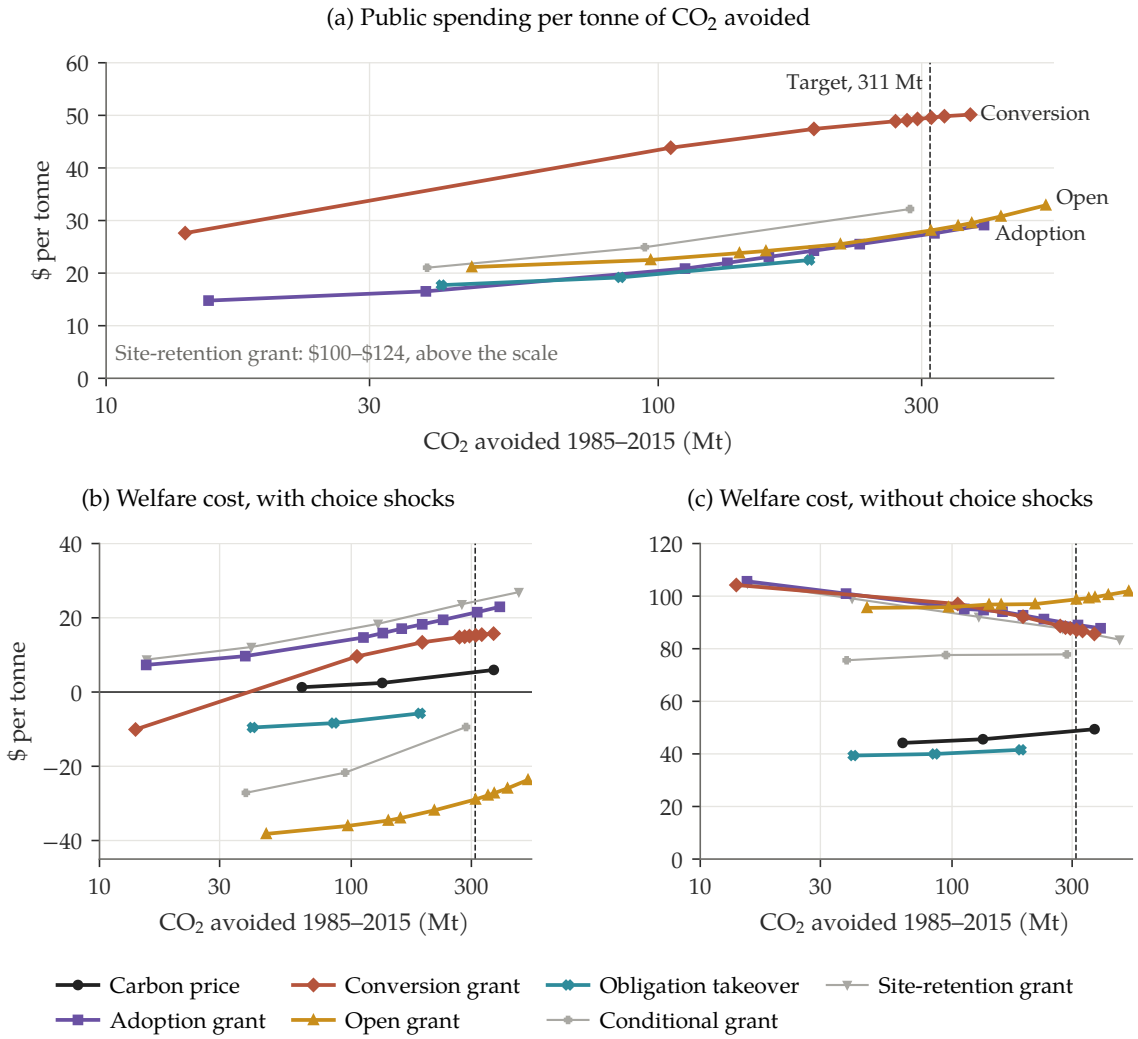
6.3 Sensitivity of the comparison

The conversion grant costs the most in every robustness check in which it is computed. The adoption and open grants cost so nearly the same that the inputs decide which costs less. The checks work through the three factors of Section 6.2, and all are in Appendix E.2. At baseline inputs, the adoption grant is the cheaper capacity grant at every target studied, up to 389 Mt, by a margin that shrinks as the target rises, as Figure 7(a) shows. Within its reach, the obligation takeover can cost less.

The first factor is how much entry would come without support, which sets the open grant's non-additional share. The entry cost decides it, and Figure 8 shows spending against the entry cost of flat-product mills. At low entry costs, many mills would come anyway, and 83% of the open grant's payments are non-additional. At high entry costs, few would, but the open grant must be larger to bring mills in. With the long-product entry cost at its estimate, the open grant therefore costs more at all seven flat-product entry costs tested. It costs less only when the entry costs of flat and long mills are both at the upper ends of their 95% intervals, at $27.5 against $29.2 per tonne. A cheaper scrap price makes new mills more valuable, so more would come anyway. On the 25th-percentile scrap path, 78% of the open grant's payments are non-additional, and on both the 25th- and 75th-percentile paths the adoption grant still costs less. A three-year entry lag leaves the two grants almost tied.

The second factor is how much CO_2 each added tonne of capacity avoids. When steel

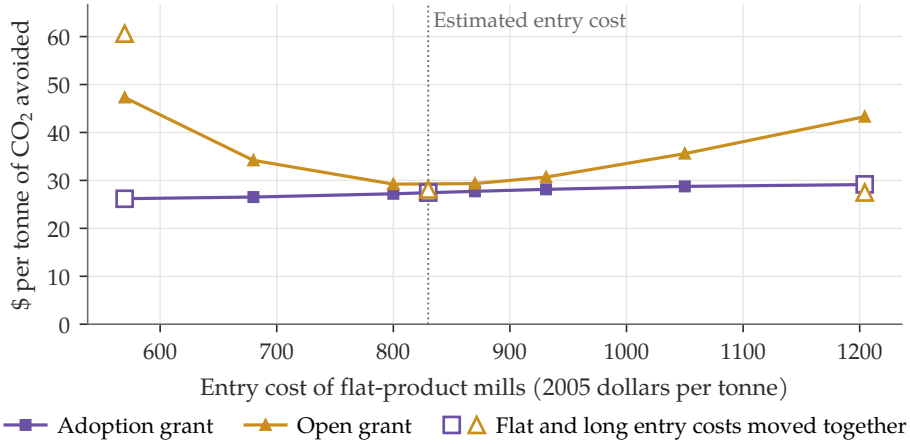
Figure 7: Spending and welfare cost by abatement



Notes: Each marker is one level of an instrument, at the point estimate with entry and prices responding. CO_2 avoided over 1985–2015, on a logarithmic scale. Abatement targets: the CO_2 avoided at each level of the main runs of the adoption, open, conditional, and site-retention grants and the obligation takeover, and at a carbon price of $25, with the other instruments interpolated linearly along their curves to it where they reach it. The abatement axis runs from 10 to 520 Mt, just above the open grant's highest level run. (a) Grants paid over CO_2 avoided. The carbon price raises revenue and is not shown. The site-retention grant lies above the vertical scale. (b), (c) Welfare cost: the loss of steel buyers, U.S. plants and entrants, and the government per tonne of CO_2 avoided, before the value of CO_2, with (b) and without (c) the choice shocks in producer surplus. Lower is better. 2005 dollars, undiscounted. Carbon price: per tonne of CO_2 on both routes. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works. Conversion grant: paid to old works that convert. Conditional grant: paid when an old works retires its blast furnaces. Obligation takeover: a public fund pays a share of the shutdown obligations when they fall due. Site-retention grant: paid each year per tonne of EAF capacity at an old site. EAF: electric arc furnace, which melts scrap with electricity.

demand responds weakly to prices, new mills displace more domestic output and add less to consumption, so each tonne the open grant adds avoids more CO_2. With the flat- and long-product demand elasticities moved together, the open grant costs less below a flat-product elasticity of about 0.15, against the central 0.20. That threshold lies inside the 95% Anderson–Rubin confidence set (Anderson and Rubin 1949) of the demand estimate but below the range of 0.20 to 0.60 given for flat products in a steel investigation of the

Figure 8: Sensitivity to the entry cost



Notes: Each grant at the level that avoids 311 Mt of CO_2 over 1985–2015, against the entry cost of new flat-product mills. Lines: the long-product entry cost held at its estimate. Hollow markers: the entry costs of flat-product and long-product mills moved together to the low end, center, and high end of their 95% intervals. 2005 dollars. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works. EAF: electric arc furnace, which melts scrap with electricity.

U.S. International Trade Commission (USITC 2001). If part of what an add-on's EAF melts is iron from the works' own blast furnaces, each add-on replaces less blast-furnace steel. The open grant then costs less already at 10%, the lowest share tested. Counting EAF electricity with state-by-year grid factors, instead of a fixed 0.4 tonnes per tonne of EAF steel, lowers the CO_2 each grant avoids by 4% to 6%, and the open grant then costs slightly less, $29.5 against $29.6 per tonne. Both recount emissions with the plants' choices held fixed.

The third factor is the grant old works need, which rises with the fixed adoption cost. At the lower end of its interval, $0.19 billion, the two grants cost about the same, $23 per tonne. Near the upper end, at $1.96 billion, old works respond so little that even a grant of $400 per tonne, above the $260 cost of building the EAF, avoids only 175 Mt, about half the target. The open grant still reaches it, at $39.4 per tonne. On the joint estimate of entry and the plant model, the adoption grant costs $27.2 and the open grant $27.8. The adoption grant also costs less under every assumed value of the plant model, with half the obligations due on conversion and retirement, and in seven of the nine re-estimates of Section 5.4. The open grant costs less in the other two, with the EAF charge priced from scrap and pig iron and without Lorain's conversion. Beside a carbon price of $25, each grant set to avoid a further 311 Mt, the open grant costs slightly less, and beside $50 the adoption grant does.

6.4 Welfare and incidence

Spending per tonne says what a tonne of CO_2 costs the government, not whether the country gains. For that, I add up the change in U.S. welfare over 1985–2015:

$$\Delta W = \Delta \text{CS} + \Delta \text{PS} - \mathit{MCPF}\,(\text{grants} - \text{carbon revenue}) + \mathit{SCC} \cdot \Delta \text{CO}_2. \tag{18}$$

Here ΔCS is the change in steel buyers' surplus and ΔPS the change in the profits of U.S. plants and entrants, including the grants they receive and the carbon they pay, net of building, entry, and cleanup costs (Appendix E.3). The obligations to retirees are transfers between owners and workers, while cleanup uses real resources and counts. I set the marginal cost of public funds, *MCPF*, to one, so grants and carbon payments are transfers between the government and the firms. Public spending is reported separately, as spending per tonne of CO_2 avoided in Section 6.1. A value above one would raise the welfare cost of each grant in proportion to its discounted spending and lower that of the carbon price, which raises revenue. The social cost of carbon is *SCC*. Every flow is discounted to 1985 at 2%, the social rate behind the carbon value of the Environmental Protection Agency (EPA), not the owners' discount factor β. Displaced workers' earnings losses are reported as incidence, not added.

Because the instruments avoid the same CO_2 at similar dates, the term $SCC \cdot \Delta CO_2$ is nearly common to all of them, and differences in welfare come from the cost side. I therefore report the *break-even carbon value*, the *SCC* at which an instrument's ΔW is zero, rather than rank instruments at one assumed *SCC*, as Fowlie, Reguant, and Ryan (2016) report welfare as a function of the carbon value. The ranking depends on one part of the change in producer surplus ΔPS, the expected value of the choice shocks of the actions taken (Small and Rosen 1981). With logit entry, these shocks include those of the extra entrants a grant draws in. The marginal entrant earns less than its entry cost in the model's payoffs, and its shock is what makes entry worthwhile to it. The term is consistent with the estimates, but no observed payment corresponds to it, and free entry can be socially excessive (Berry and Waldfogel 1999). I report welfare with and without the choice-shock term.

Figures 7(b) and 7(c) compare the instruments' welfare cost at 20 abatement targets. With the choice-shock term, the open grant has the lowest welfare cost at 19 of them. Without it, the obligation takeover is lowest at the 13 targets it reaches and the carbon price at the other 7, and no grant is lowest at any target. Among the instruments that reach the target, the break-even carbon values in Table 4 are lowest for the open grant with the choice-shock term and for the carbon price without it. For reference, the value of EPA (2023) at a 2% discount rate is \$147 per tonne and the interim value of the Interagency Working Group on Social Cost of Greenhouse Gases (2021) at 3% \$39.5, for emissions in 2020 and in 2005 dollars. At the EPA value, every instrument that reaches the target raises U.S. welfare, with or without the choice-shock term. At the interim value, it does so only with the term.

At equal abatement the open grant makes steel buyers gain \$30.5 billion and the owners of existing plants lose \$41.7 billion. The carbon price makes buyers lose \$41.9 billion and the owners of existing plants \$22.5 billion. The open grant thus moves surplus from the owners of existing plants to steel buyers, and the carbon price takes it from both. The adoption grant closes less existing capacity than the open grant and costs fewer jobs at existing plants, about 4,268 against 9,083 (Appendix E.3). These are jobs at the works, including those lost when a works shrinks. Counting the jobs at new mills, the open grant

Table 5: The gap to DRI-EAF in 2015

		$ per tonne of site capacity					$ billion
	Pellets	Gap	Range	Engineering	Premium	Route	Total
Scrap EAF	–	510	360–823	218	292	0	22.2
DRI-EAF, by cost of the DRI plant							
Low	Market	592	442–904	311	280	+82	25.7
Low	Captive	507	361–818	206	302	−3	22.1
Nucor	Market	690	540–1,003	428	262	+180	30.0
Nucor	Captive	605	458–916	319	286	+95	26.3
High (central)	Market	726	576–1,039	470	256	+216	31.6
High	Captive	641	493–951	361	280	+131	27.9
High, no high-end cap	Market	704	555–1,016	467	238	+194	30.6

Notes: Adoption gap: the one-time payment that would make building a DRI-EAF beside the blast furnaces as good to the owner as the better of keeping and closing the works, at the 13 works with blast-furnace capacity in 2015, capacity-weighted means, 2005 dollars per tonne of site capacity. DRI-EAF: an EAF melting direct-reduced iron made with natural gas in a plant built with it, at the cost estimates of CRU (2024) and Nucor's reported cost (LED 2014). Pellets: Market, bought at market prices. Captive, from the owner's mines at cost. –: the scrap EAF uses none. Low, Nucor, High: the DRI plant's building cost, CRU's low estimate, Nucor's reported cost, and CRU's high estimate, with High the central case. Range: the adoption gap at ϕ_C = \$0.19 billion, the lower end of its 95% interval, and \$1.96 billion, near the upper end. Engineering: building cost and forgone profit. Premium: the adoption gap less its engineering part. Route: the adoption gap less that of the scrap EAF. Total: the adoption gap times capacity, summed over the works. No high-end cap: the DRI-EAF sells the works' own high-end share. EAF: electric arc furnace, which melts scrap with electricity.

costs fewer jobs on net, about 3,415 against 4,022 under the adoption grant, because its new mills add jobs.

6.5 Extension: the remaining blast furnaces

In 2015, 13 integrated works with 43.5 Mt of capacity still ran blast furnaces. The route on offer for them is an EAF fed with iron made from ore with natural gas, direct-reduced iron (DRI). Governments have supported DRI-based steelmaking at old works in the United States and Europe, among them Middletown in Ohio, and at new mills in Europe (Appendix E.5).[6] Support at old works has not always led to adoption. In 2026, after Cleveland-Cliffs gave up its project at Middletown in 2025, the U.S. Department of Energy announced an award to upgrade the works' blast furnace instead (DOE 2026).

I recompute the adoption gap of Section 5.3 for these works in 2015, with a DRI-EAF built beside the running blast furnaces, the cost inputs of Appendix E.5, and the adoption parameters estimated on the scrap route carried over, since none of the observed adoptions used DRI. The DRI-EAF costs more to build, not to run. The adoption gap is \$726 per tonne of site capacity in the central case, against \$510 for the scrap EAF, and the difference lies in the costs an engineering comparison would count, mostly the building cost of the DRI plant, as Table 5 shows. Over the 13 works, the central-case gap adds up to \$31.6

[6] Engineering studies estimate what this route and alternatives such as carbon capture would cost the U.S. steel industry (Atouife, He, and Jenkins 2026; Jordan et al. 2025).

billion, the one-time payment that would leave each owner as willing to add a DRI-EAF as to keep the works running or close it. At the lower end of the interval for the fixed adoption cost, $0.19 billion, and near its upper end, $1.96 billion, the adoption gap runs from $576 to $1039 per tonne. The Department of Energy's offer for Middletown came to about $116 per tonne of the works' capacity, against a central-case gap 6.3 times as large. Whether grants for this route should also be open to new DRI-fed mills depends, as for the scrap route, on how much of their entry would come without support.

7 Conclusion

In the U.S. steel industry, restricting clean-investment grants to existing plants would have changed whom the public paid more than how much it paid per tonne of CO_2 avoided. At baseline, and with add-ons allowed, the adoption grant and the open grant spend about the same, $27.5 and $28.1 per tonne. The restriction removes most payments for investment that would happen anyway, but old works need grants more than twice as large per tonne of new EAF capacity to adopt, and the two effects nearly cancel. Which grant is cheaper depends on how much entry would come without support, how much CO_2 each added tonne of capacity avoids, and how large a grant old works need. Requiring old works to replace their blast furnaces, instead of adding an EAF beside them, nearly doubles spending.

Beyond the new furnace and the profit its blast furnaces give up, the owner of an old works bears a fixed cost of about $0.77 billion per adoption, which raises the grant needed to induce adoption. Retiring the blast furnaces also brings due obligations to the owner's workers and retirees. These obligations favor adding the new furnace beside the blast furnaces and make replacement need a larger grant still.

The restriction changes who gains and who keeps their jobs. The open grant draws in new mills, which lower steel prices, so steel buyers gain and the owners of existing plants lose. Restricting grants keeps more jobs at existing plants, about 4,268 lost against 9,083, but not more jobs in the industry, because new mills add jobs too. These magnitudes belong to steel. The distinction behind them, between paying for investment that would come anyway and paying what it takes to move an old plant, carries over to other industries in which clean entrants compete with long-lived plants, such as cement, chemicals, and electricity. In the U.S. steel industry, keeping the old sites and lowering the public cost of abatement turned out to be separate goals.

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A Data Construction

Terms used throughout the appendix. An *integrated works* makes steel from iron ore in two steps. Its blast furnaces reduce the ore with coke to liquid iron, and its basic oxygen furnace (*BOF*) turns the iron, with some scrap, into steel. An electric arc furnace (*EAF*) melts scrap with electricity, and an *EAF mill* is a plant built around one, without blast furnaces. A *new mill* is an EAF mill that entered after 1985. An *add-on* is an EAF built beside an integrated works' running blast furnaces, and a *conversion* builds it in their place and shuts them. A *hybrid* runs an EAF beside its blast furnaces, after an add-on or, for the legacy hybrids, already in 1985.

A.1 The plant record

Directories and roundups. The record rests on 39 editions of the plant directories of the Association for Iron & Steel Technology (AIST) and its predecessor, the Association of Iron and Steel Engineers, each describing the year before (AIST 2004–2022; AISE 1983–2003). Most editions to 2014 were scanned from library copies at TIB Hannover (1983–1995), the Carnegie Library of Pittsburgh (1996–1998), and TU Bergakademie Freiberg (1999–2014). Later editions are digital, from the same Carnegie Library and, for 2018 and 2020, from AIST. I read the scans with optical character recognition and extracted one record per site and year, with the owner, the steelmaking furnaces and their stated capacities, coke batteries, and finishing lines. The 37 editions of 1985 to 2022 give 6,401 site-years from 1984 to 2021. The combined edition of 2001–2002 gives no record for 2001. The equipment roundups of the Iron & Steel Society and of AIST (AIST 2007–2023; ISS 1988–2003) are yearly tables of furnaces by process. They date furnaces, check capacities and idlings, and give the output of integrated works. Those from 2002 are AIST's digital editions, and I scanned the earlier ones from *Iron & Steelmaker* at the British Library.

Reconciliation with the King reports. The Steel Plant Capacity Reports of King (2025) list every blast furnace, basic oxygen furnace (BOF) vessel, electric arc furnace (EAF), and open-hearth furnace (an older steelmaking furnace) with its site, opening year, closing year, any rebuild, and rated capacity in short tons. I keep King's short tons in the panel and convert them to metric tonnes in every number the paper reports. A site-year exists if at least one steelmaking furnace is open. The panel covers 166 sites and 4,384 site-years from 1985 to 2020. Site capacity is the sum of open furnaces. Technical age is the years since the furnace opened, reset at a recorded rebuild.

I change a King entry only when outside evidence contradicts it: two independent sources state the corrected fact, or one does and no source supports King's record. Each of the 118 applied corrections is a dated row with its sources in a correction register, and they add closures King missed, re-date openings and closings, re-rate capacities, record idle spells, and remove duplicate sites. A site that operated in any part of a year counts as operating, so a closure year is the first year with no operation. Idle years, with capacity on the books and no output, are coded where an outside source dates the spell.

Capacity is nameplate capacity: King's rating, or the rating in the roundups (AIST 2007–2023; ISS 1988–2003) or the Global Iron and Steel Tracker (GIST) of Global Energy Monitor (GEM 2026) where these correct it. Where no rating exists, it is the furnace's heat size (the steel tapped in one batch) times a fixed number of heats a year for its type, which gives 63% of EAF capacity in 1985. Where King gives one rating for a furnace upgraded later, that rating applies to all its years. The re-estimate in Table D.4 with EAF capacity from the capacities printed in the AIST directories keeps ϕ_C inside the baseline interval.

Verification against other sources. Each site-year is matched to outside sources: the records of the Greenhouse Gas Reporting Program (GHGRP) and the Toxics Release Inventory (TRI) of the Environmental Protection Agency (EPA) (EPA 2024, 2025), the AIST directories and roundups, the cost estimates of CRU (2024), GIST, SEC filings, the Minerals Yearbook (USGS 2025), the dated events in Capital IQ Key Developments (S&P Global Market Intelligence 2026a), and a fact base of dated events with saved quotes. Sources that share an origin, such as the AIST directories and roundups, count once. Of the 166 sites, 138 are confirmed by at least two families of sources besides King, and no site in the estimation scope rests on King alone. All 19 in-scope closures that TRI can test end melting within one year of the panel's last year, while the closure year of 16 in-scope sites that close before 2016, most of them small EAF mills, rests on King alone. Plant coordinates come from a geocoded list of King's sites, checked against county boundaries and facility locations in GHGRP, TRI, and GIST, and the check corrected 52 rows.

Output and utilization. Plants rarely run at full capacity, so the model scales capacity by how much of it a route and a plant use. The national utilization of a route and year is the route's steel output in the Steel Statistical Yearbooks (worldsteel 1994–2022) over the operating capacity of the panel, which leaves out idle capacity. A plant's utilization factor is its output per tonne of operating capacity relative to the same ratio of the plants covered by its source in that year, averaged over the years before the decision, shrunk toward one when few years are available, and one for plants without a record. For BOF capacity, both use the effective capacity of Section 4.1, the smaller of BOF capacity and blast-furnace supply. I leave out the two years before a closure, an idling, or a change of configuration, because output runs down before them. Output of EAF mills comes from the plant estimates of CRU (2024) for 2006–2015 and otherwise from the zinc in the waste that mills report to the TRI, fitted to those estimates. Output of integrated works comes from the hot metal, the liquid iron of the blast furnaces, in the AIST roundups (AIST 2007–2023), and from CRU (2024) where these are missing.

A.2 Estimation scope

Integrated works hold a BOF. EAF mills are carbon-steel mills if any of their units makes carbon products. Mills making special-quality bars count as carbon EAF mills, because they melt scrap in the same furnaces. Out of scope are 18 specialty-steel and 18 stainless

Table A.1: Plants and owners in the estimation sample

	Integrated works	Hybrids	EAF mills
A. Plant			
Capacity, Mt	3.20	4.54	0.80
	(1.49)	(0.75)	(0.62)
Flat-product share of capacity	0.93	0.84	0.16
	(0.23)	(0.31)	(0.36)
Age of steelmaking, years	30	29	18
	(11)	(8)	(12)
Idle share of capacity	0.02	0.00	0.01
	(0.14)	(0.00)	(0.09)
B. Owner			
Debt to assets	0.23	0.24	0.28
	(0.14)	(0.11)	(0.18)
Operating margin	0.08	0.08	0.14
	(0.07)	(0.07)	(0.09)
Unfunded obligations, $ per tonne	178	157	–
	(118)	(91)	
Owner in Chapter 11	0.13	0.06	–
Plant-years	518	85	2,160
Sites	21	6	100
Compustat data available, share	0.81	0.86	0.69
Obligation data available, share	0.61	0.56	–

Notes: Decision years 1985–2014 of the estimation sample, by configuration in the year. Hybrids: legacy hybrids and the hybrid after an add-on. Means, with standard deviations in parentheses. Debt to assets and operating margin: Compustat (S&P Global Market Intelligence 2026b). Unfunded obligations: the owner's pension shortfall, floored at zero, plus its unfunded or accrued retiree health obligations, at its latest record before the year in Compustat or its 10-K notes, per tonne of its capacity. Chapter 11: owner in bankruptcy reorganization, recorded for the owners of integrated works. –: for EAF mills, obligations are not defined, since they carry none in the model, and Chapter 11 is not reported, since only the spells of the integrated firms are recorded.

sites, and 4 foundries, forges, and shops that melt in induction furnaces. That leaves 26 integrated works and 100 EAF mills.

Table 2 gives the sample's 36 closures and 30 idle years, which count as decisions to keep. Estimation uses decisions from 1985 to 2014 and their outcomes to 2015. I hold out the decisions of 2015–2019, with their outcomes in 2016–2020: 434 decision years at 88 sites, among them Fairfield's conversion. Table A.1 describes the plants and their owners by configuration.

The estimation sample has 8 closures of integrated works and hybrids in its decisions of 1985–2014 (6 integrated works and 2 legacy hybrids). Table 2 counts 28 closures of EAF mills, which include the EAF steelmaking shops of the Farrell works and of U.S. Steel's South Works, whose BOF had closed before 1985. The likelihood counts 29 and has 2,760 decisions against the table's 2,763, for the reasons Appendix D.3 gives.

King lists the Farrell works of Sharon Steel as two sites, one with its oxygen furnaces and one with its EAFs, which close together when the works shut down in November

1992. The sample therefore counts this shutdown as one integrated and one EAF closure. Two other sets of same-year closures are single corporate events: Birmingham Steel's shutdown of two steelmaking shops and consolidation of a third (fiscal 1991), and RG Steel's idling of Sparrows Point and Warren after its Chapter 11 filing in May 2012. The model treats each closure as a separate decision, and the firm bootstrap of Appendix D.4.3 resamples firms with all their plants.

A.3 Owners, obligations, and cleanup

Ownership. The owner of each site-year is the company heading the site's entry in the following year's edition of the AIST directories. Where no edition has the site, the owner comes from the GHGRP parent company, the fact base, or the owner history in the CRU estimates, in that order. A firm is the controlling group on 31 December (an equity link above one half). A 50/50 joint venture is a firm of its own. Changes of owner are dated by completed deals from SDC Platinum and Orbis M&A (London Stock Exchange Group 2026; Moody's Analytics 2026), which override the lag of the directories. The GHGRP parent agrees with the table in 99.7% of the site-years both cover, while King's own owner codes agree in only 76% of site-years before 2002 and 93% after. Of the 174 changes of owner or firm, 156 are dated by a completed deal.

Obligations. For each firm and year the table holds the pension plans' projected benefit obligation and assets, the retiree health obligation, and the date on which the Pension Benefit Guaranty Corporation (PBGC), the federal insurer of private pensions, became trustee of the firm's plans. Pension values come from the Compustat Pension Annual file (S&P Global Market Intelligence 2026b), replaced where possible by the notes to the firm's 10-K filings (18 filers, fiscal years to 2005), and the projected benefit obligation is identical in 123 of the 125 firm-years that both cover. Retiree health obligations come from the 10-K notes, with Compustat's net balance-sheet amount used where no note is saved. The dates on which the PBGC took over the plans of 22 steel firms, 1983–2010, come from the PBGC's list of trusteed plans, and from that date the plan's unfunded obligation is the PBGC's. Records are matched to plants through the owner table, and a firm's latest record is carried forward for at most 3 years. The obligation per tonne divides the unfunded obligation, pension obligation less plan assets plus the retiree health obligation net of any assets, by the firm's steelmaking capacity in the panel. By this obligation per tonne, the model classes each firm-year as having no, moderate, or large obligations. Matched to owners, the records cover 53% of the sample's capacity. Owners without a usable record take the middle level, and Table D.6 varies the cutoffs between levels.

Cleanup accruals. Cleanup accruals come from the saved annual reports of the integrated firms, fiscal years 1993 on. Table A.2 lists them by owner. I label each passage with an environmental accrual or reserve as a firm total, a site-specific amount, an asset retirement obligation, or not usable, and every quoted amount is checked against the filing. The result is 107 owner-years of firm totals. I use a site-specific amount where the

Table A.2: Site cleanup accruals of the integrated firms

Owner	Years	Firm-years	Accrual ($ million)		
			Median	Maximum	Per tonne
International Steel Group	2003–2004	2	216	221	10.9
U.S. Steel	1993–2015	23	150	201	11.2
LTV	1994–2000	7	131	181	12.2
Bethlehem	2002	1	125	125	14.5
AK Steel	1993–2015	23	53	111	10.4
Ispat Inland	1998–2004	7	30	39	5.7
Inland	1993–1997	5	29	32	5.4
Republic	1999–2002	3	22	25	1.1
National	1993–2002	10	14	28	2.0
Wheeling-Pittsburgh	1993–2006	14	13	21	4.3
Weirton	1996–2002	7	10	10	2.3
Acme	1993–1997	5	0	1	0.7

Notes: Environmental cleanup accruals and reserves in the owners' 10-K filings, fiscal years 1993 on, million 2005 dollars. Firm-years: years with a usable accrual. Per tonne: median over works-years of the accrual per tonne of the owner's BOF capacity, site-specific where the filing names the works, else the firm total split by BOF capacity, 2005 dollars per tonne. Accruals are lower bounds, because firms book only what is probable and estimable.

filing names the works and otherwise split the firm total by BOF capacity, which gives a value for 268 works-years in 2005 dollars. I do not add asset retirement obligations, and works-years without a record take the mean.

A.4 Adoptions by integrated works

Table A.3 lists the three integrated works that adopted the EAF between 1985 and 2020. The capacity of an add-on and of a conversion in the model, 0.70 and 0.46 of the works' capacity, are the ratios of Steubenville and Lorain, while Fairfield's conversion (0.67) falls in the held-out years.

B Prices, Costs, and Margins

B.1 Steel prices and product mix

Steel prices. All prices and costs are in 2005 U.S. dollars per metric tonne, deflated with the GDP deflator of the Bureau of Economic Analysis (BEA 2026). The Census Current Industrial Reports (CIR) on steel mill products (U.S. Census Bureau 1983–2010) give each product's quantity shipped and its value at the plant gate, so their ratio is a realized price. I extracted 27 editions from 1983 to 2010, which cover every year from 1982 to 2010 because each edition also reports the year before, and checked each of the 7,095 rows against its source line. I use the hot-rolled and cold-rolled lines through 2001. From 2002, the flat prices are the hot-rolled band and cold-rolled coil prices of SteelBenchmarker (2026) times the median ratio of the CIR value to them over 2002–2010 (0.896 for hot-rolled and 0.971

Table A.3: EAF adoptions by integrated works, 1985–2020

	Steubenville	Lorain	Fairfield
Type	Add-on	Conversion	Conversion
Products after adoption	Flat	Long	Long (rounds)
BOF capacity before (Mt)	3.46	2.54	2.25
EAF capacity after (Mt)	2.42	1.18	1.51
EAF over old capacity	0.70	0.46	0.67
Owner bankruptcy before	2000	2001, 2003	None
Blast furnaces stopped	2008 [a]	2008	2015
EAF first heat	2004	2013	2020
Decision year in the model	2003	2011	Holdout

Notes: Add-on: an EAF built beside blast furnaces that keep running. Conversion: an EAF that replaces the blast furnaces, built after years in which the works made no steel. Capacity in Mt a year from the plant panel. Steubenville's BOF capacity after the add-on is 1.73 Mt. EAF over old capacity: EAF capacity after over integrated capacity before. Decision year: the decision the model reads as the adoption. Holdout: after the estimation years. [a] The year the oxygen-furnace shop was idled, as reported in the 2012 BOF roundup of the Association for Iron & Steel Technology (AIST 2007–2023). The King reports retire the blast furnaces in 2010.

for cold-rolled sheet). After 2010, coated sheet follows the import unit value of coated flat-rolled steel (HS 7210, times 0.905) (Comtrade 2026) and rebar the producer price index for hot-rolled bars, plates, and shapes (times 3.288) (BLS 2026b), each on the CIR level.

Plant prices. Each in-scope site has, for each year, shares of its output across the flat products (hot-rolled, cold-rolled, and coated sheet, tin-mill products, plate) or the long products (rebar, merchant bar, shapes, wire rod). A prior from the finishing lines that the AIST directories print for the works is calibrated to the product shipments that firms report in their 10-K filings or Compustat Segments (S&P Global Market Intelligence 2026b), but from 2006 the plant-level sales estimates of CRU (2024) replace it. The plant price is the share-weighted mean of the products' CIR unit values. Relative to firms' reported revenue per tonne shipped, the base-product price gives 0.75 on average and the product mix 0.94.

Finishing costs. A product beyond the base product (hot-rolled sheet for flat works, rebar for long works) also costs more to make. Its finishing cost is its price premium over the base product less its margin premium in the product-line accounts of the U.S. International Trade Commission (USITC), from its reports in steel investigations (USITC 1993–2017), so that the cost model reproduces the margin differences producers reported. Before 1990 USITC's 1990–92 level is carried back.

High-end cap on the new EAF. The cap $\bar{w}_t$ of Section 4.1 is the share of cold-rolled and coated products at EAF sheet mills in each period, $\bar{w}_t = 0.32$, 0.30, and 0.21 in 1985–95, 1996–2005, and 2006–15. The shares are those of the plant product mixes above: before 2006 the directory prior calibrated to the firms' reported shipments, and from 2006 the CRU sales estimates. Figure B.1(b) shows the high-end shares of integrated works and

EAF flat mills from 2006. The cap uses EAF sheet mills, weighted by output, and so lies above the line for all EAF flat mills, which include plate mills.

B.2 Costs

Input prices and coefficients. The cost model takes its coefficients and its levels from 2006 on from the cost estimates of CRU (2024). Iron ore is the average value at the mine (USGS 2025) times 1.147, which scales it to Cleveland-Cliffs' realized pellet price (Cleveland-Cliffs 2005–2020), and coking coal the price of coal delivered to coke plants (EIA 2026b). Scrap prices are the U.S. Geological Survey's prices of No. 1 heavy melting steel at Chicago, Philadelphia, and Pittsburgh and their composite (USGS 2025), and electricity prices the industrial prices of the plant's state (EIA 2025c). The metal an EAF melts, scrap and the iron mixed into it, costs 1.18 times the scrap price for flat products from 1989 and more before, a quality penalty on EAF flat steel before thin-slab casting brought EAF mills into sheet, and 1.10 times for long products.

Non-material and downstream costs. The cost estimates give labor, overhead, and other operating cost by route only from 2006. I set hours per tonne and other costs to the levels of Barnett and Crandall (1986) for representative plants of 1985 and to the CRU estimates for 2006–2015. Between the two, national hours per tonne of raw steel set the timing. Labor cost is hours per tonne times compensation per hour (BLS 2026a), including benefits, times the route's relative wage. Casting and rolling cost the route's mean in the CRU estimates, plus a premium at integrated works for casting in ingots, the older method of pouring steel into molds, which vanishes by 2000. For rebar, I calibrate the level to USITC's cash cost less the cost model's cost of the liquid steel over 1996–2016.

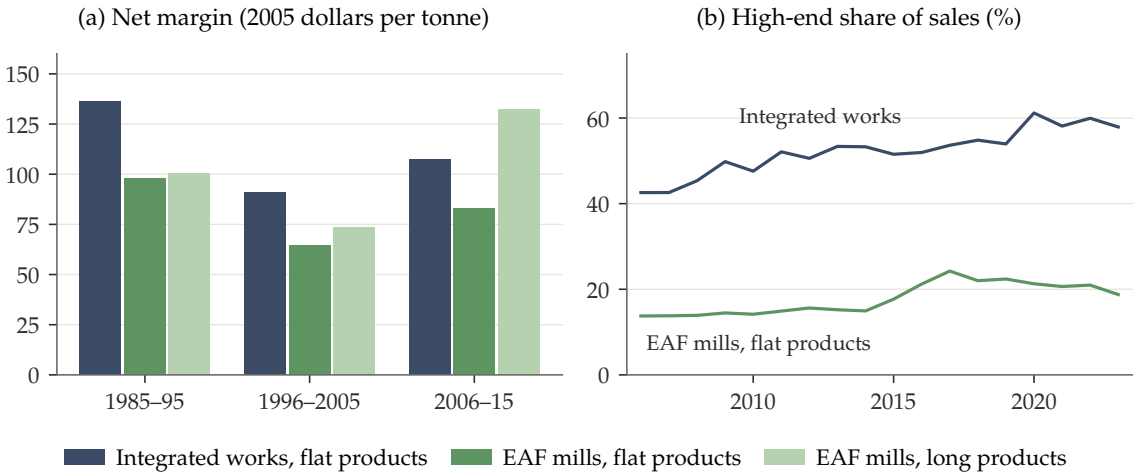
Building cost. The building cost of an adoption is the replacement cost of an EAF steelmaking shop in the CRU estimates, $260 per tonne of EAF capacity (median over U.S. EAF mills, 2020). It excludes rolling and finishing mills, which an adopting works already has.

B.3 Margins against reported profits

The model's net margin is the plant price at its own product mix minus material, energy, labor, other non-material, and finishing costs, before capital costs. At integrated flat works, it averaged $136 per tonne in 1985–95, $91 in 1996–2005, and $108 in 2006–15, while at EAF flat mills $98, $64, and $83. The margins in Figure B.1(a) leave out selling and administrative expense, retiree pension and health expense, restructuring charges, and the cost of idle capacity, so they differ from reported profits.

Table B.1 compares the cost model with the product-line accounts of USITC. The hot-rolled margin is not calibrated, yet it is within $30 per tonne of USITC's in each decade, above it in the 1990s and 2000s, and moves with it, except in the recession of 1990–92 (annual data, not shown), when fixed costs per tonne rose with idle capacity. The rebar cost level is calibrated to the accounts, and the cost model follows their year-to-year movement

Figure B.1: Net margins and high-end sales



Notes: (a) Net margin, 2005 dollars per tonne: the plant price at its product mix less material, energy, labor, other non-material, and finishing costs, before capital costs, output-weighted across plants and averaged over the years of each period. (b) High-end share: cold-rolled and coated products as a share of finished sales, capacity-weighted, 2006–2023. Sources: steel prices from the Census Current Industrial Reports on steel mill products (U.S. Census Bureau 1983–2010), with hot- and cold-rolled sheet extended from 2002 by SteelBenchmarker (2026) and coated sheet and rebar after 2010 by Comtrade (2026) and BLS (2026b), and cost coefficients and high-end shares from CRU (2024).

except in the swings of 2007–2009 and 2015–2016. The cost of cold rolling over hot-rolled sheet is calibrated to the same accounts, and the model's cold-rolled cost in 1990–92 is close to USITC's.

For 2006–15, the model's margins are close to the CRU estimates at the plants those estimates cover, weighted by the plants' sales in them: $112 against $118 per tonne for integrated works, a different weighting from the $108 above, and $71 against $78 for EAF sheet mills. Reported profit is operating income before depreciation per tonne shipped, from 10-K filings and Compustat. With the expenses the margins leave out added back, except idle capacity, reported profits keep the model's ordering in 1985–95, at half the model's integrated advantage over EAF long producers ($92 against $75, against the model's $136 against $100). The 2 listed EAF flat producers earned more than integrated firms after 1995 ($126 and $139 against $41 and $61), but they sold mostly plate, structural shapes, and rail. Table D.4 re-estimates the plant model with the EAF flat margin $40 and $80 per tonne higher. The obligations and the cost of idle capacity enter the adoption comparison separately.

B.4 The price process

The plant model needs expectations of future margins, which three margin indices summarize: the national price of hot-rolled sheet or rebar minus the material and energy cost of the route (integrated flat, EAF flat, EAF long), averaged over the route's in-scope plants with capacity weights. Each index follows a stationary autoregression of order one with correlated innovations, estimated as a system of seemingly unrelated regressions on 1986–2015, with the estimates in Table B.2. No index has a significant trend: with a common flat

Table B.1: Prices, costs, and margins against USITC accounts

			Price		Cash cost		Margin	
Product	Years	Obs.	USITC	Model	USITC	Model	USITC	Model
Hot-rolled	1990–1999	7	433	441	396	380	37	61
Hot-rolled	2000–2009	10	509	512	440	413	69	99
Hot-rolled	2010–2015	4	571	553	529	521	42	33
Rebar	1996–1999	4	382	389	328	340	53	48
Rebar	2000–2009	8	455	442	375	375	80	68
Rebar	2010–2016	7	565	559	500	494	64	65
Cold-rolled	1990–1992	3	627	654	571	563	57	91
Cold-rolled	2013–2015	3	670	627	633	602	36	25

Notes: 2005 dollars per tonne, means over the years with data in the product-line accounts of the U.S. International Trade Commission (USITC). Obs.: years with data. USITC: net sales, cost of goods sold less depreciation, and their difference. Model: the model's price, the cash cost of liquid steel plus casting and rolling, and their difference. Hot-rolled: the capacity-weighted mean of the two routes. The rebar level is calibrated to these data, so only its time pattern is a test. Cold-rolled: the hot-rolled cost plus the cost of cold rolling over hot-rolled sheet that the model's product mix uses, in the same years.

persistence the trends are \$−0.9 (standard error 1.8), \$−2.0 (1.2), and \$−0.2 (1.0) dollars per tonne a year. The persistence is 0.25, 0.44, and 0.48 for the integrated flat, EAF flat and EAF long indices. A common flat persistence (0.38) is rejected (p-value 0.009), and the Bayesian information criterion prefers own persistence, 957.3 against 961.1. Demand shifters, import shares, and the aggregate EAF share worsen the holdout forecasts, so no aggregate state beyond the margins enters the model. Dynamic forecasts of the 2016–2020 margins, which were not used in estimation, have a root mean squared error of \$57 per tonne, against \$105 for a random walk from 2015, and \$65 for the specification with trends.

C Descriptive and Reduced-Form Evidence

C.1 Decomposition variants

The decomposition of Section 3.1 splits the change in the capacity-weighted CO_2 intensity $\bar{e}_t = \sum_i s_{it} e_{it}$ of the 166 plants of the panel, where s_{it} is plant i's share of fleet capacity and e_{it} its emission intensity in tonnes of CO_2 per tonne of capacity: 2.0 for blast-furnace capacity, and for EAF capacity 0.08 of direct emissions plus 0.52 MWh of electricity per tonne times the CO_2 factor of the state's power sector in that year (EIA 2025c, 2026c). Following Olley and Pakes (1996), extended to entry and exit, with subscripts 0 and 1 for 1985 and 2020, Δ the change from 1985 to 2020 (so $\Delta e_i = e_{i1} - e_{i0}$, $\Delta s_i = s_{i1} - s_{i0}$, and $\Delta \bar{e} = \bar{e}_1 - \bar{e}_0$), and *Entry*, *Exit*, and *Stay* the plants that open, close, or operate in both years,

$$\Delta \bar{e} = \underbrace{\sum_{i \in Entry} s_{i1}(e_{i1} - \bar{e}_0)}_{\text{entry}} - \underbrace{\sum_{i \in Exit} s_{i0}(e_{i0} - \bar{e}_0)}_{\text{closures}} + \underbrace{\sum_{i \in Stay} s_{i0}\,\Delta e_i}_{\text{change at surviving sites}} + \underbrace{\sum_{i \in Stay} \Delta s_i (e_{i1} - \bar{e}_0)}_{\text{reallocation}}. \tag{19}$$

Table B.2: The price process of the margin indices, 1986–2015

	Constant	Trend	Persistence	Mean	Innovation sd	RMSE	BIC
A. Own persistence							
Integrated, flat	253 (43)	–	0.25 (0.12)	338	87	71	
EAF, flat	139 (30)	–	0.44 (0.11)	248	61	60	
EAF, long	117 (30)	–	0.48 (0.13)	223	44	31	
All indices						57	957.3
B. Common flat persistence							
Integrated, flat	209 (39)	–	0.38 (0.10)	337	90	72	
EAF, flat	155 (29)	–	0.38 (0.10)	249	61	58	
EAF, long	115 (30)	–	0.49 (0.13)	223	44	31	
All indices						56	961.1
C. Common flat persistence and trends							
Integrated, flat	275 (51)	−0.9 (1.8)	0.23 (0.12)	–	86	72	
EAF, flat	224 (41)	−2.0 (1.2)	0.23 (0.12)	–	57	79	
EAF, long	127 (39)	−0.2 (1.0)	0.44 (0.14)	–	44	33	
All indices						65	963.4
Random walk from 2015						105	

Notes: 2005 dollars per tonne. Margin index: the national price of hot-rolled sheet or rebar less the route's material and energy cost, averaged over the route's in-scope plants with capacity weights. Each index regressed on its lag, and in panel C on a trend, as seemingly unrelated regressions on 30 transitions, standard errors in parentheses. Trend: dollars per tonne a year. Mean: the constant over one minus the persistence. Innovation sd: the standard deviation of the innovation. RMSE: root mean squared error of forecasts of 2016–2020 from the 2015 margins. BIC: Bayesian information criterion of the system. –: not in the specification.

Table C.1 compares the headline split with a fixed EAF intensity of 0.4 and with variants that move the direct emissions and the electricity use, hold the grid at its 1985 factors, or price net electricity imports at the U.S. factor, and entry is the largest channel in every variant. Holding the grid at its 1985 factors for all plants, new mills included, cleaner electricity accounts for about 26% of the decline (23% to 31% across the parameter range). The cleaner-power channel of the table counts only EAF capacity that operates in both years. Within a route, emissions per tonne change through the state electricity factors of EAF mills, with other gains in efficiency, the technique effect of Shapiro and Walker (2018), held fixed.

C.2 Integrated firms' other EAF investments

Outside their own works, integrated firms adopted EAF capacity in 14 cases over 1985–2021: 2 ventures building new mills, 6 targeted purchases, and 6 EAF mills bundled in whole-company deals. ISG and Severstal, which bought works without their pension plans, added EAF capacity within a few years: ISG with the Steelton and Coatesville shops that came with Bethlehem's assets in 2003 and the Georgetown mill it bought in 2004, and Severstal with the Columbus mill it began to build in 2005. The firms that still carried theirs (LTV, Bethlehem, AK Steel, U.S. Steel) bought plate, specialty-steel, and tubular businesses. LTV built its one flat EAF mill as a separate venture, Trico, which ran from

Table C.1: Decomposition under other EAF intensities

	Fixed	Grid	Grid 1985	Low	High	Consumption
EAF parameters	0.4	0.08, 0.52	–	0.04, 0.45	0.15, 0.60	–
Intensity 1985	1.247	1.279	1.279	1.236	1.340	1.280
Intensity 2020	0.947	0.886	0.989	0.839	0.955	0.882
Fall (%)	24.1	30.7	22.7	32.1	28.7	31.1
Share of the fall (%)						
Entry	88.1	75.4	87.2	77.2	73.1	75.2
Surviving plants	19.1	29.0	18.3	27.6	30.8	29.1
Route change	–	13.5	18.3	14.3	12.5	13.4
Cleaner power	–	15.5	0.0	13.3	18.3	15.6
Closures	−11.4	−8.9	−12.0	−9.2	−8.4	−8.6
Integrated works	33.4	24.5	33.2	25.7	22.9	24.1
EAF mills	−44.8	−33.4	−45.2	−35.0	−31.3	−32.7
Reallocation	4.2	4.5	6.5	4.5	4.5	4.4

Notes: Capacity-weighted CO_2 intensity of all plants in the panel, tonnes per tonne of capacity, and shares of its 1985–2020 fall by channel: entry (new plants), closures, surviving plants, and reallocation (shifts among them). Variants differ in EAF intensity: fixed, grid-based (the paper's baseline), the grid variant with low and high parameters, grid at 1985 factors, and consumption-based, with net electricity imports at the U.S. factor. EAF parameters: direct emissions in tonnes of CO_2 and electricity in MWh per tonne, or the intensity in the fixed variant. Route change: adoption, and EAF shops closed at surviving works. Cleaner power: the fall in grid factors of surviving EAF capacity. Reallocation: shifts among surviving plants. –: not reported.

1997 to 2001, rather than at one of its works, and none of these firms bought EAF capacity for sheet until 2019.

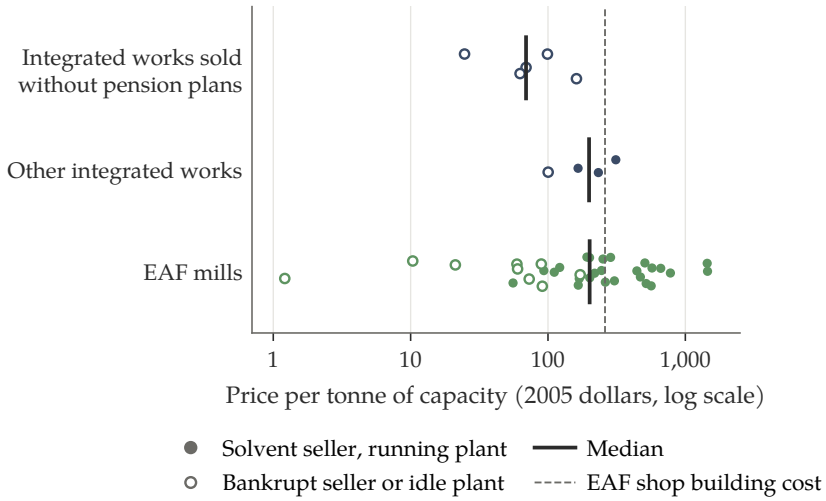
C.3 Deal prices

Figure C.1 shows what buyers paid for a going works once the obligations stayed behind. The median over 10 integrated deals with a usable value is $119 (2005) per tonne of steelmaking capacity, less than half the cost of an EAF steelmaking shop. The 5 works bought out of bankruptcy without the seller's pension plans sold for a median of $69, and EAF mills for $201.

C.4 Relines, closures, and financial distress

A blast furnace must be relined, its refractory lining rebuilt, every one to two decades, so the choice to reline or close falls due at an age that engineering largely sets. The risk set is every furnace-year at the 24 integrated works of the estimation sample in 1986–2015 in which the furnace is of unknown age or at least 11 years since its last reline, the age by which a quarter of campaigns with a known start have ended in a reline: 991 furnace-years of 72 furnaces, with 45 relines, 33 closures, and 2 bankings (furnaces taken out of service for a time). Obligations are the owner's pension and retiree health obligations per tonne of its capacity, before plan assets, and Table C.2 also counts them net of plan assets. The model uses the net measure, because a shutdown brings due the shortfall of the plans, not their full obligation. I date the regressors $t-1$ and penalize the logits (Firth 1993), which

Figure C.1: Transaction prices of steel plants, 1985–2020



Notes: Carbon-steel plant sales with a usable value, 1985–2020, 2005 dollars per tonne of the target's steelmaking capacity, log scale, one dot per deal at a random height within its row. Integrated works sold without pension plans: bought out of bankruptcy without the seller's plans. Bankrupt seller or idle plant: from court, company, and press records. EAF shop building cost: $260 per tonne. The 2011 sale of integrated works together with an EAF mill is not shown.

keeps the estimates finite when closures are rare. The design assumes that, once a reline is due, its timing does not respond to unobserved shocks that also move the regressors. A works in decline may stop relining early, so I also compare years within the same owner, and the odds ratio of the obligations stays below one (0.70).

Distress could change closure decisions and the obligations an owner carries at the same time: owners in Chapter 11 carried $293 per tonne against $496 for owners that had never filed. Table C.2 therefore adds distress measures dated $t-1$ to the logits of closing against continuing (944 furnace-years, 33 closures): Chapter 11, earlier filings, leverage, operating income over assets, negative book equity, and the years after a PBGC takeover.

Table C.2 gives the odds ratios that Section 3.2 summarizes. The obligation ratio stays below one in every specification, and with the balance-sheet and works controls its interval reaches one (0.65–1.00). Closure rates jump at the filing, from 2.2% a furnace-year three or more years before it to 8.9% in the filing year and the next.

Figure C.2 shows the obligations per tonne before and after each takeover, including those of LTV and Bethlehem that Section 2.3 cites. Owners at the full obligation level carry very different obligations per tonne, and the model's single scale $\bar{\lambda}$ is their mean. Estimated freely, the scale is $387 per tonne (95% interval $117 to $971), which contains it (Table D.4). A buyer did not always shed the obligations: U.S. Steel, buying National's works, brought its own plans, and obligations per tonne did not fall ($522 before, $555 after). The LTV plans alone cost the PBGC about $1.9 billion (Pension Benefit Guaranty Corporation 2002).

Table C.2: Obligations, Chapter 11, and closure

Specification	Obligations	Chapter 11
Obligations alone	0.73 [0.59, 0.88]	–
Net of plan assets, alone	0.67 [0.38, 1.09]	–
+ Chapter 11 state	0.80 [0.65, 0.96]	4.22 [2.00, 8.82]
+ balance sheet and works controls	0.82 [0.65, 1.00]	6.42 [2.23, 18.65]
+ post-takeover indicator	0.80 [0.65, 0.97]	4.04 [1.86, 8.70]
Within owner	0.70 [0.53, 0.91]	4.56 [2.10, 10.08]
Furnace-years	944	
Closures	33	

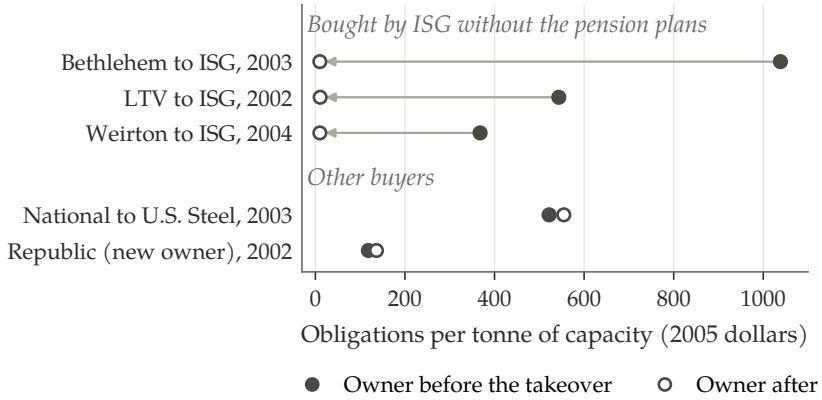
Notes: Odds ratios of closing a blast furnace due for relining (of unknown age, or at least 11 years into its campaign), penalized (Firth) logits, 1986–2015, 95% profile-likelihood intervals in brackets. Closing against continuing, over furnace-years. Obligations: the owner's pension and retiree health obligations before plan assets or, in the second row, net of them, per $100 per tonne of capacity. Chapter 11: owner in bankruptcy reorganization. Rows add the Chapter 11 state, balance-sheet and works controls (on the 829 furnace-years with every regressor), the years after a takeover of the pension plans by the Pension Benefit Guaranty Corporation (PBGC), added to the Chapter 11 row, and, in the last row, obligations as deviations from the owner's mean. Regressors dated $t-1$. –: not included in the specification.

C.5 Demand elasticities

The counterfactuals of Section 6 let steel prices respond to policy. I estimate the price elasticity of demand from annual shipments by product in the CIR (U.S. Census Bureau 1983–2010), 1985–2010, with product trends and demand shifters, instrumenting the price with the material cost of the route that makes the product, which I use to shift supply rather than demand. The short-run demand curve is close to vertical. The estimated elasticities are close to zero, -0.03 pooled, 0.03 for flat products, and -0.10 for long products, with first-stage F statistics of 134 to 173 for the excluded instrument, and the flat-product estimate has the wrong sign. Their 95% Anderson–Rubin confidence sets, which remain valid with weak instruments, include zero. Restricted to downward-sloping demand, they rule out elasticities above 0.17 pooled, 0.18 for flat products, and 0.28 for long products, in absolute value. The flat-product and pooled estimates lie below the elasticity of about 0.15 at which the open grant becomes the cheaper one (Section 6.3).

Input prices also move with demand, which would bias these estimates toward zero, so the counterfactuals use 0.20 for flat and 0.25 for long products as central values of the absolute elasticity, both more elastic than the point estimates. The long value lies within the long bound and at the low end of the range of 0.25 to 0.75 given for rebar by USITC (USITC 2017), while the flat value is slightly more elastic than the flat bound and at the low end of the range of 0.20 to 0.60 given in an earlier steel investigation (USITC 2001). The sensitivity runs of Appendix E.2 use 0.05 and 0.40 for flat and 0.10 and 0.60 for long products, a low value just above the point estimates and a high value inside the USITC

Figure C.2: Owners' obligations at the PBGC takeovers



Notes: Unfunded pension and retiree health obligations of the owner per tonne of its steelmaking capacity, 2005 dollars, before (filled) and after (open) the year the works changed hands at a PBGC takeover of the owner's pension plans. Top group: works that ISG bought without the pension plans. Bottom group: other buyers. ISG: International Steel Group. PBGC: Pension Benefit Guaranty Corporation. Source: Compustat (S&P Global Market Intelligence 2026b), the owners' 10-K filings, and the PBGC's list of trusteed plans (Pension Benefit Guaranty Corporation 2026).

ranges.

The elasticity of import supply comes from annual changes in log imports on changes in the log U.S. price, 1994–2015. OLS gives 0.70 for flat and 0.68 for long products. Instrumenting the price with the growth of U.S. durable-manufacturing output, which shifts U.S. demand and not foreign supply, gives the central values 1.48 and 1.30, with upper interval ends 3.17 and 2.19. The instrument is weak for flat products, so the sensitivity runs use the OLS estimates as low and the upper interval ends as high values, and neither changes the ranking of the grants (Appendix E.2).

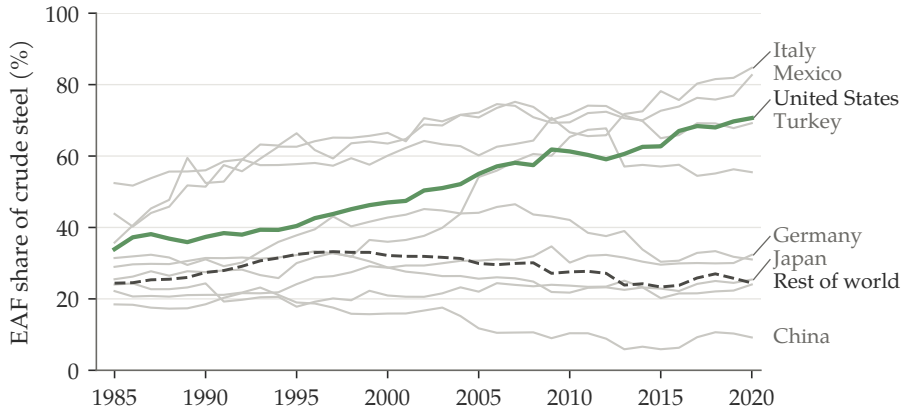
C.6 Alternative explanations

Added one at a time to the margin process of Appendix B.4, only durable-manufacturing growth improves the fit, and it matters for EAF long margins ($3.6 per tonne per point of growth, standard error 1.5) more than for integrated flat margins ($3.4, 2.7). Demand moves the margins of both routes together, and the model carries it through the margin process. One point more of last year's import share goes with an integrated flat margin $−10.1 per tonne lower (standard error 4.8), against $−5.6 (3.4) for EAF flat, while broad trade measures are imprecise ($9.5, 43.4). Imports enter the model through the margins of integrated works.

After 2008 the real gas price fell 73%, but electricity at EAF flat and long plants fell only 7% and 11%. Electricity explains $1.9 of the $−263 change in the EAF flat margin index over those years, against $−445 for the steel price. Cheap gas mattered for differences in EAF costs across states more than for the industry margin, and it came late in the period.

Air-quality rules bind through nonattainment designations, which tighten permitting in a county. Integrated works expected to face more enforcement were more likely to close (Deily and Gray 1991). Across manufacturing, nonattainment slowed the growth of polluting plants relative to the same industries in attainment counties, for iron and steel

Figure C.3: EAF share of crude steel by country, 1985–2020



Notes: Share of crude steel made in electric arc furnaces (EAF), in percent, 1985–2020. Rest of world: world production less the United States. Unlabelled lines: other large producers. Source: Steel Statistical Yearbooks of the World Steel Association (worldsteel 1994–2022).

clearly so under the carbon monoxide rules (Greenstone 2002), and rules stricter for new sources and major modifications give owners a reason to keep old plants running (Bialek-Gregory et al. 2025; Stavins 2006). Regulation added to the pressure on old integrated works, but the data do not show it as the force that decided between converting and closing.

C.7 Evidence from other countries

Figure C.3 shows the EAF share of crude steel by country, from the Steel Statistical Yearbooks of the World Steel Association (worldsteel 1994–2022): the rest of the world stood at 24% in 1985 and 24% in 2020, while Italy and Mexico reached higher EAF shares than the United States, and Turkey about the same. Regressing the log U.S. scrap price on the log world price and the U.S. EAF share, 1989–2015, gives 1.2 % per point of EAF share without a time trend and 0.85 % with one.

D Model and Estimation

D.1 States and payoffs

A configuration is its BOF and EAF capacity as shares of the spell's site capacity K. An integrated works can reach the add-on hybrid (EAF share κ_{add}), the EAF mill after a conversion (share κ_{conv}), and the EAF mill after the hybrid retires its blast furnaces. A legacy hybrid keeps its observed EAF share. A node is a configuration with whether the site operates, is idle, or is under construction, and every configuration has an idle node. A node also holds the campaign age of the main blast furnace, the years since its last reline, up to a cap of 25 years. Idle years do not age it and a reline resets it. A conversion passes through $T^{\text{conv}} - 1$ construction years with building-cost installments and no steel, an add-on through $T^{\text{add}} - 1$ years while the blast furnaces run. Other changes in capacity follow the data. Each starts a new spell, whose characteristics the owner takes as given.

The three margin indices follow the price process of Appendix B.4: a joint chain of all three for flat sites (Tauchen 1986, 125 states), their projection for the two long integrated works, and a 7-state Rouwenhorst chain for EAF long mills. After 2015 costs are frozen at their 2015 values, utilization is its 2011–15 mean, and the furnace-replacement hazard is 0.28 per 100 mill-years, the rate of source-dated replacements in 2016–2020.

A firm's obligation per tonne of its capacity is constructed in Appendix A.3. The level is $L_f = 0$ below \$5 per tonne, $L_f = 1$ at or above \$50, and 0.5 in between or when no usable record exists. The scale $\bar{\lambda}$ is the mean obligation per tonne at $L_f = 1$ over the decisions of integrated works. On the gross basis, a robustness check of Section 5.4, the scale would be \$520 per tonne.

Appendix B.2 gives the building cost I^C. The adoption sizes and building times follow the observed adoptions. An add-on builds an EAF of 0.70 of the works' capacity and keeps 0.50 as BOF capacity, and the EAF produces on the other 0.50. A conversion leaves an EAF mill of 0.46 of the works' capacity and takes 2 years to the first heat, and an add-on takes 1 year. I set the share α of the BOF non-material cost that idle blast-furnace capacity still costs at 0.5, close to the labor share of that cost, and the time a new mill takes to produce at 2 years, about the time the two observed conversions took to build. I take the demand elasticities from my estimates and the literature and estimate the import-supply elasticities (Appendix C.5). Appendix D.4.5 varies α, the entry lag, the obligation cutoffs, and the campaign values.

The plant utilization factor U_i^{p} of Equation (1) is the plant's average output relative to its route's in the years before the decision, leaving out run-down years, as Appendix A.1 describes. The term $p_{it}^{\mathrm{mix},r}$ prices the plant's own product mix: with shares w_{ijt} of products j, prices p_{jt}, and finishing costs C_{jt}^{fin} over the base product, hot-rolled sheet or rebar, whose price is the segment price p_{yt} of Equation (11),

$$p_{it}^{\mathrm{mix},r}(\zeta) = \sum_j w_{ijt}\left(p_{jt} - C_{jt}^{\mathrm{fin}}\right) - p_{yt}. \tag{20}$$

The high-end cap $\bar{w}_t$ of Section 4.1 applies in the configurations that adoption creates and in the EAF mill left when a hybrid retires its blast furnaces, and Appendix B.1 builds it. It is part of the EAF technology path, which is exogenous to plants and policy: the cap by period, the trend in the entry cost, and the quality penalty on EAF flat steel before 1989 (Appendix B.2). The cleanup accrual C_{it}^{rem} per tonne of BOF capacity comes from the owners' annual reports, as Appendix A.3 describes.

D.2 Relines, idling, and furnace replacements

I estimate the three hazards in a first step and do not carry their estimation error into the intervals. The reline hazard $h^R(\nu)$ is a logit of the reline indicator on a constant, the campaign age, an indicator for the age cap, and one for the years after 2000, fitted to 33 major relines in 554 works-years. It rises from 2.4 % a year at age zero to 23 % at age 24. King's reline table records fewer relines after 2000, so the logit has an indicator for those years, which I set to zero in the model. The idle hazard h^I is the share of operating

Table D.1: Parameters

Parameter	Description	Value	Source
A. Adoption and closure			
ϕ_C	Fixed adoption cost, $ billion per adoption	$0.77	Table 3
S^X_{EAF}, S^X_{BOF}	Closure values	$96, $475	Table 3
I^C	Building cost per tonne of new EAF capacity	$260	Appendix D.1
κ_{add}, κ_{conv}	EAF capacity of an add-on, of a conversion	0.70, 0.46	Appendix D.1
T^{add}, T^{conv}	Years to the first heat	1, 2	Appendix D.1
	Add-on capacity in use, BOF and EAF	0.50, 0.50	Appendix D.1
α	Cost share of idle blast-furnace capacity	0.5	Appendix D.1
B. Obligations and events			
$\bar{\lambda}$	Obligation scale	$206	Section 2.3
L_f	Obligation levels	0, 0.5, 1	Appendix D.1
h^R, h^I, h^F_t	Reline, idling, furnace-replacement hazards	–	Appendix D.2
C^R	Reline cost	$17	Appendix D.2
C^I, C^H, C^S	Idling, holding (a year), restart costs	$10, $8, $20	Appendix D.2
C^A, $\bar{v}$	Aging cost a year, campaign length	$2, 15	Appendix D.2
C^F	Furnace replacement	$99	Appendix D.2
C. Shocks			
σ, ρ	Shock scale, elasticity to capacity	$158, 0.59	Table 3
D. Entry			
$F^{\text{ent}}_{\text{flat}}$, $F^{\text{ent}}_{\text{long}}$, τ	Entry costs, trend	$805, $1059, $13.7	Table 3
$\bar{N}$	Potential entrants	10	Section 5.1
T^{ent}	Entry lag, years	2	Appendix D.1
E. Prices and other			
z_t	Margin process	–	Appendix B.4
η^d_y, η^m_y	Demand, import-supply elasticities	0.20, 0.25; 1.48, 1.30	Appendix C.5
U^r_t, U^{P}_i	National, plant utilization	–	Appendix A.1
β	Discount factor (annual)	0.85	Section 5.1

Notes: Parameters of the model and where each is set. The fixed adoption cost ϕ_C, the closure values, the shock parameters σ and ρ, and the entry costs are estimated by maximum likelihood (the entry costs on the joint estimate), the hazards are estimated in a first step, and the others are set where the Source column shows. The policy experiments use the entry costs estimated given the plant model, $830 and $1089 with a trend of $14.0 a year. 2005 dollars per tonne of the capacity concerned unless stated. κ_{add}, κ_{conv}: shares of site capacity. L_f: the owner's level, a discretization that keeps the state small: 0 below $5 of unfunded obligations per tonne, 1 at or above $50, 0.5 between. C^F: per tonne of furnace capacity, on 97% of mill capacity. Elasticities for flat, then long products, demand elasticities in absolute value. U^r_t: national utilization of route r by year. U^{P}_i: plant i's utilization relative to its route. –: estimated or measured by year or plant, not a single value.

site-years in which a site was idled, 0.33 % (9 in 2,733). The furnace-replacement hazard h^F_t is the rate of source-dated replacements at EAF mills, 2.51, 1.24, and 0.71 per 100 mill-years in 1986–95, 1996–2005, and 2006–15.

The costs of these events come from company filings and the trade press, per tonne of the capacity concerned and in 2005 dollars. A reline costs $17 per tonne of BOF capacity, the median of three relines: Edgar Thomson No. 3 in 2001 (Boselovic 2001), Warren in 2004 (Association for Iron & Steel Technology 2004), and Burns Harbor D in 2008 (Holecek

2008). Idling costs \$10 per tonne and holding an idle works \$8 per tonne a year, from AK Steel's charge for idling the Ashland Works blast furnace and steelmaking operations in 2015 and its costs of keeping them idle in 2016 and 2017 (AK Steel Holding Corporation 2016, 2018). A restart costs \$20 per tonne, U.S. Steel's costs of restarting the two blast furnaces at Granite City in 2018 as its third-quarter report gives them (United States Steel Corporation 2018). A furnace replacement costs \$99 per tonne of furnace capacity on 97% of an EAF mill's capacity, close to the cost per tonne of AK Steel's new furnace and ladle furnace at Butler (AK Steel Holding Corporation 2009) and to the EAF in the cost estimates of CRU (2024). I set the cost of an aging campaign at $C^A = \$2$ per tonne of BOF capacity for each year beyond $\bar{v} = 15$ years. It reaches \$20 per tonne at the age cap, about a fifth of the BOF non-material cost, and $\bar{v}$ is about the median campaign of the fitted reline hazard, 14 years. Table D.6 varies both.

D.3 Solution and likelihood

Let $\mathcal{A}^{\text{idle}}(n)$ be the choices open to an idle site: hold, restart, convert if the works is integrated, and close. An idle site pays a holding cost of C^H per tonne a year and has the value $V_t(n,z) = -C^H K + \bar{v}_t(\mathcal{A}^{\text{idle}}(n) \mid n,z)$. A construction year pays the holding cost and the building-cost installment and moves to the next node without a choice. Within a menu $\mathcal{A}$, the probability that the owner chooses a is the logit of Equation (8). For each spell and parameter vector, the stationary continuation $V_\infty(n,z)$ with the primitives of 2015 frozen solves Equation (7) by value iteration, a contraction of modulus β. Backward induction then runs from 2015 to the spell's first decision year, with the expectation $\sum_{z'} \Pr(z' \mid z) V_{t+1}(n',z')$ over the price-state chain.

Each decision contributes the probability of the observed choice. Because relines and idling are events, that probability mixes the menu $\mathcal{A}^{\text{reg}}$ of an operating site in a regular year and the menu $\mathcal{A}^{\text{arr}}$ when a reline need arrives. The probabilities of keeping, of relining, and of a choice a open in both menus, such as closing, adding an EAF, or converting, are

$$\begin{aligned}
&\text{keep:} && (1-h^I)(1-h^R)\ \Pr_t(\text{keep} \mid \mathcal{A}^{\text{reg}}),\\
&\text{reline:} && (1-h^I)\,h^R\ \Pr_t(\text{reline} \mid \mathcal{A}^{\text{arr}}),\\
&a \in \mathcal{A}^{\text{reg}} \cap \mathcal{A}^{\text{arr}}: && (1-h^I)\big[(1-h^R)\ \Pr_t(a \mid \mathcal{A}^{\text{reg}}) + h^R\ \Pr_t(a \mid \mathcal{A}^{\text{arr}})\big].
\end{aligned}$$

The choices of an idle site are logits within $\mathcal{A}^{\text{idle}}$. The timing states recode two sites, so the likelihood has 2,760 decisions against the 2,763 of Table 2 and counts 29 closures of EAF mills against 28: Kentucky Electric Steel closes in its last operating year and its later idle years are dropped, and the construction year of Lorain's conversion is dropped.

The plant log likelihood $\ell^P(\theta)$ of Equation (13), with $\theta = (\phi_C, \sigma, \rho, S^X_{\text{EAF}}, S^X_{\text{BOF}})$, is maximized by a quasi-Newton method, with exact gradients from forward-mode automatic differentiation through the fixed point.

In the policy experiments and in the baseline estimate of the entry costs used for them, each potential entrant has the mean capacity K^{ent}_y of its segment's observed entrants and a utilization factor of one. The joint estimate also evaluates entry at K^{ent}_y but averages

the value of entry over five utilization factors drawn from those of the observed entrants, which a mill learns after it builds and keeps thereafter. In the joint estimate, entered capacity is counted with five equal-weight sizes of the segment's entrants around a log-linear trend in the year of entry. Given θ, the entry block of the likelihood, Equation (14), is concave in $(F^{\text{ent}}_{\text{flat}}, F^{\text{ent}}_{\text{long}}, \tau)$, which are concentrated out. The joint estimate holds ρ at its plant-model value and gives the same ranking of the grants.

D.4 Robustness and validation

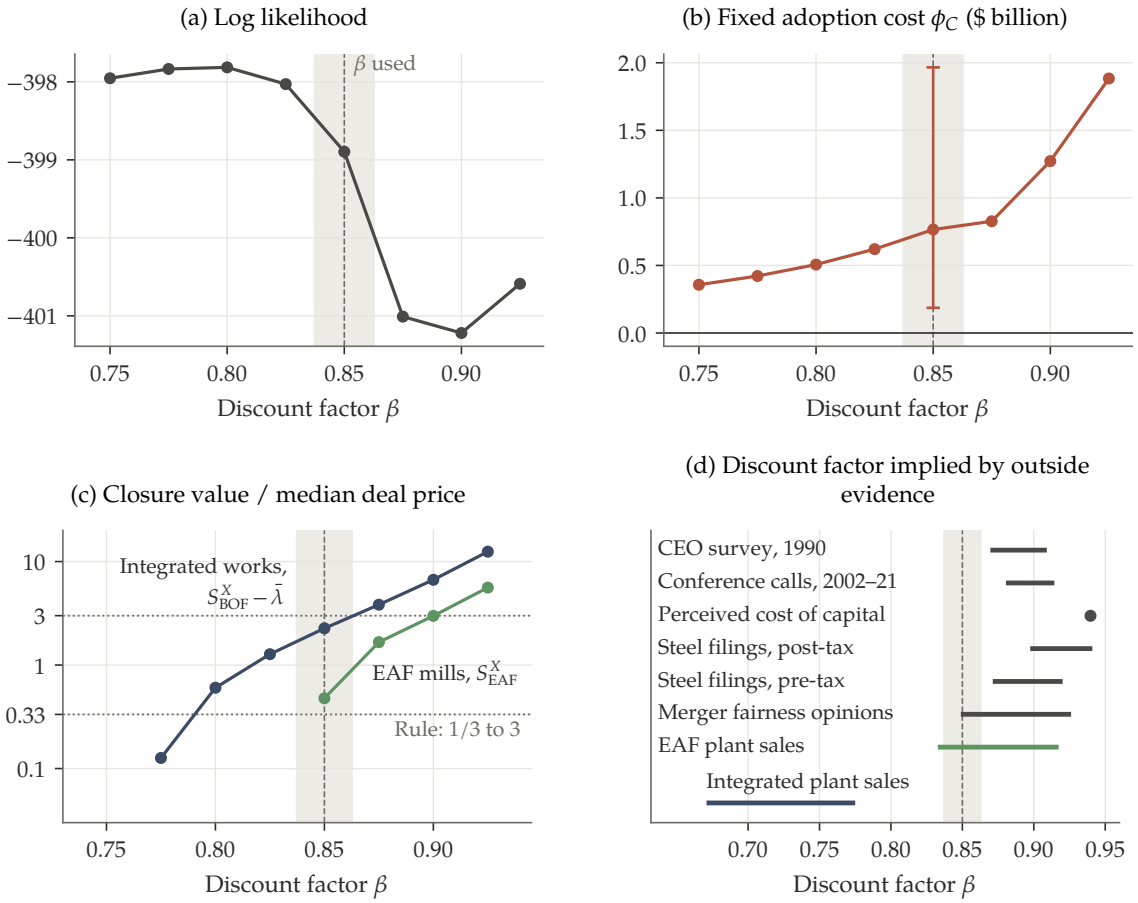
D.4.1 The discount factor

I fixed a rule for β before estimating on a grid from 0.75 to 0.925: a value is plausible if both closure values, what closing is worth to an owner per tonne of capacity, lie within a factor of 3 of the median price buyers paid for going plants of that kind in Appendix C.3, S^X_{EAF} against \$201 per tonne for EAF mills and $S^X_{\text{BOF}} - \bar{\lambda}$, net of the obligation scale $\bar{\lambda}$, against \$119 for integrated works. Figure D.1(c) shows that only $\beta = 0.85$ passes. The choice does not hinge on the factor: any factor from about 2.3 to 3.8 selects the same value, and only a larger one admits the next grid value too. Below $\beta = 0.85$ the closure value of EAF mills is negative, while above it that of integrated works net of obligations exceeds 3 times the median price. The likelihood is nearly flat up to 0.85: its best value is 0.80, and the likelihood-ratio statistic of 0.85 against it, 2.2, does not reject 0.85. The real rate that $\beta = 0.85$ implies is 18% a year. Outside evidence, in Figure D.1(d), points to a higher β: hurdle rates in a 1990 survey of chief executives (Poterba and Summers 1995) give 0.87 to 0.91, and conference calls in 2002–21 (Gormsen and Huber 2025), impairment tests, merger fairness opinions, and sales of EAF mills give similar or higher values, while sales of integrated works imply a lower β. Against its best value, the likelihood rejects every grid value above 0.85, with likelihood-ratio statistics from 5.6 to 6.8 against the 5% critical value of 3.84. A higher β raises the friction estimate: from $\beta = 0.825$ to 0.90, ϕ_C rises from \$0.62 to \$1.27 billion.

D.4.2 Monte Carlo experiments

The experiment re-estimates the baseline model on panels simulated with known parameters on the sample's own plants, states, and price history, at two design points for the shock scale σ_0: the estimate, \$157.7 per tonne, and a lower value, \$90.5 per tonne. At each design point ϕ_C and the closure values are calibrated so that the simulated panels reproduce the observed numbers of closures and adoptions, which gives a true ϕ_C of \$0.67 billion at the estimated scale. Coverage and finiteness use all 200 replications per point, and median width uses the finite intervals among them. The criteria, scaled by the larger of the true $|\phi_C|$ and the mean building cost of an adoption, are: (G1) the estimate is interior in at least 90% of replications; (G2) the coverage of the 95% likelihood-ratio interval lies between 0.90 and 0.99; (G3) the median bias is at most 0.25 times the scale; (G4) the interval is finite in at least 90% of replications, with median width at most 2 times the scale.

Figure D.1: Choosing the discount factor



Notes: The plant model re-estimated at each discount factor β. (a) Log likelihood at the estimate. (b) Fixed adoption cost ϕ_C, with its 95% profile-likelihood interval at $\beta = 0.85$. (c) Closure values over the median deal price for plants of the kind, log scale: S^X_{EAF} for EAF mills and $S^X_{BOF} - \bar{\lambda}$ for integrated works. S^X_{EAF} and S^X_{BOF} are what closing is worth to the owner, per tonne of capacity before shutdown costs, and $\bar{\lambda}$ is the scale of the shutdown obligations per tonne. (d) $\beta = 1/(1 + \text{real discount rate})$, with nominal rates made real at the mean inflation of the GDP deflator of the Bureau of Economic Analysis (BEA 2026) over 2002–2020. Bars span each source's range. CEO survey: real hurdle rates of chief executives in 1990 (Poterba and Summers 1995). Conference calls: hurdle rates firms state in earnings calls, 2002–2021, and (dot) their perceived cost of capital (Gormsen and Huber 2025). Steel filings: discount rates in the impairment tests and valuations of steel firms' 10-K filings, 2008–2021, post-tax and pre-tax. Merger fairness opinions: discount rates in advisers' valuations of steel mergers, 2006–2008. Plant sales: the model's expected cash flow of the plants sold over the price paid, in sales by sellers not in distress, 1985–2014. Green: EAF mills. Dark: integrated works.

At the estimated scale the estimate is interior in at least 90% of replications, its median bias is $0.049 billion against a limit of $0.168 billion, and the coverage of the 95% interval is 0.915. Coverage is lowest in the 19 panels without an adoption, 74%, against 96% in the panels with two adoptions, as in the data. The very large estimates in panels without an adoption pull the mean estimate up to $1.70 billion, while the median bias stays small. The interval is finite in 0.905 of the panels, and infinite only in panels without an adoption. Its median width, $1.66 billion, is above the limit of $1.34 billion. At the lower design point (true ϕ_C = $0.02 billion), every criterion holds except the share of finite intervals, 0.870, again because some panels simulate no adoption.

Two further designs test the rejection of $\phi_C = 0$ and the interval at the estimate. Under the null, the panels are simulated from the model estimated with $\phi_C = 0$, the other

parameters re-estimated, which predicts 3.7 adoptions per panel against the observed two. Over 200 panels, the likelihood-ratio test of $\phi_C = 0$ rejects in 1%, 6.5%, and 12% of them at the 1%, 5%, and 10% levels (Monte Carlo standard error 1.7 points at 5%), and its 95th percentile is 4.52 (95% order-statistic confidence interval for that percentile, 3.16 to 5.60), against 3.84 for the $\chi^2(1)$ distribution. None of the panels yields a statistic as large as the observed 9.27, and none of the 29 panels with two adoptions rejects. At the estimate, the panels simulate 1.7 adoptions on average, and none in 16.5% of them. The 95% interval for ϕ_C contains the true value in 94% of 200 panels (Monte Carlo standard error 1.7 points), in all 54 with two adoptions, and in 88% of those without an adoption, and the median bias is \$0.12 billion. The intervals for σ, S^X_{EAF}, S^X_{BOF}, and ρ contain their true values in 95.5% to 97% of the panels.

The experiment for the joint estimator draws plant decisions and entry counts at the two calibrated design points described above, with entry costs calibrated to the observed entries, in 100 replications at the estimated scale and 50 at the lower one. Its criteria are: (J1) at least 95% of replications converge; (J2) the coverage of the 95% likelihood-ratio intervals for σ, the two entry costs, and their trend τ lies between 0.90 and 0.99; (J3) the absolute median bias of these parameters is at most 10% of the true value, 25% for τ; (J4) ϕ_C meets the coverage and bias limits of G2 and G3; (J5) the root mean squared error of σ is at most 1.05 times that of the plant model alone. J2 to J5 hold at both design points, except the coverage of the entry-cost trend τ at the low one, 1.00, which is above the upper limit. Every final estimate converges: each fit over the plant parameters reports success, and the maximization over the entry costs, which are concentrated out for given plant parameters, has converged at the final estimates in 100% of the 24 replications that miss J1. J1 also counts intermediate evaluations at which that maximization has a gradient above 10^{-8} or a Hessian that is not negative definite, and 88% and 76% of replications meet it. Solving those evaluations more tightly leaves the estimates of σ, S^X_{EAF}, S^X_{BOF}, and the entry costs unchanged to three decimal places.

D.4.3 Inference

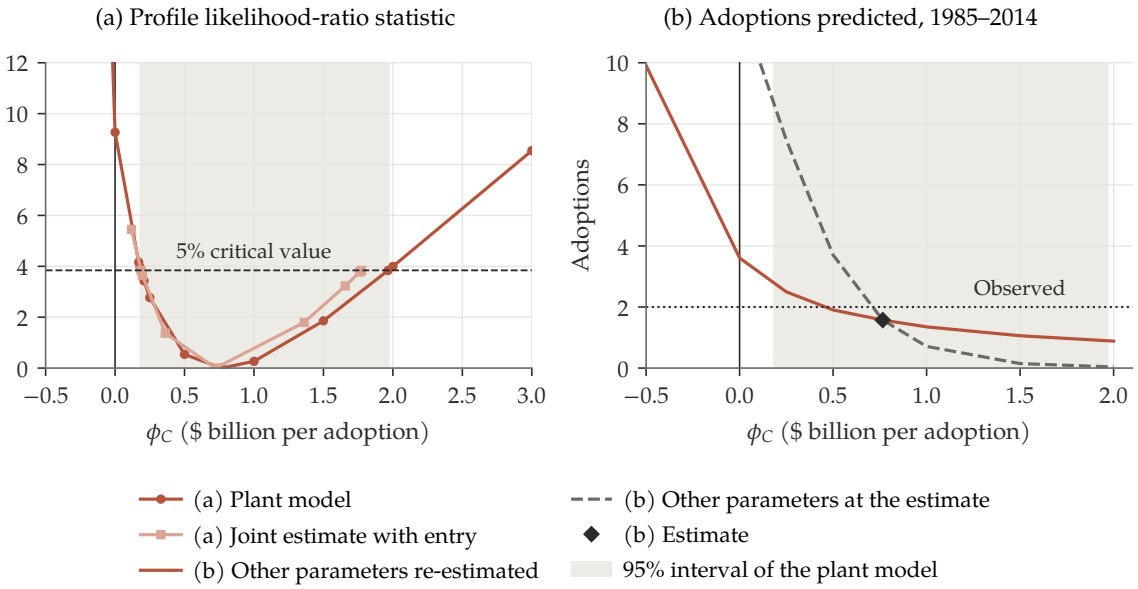
The 95% interval of a parameter ϑ of θ is the set where the profile log likelihood

$$\max_{\theta_{-\vartheta}} \ell^P(\vartheta, \theta_{-\vartheta})$$

is within $\chi^2_1(0.95)/2$ of the maximum. The closures of EAF mills pin down the shock scale. With $\phi_C = 0$ and the other parameters re-estimated, the shock scale falls to \$91, which those closures do not support, and the model still predicts 3.6 adoptions in 1985–2014 against the two observed and 1.6 at the estimate, as Figure D.2(b) shows. These counts come from histories simulated from 1985, while Section 5.2 sums the choice probabilities along the observed paths. The count falls as ϕ_C rises: it passes the two observed adoptions below the estimate and reaches 1.1 at $\phi_C =$ \$1.5 billion.

The profile intervals treat the shocks of different plants as independent, and same-year closures of different sites of one firm co-move more than the model explains (permutation

Figure D.2: Profile likelihood and predicted adoptions



Notes: (a) Profile likelihood-ratio statistic of the fixed adoption cost ϕ_C (billions of dollars per adoption), with the other free parameters re-estimated at each value, for the plant model and the joint estimate. (b) Adoptions in 1985–2014 predicted from 4,000 simulated histories at each ϕ_C, other parameters, including the elasticity ρ of the shock scale with respect to plant capacity, re-estimated (solid) or held at the estimate (dashed).

p-value 0.007, but 0.57 without three firm-years, see Appendix A.2). The firm bootstrap resamples firms with their plants, 100 draws, and re-estimates the five parameters, with the first-step estimates and the other parameters fixed. All 100 draws converged, and the standard error of σ is 107 against the Wald 49. Over all draws, the percentile interval for ϕ_C runs from $0.42 to $12.3 billion, so its lower end stays above zero. Among the 89 draws with an adoption, it runs from $0.40 to $1.83 billion, inside the profile interval. In the 11 draws without one, only closure and idling decisions inform ϕ_C, and its estimate lies between $5.8 and $28.1 billion.

D.4.4 Shapley decomposition

Let $\mathcal{N}$ be the seven parts of the adoption gap in Equation (12), listed in Table D.2, and $g_{it}(a, \mathcal{S})$ the adoption gap computed with only the parts in $\mathcal{S} \subseteq \mathcal{N}$ switched on, the model solved again at the estimated parameters, so that $g_{it}(a, \mathcal{N}) = \Gamma_{it}(a)$ and the baseline is $b_{it}(a) \equiv g_{it}(a, \varnothing)$. The Shapley part of part k averages its effect over all orders in which the parts can be switched on:

$$c_{it}^{k}(a) = \sum_{\mathcal{S} \subseteq \mathcal{N} \setminus \{k\}} \frac{|\mathcal{S}|!\,\big(|\mathcal{N}| - |\mathcal{S}| - 1\big)!}{|\mathcal{N}|!} \Big[g_{it}\big(a, \mathcal{S} \cup \{k\}\big) - g_{it}(a, \mathcal{S}) \Big], \tag{21}$$

and the parts add up exactly to the adoption gap, as in Equation (16). The baseline is not zero although a works and a converted EAF mill have the same flows and closure values, because a works draws a choice shock for each of its four choices and a mill for two. For the gap to convert, the baseline also holds site cleanup and the output lost while the new

Table D.2: Components of the adoption gap

k	Part	Switched off
1	Building cost	$I^C = 0$
2	Forgone profit	Margin of the replacing EAF
3	Shutdown obligations	$\bar{\lambda} = 0$
4	Smaller shop	$\kappa_{\text{add}} = \kappa_{\text{conv}} = 1$
5	Product cap	No cap $\bar{w}_t$
6	Fixed adoption cost	$\phi_C = 0$
7	Closure value	Closing valued as EAF capacity

Notes: The seven parts k of the adoption gap and the input that switches each off. The adoption gap is the one-time payment that would make adopting as good to the owner as the better of keeping and closing. Each part is its average contribution to the adoption gap when switched on, over all orders. I^C: building cost per tonne of new EAF capacity. $\bar{\lambda}$: scale of the obligations due on shutting the blast furnaces, per tonne of BOF capacity. κ_{add}, κ_{conv}: EAF capacity of an add-on and of a conversion, as shares of site capacity. $\bar{w}_t$: cap on the cold-rolled and coated share of a new EAF's output. ϕ_C: fixed adoption cost. Technology (the price of the technology): parts 1, 4, and 5. Forgone profit: part 2. Obligations: part 3. Fixed adoption cost: part 6. Obligations and the fixed adoption cost are the structural frictions. Part 7, the closure value, is not part of adoption.

shop is built, so it is \$213 per tonne against \$158 for the add-on. I net out both baselines the same way. At the estimate, the fixed adoption cost of \$0.77 billion per adoption contributes \$222 per tonne of site capacity to the gap to the add-on. Table D.3 gives the means of the adoption gap, the net gap, and the shares of its parts at the estimate, at the lower end and near the upper end of the interval for ϕ_C, by period, and for the gap to convert.

D.4.5 Alternative specifications

Table D.4 gives the re-estimates of Section 5.4, each changing one setting of the baseline, and the runs of Section 5.2 that leave one decision out.

Margins and output. Pricing what the EAF melts at the prices of scrap and pig iron from 1991 on, and raising the EAF flat margin by \$40 or \$80 per tonne, make adding an EAF at an old works more profitable. The profit the running blast furnaces give up then falls (Table D.5), so a larger fixed adoption cost is needed to explain why only two works adopted, ϕ_C = \$1.25, \$1.30, and \$2.02 billion. The engineering estimates of the finishing cost, for plate, for long products, and for both, replace the estimated ones. They lower the margins of EAF mills, so the mills' observed closures imply larger shocks, and ϕ_C, which is measured on the scale of the shocks, rises to \$0.96, \$1.35, and \$1.43 billion for plate, long products, and both. Each of these specifications fits the choices worse than the baseline. Letting output respond to the margin by route moves ϕ_C little, to \$0.79 billion, and to \$0.85 billion with the largest elasticities.

Shutdown costs. Counting the obligations before plan assets raises their scale to \$520 per tonne from \$206. The closure value of integrated works absorbs most of the larger bill, S^X_{BOF} rising from \$475 to \$664 per tonne, and ϕ_C is \$1.21 billion. Removing the closure obligation while an owner is in Chapter 11 or will file within two years gives ϕ_C = \$0.99

Table D.3: Shares of the net gap

				Share of the net gap (%)			
	ϕ_C	Γ	Net gap	Technology	Forgone profit	Obligations	Fixed adoption cost
A. Baseline estimate, gap to the add-on							
Lower end	0.19	392	268	47	33	0	19
Estimate	**0.77**	**581**	**413**	**25**	**21**	**0**	**54**
Near upper end	1.96	975	732	7	12	0	81
1985–94	0.77	635	461	21	28	0	50
1995–2004	0.77	556	389	24	21	0	55
2005–14	0.77	540	381	31	11	1	58
Gap to convert	0.77	882	657	29	17	20	34

Notes: Means over works-years of running integrated works with an observed decision, 1985–2014. Γ: the adoption gap, the one-time payment that would make adopting as good to the owner as the better of keeping and closing. Net gap: Γ less the choice-set effect and the closure value. ϕ_C in billions of dollars, the adoption gap and the net gap in dollars per tonne of site capacity. Shares: technology (building cost, smaller shop, and product cap), forgone profit, obligations, and the fixed adoption cost ϕ_C, the last two being the structural frictions. Panel A: the baseline at the lower end and near the upper end of the interval for ϕ_C, at the values of ϕ_C shown, and by period, and the gap to convert. Other rows: the gap to the add-on. A negative share means that the part lowers the adoption gap.

billion and a lower likelihood (-401.1 against -398.9), as the model then predicts too many closures among distressed owners. If converting or retiring the blast furnaces brought only half the obligations due, ϕ_C would be \$0.73 billion. Estimated freely, the obligation scale is \$387 per tonne (95% interval \$117 to \$971), which contains the \$206 of the records, with $\phi_C =$ \$0.93 billion.

Closure value, capacity, and furnace replacement. Fixing S^X_{EAF} at the median price of EAF mills in the deals, \$201 per tonne, gives $\phi_C =$ \$0.51 billion, and the likelihood does not reject that restriction (p-value 0.06). Reading EAF capacity from the directories' printed capacities gives \$0.77 billion, and dropping the expected cost of replacing EAF furnaces leaves ϕ_C unchanged.

Leaving out one decision. Without Lorain's conversion, ϕ_C is \$0.98 billion (95% interval \$0.27 to \$2.52), without Steubenville's add-on \$0.89 billion (upper end \$2.33), and without Steubenville's later retirement of its blast furnaces \$0.72 billion (\$0.19 to \$1.87). Leaving out the EAF site of the Farrell works gives \$0.79 billion. These runs drop observations, so their log likelihoods are not comparable with the baseline's.

The decomposition. Table D.5 re-runs the decomposition of Section 5.3 on the nine re-estimates for which it was recomputed. In each, the fixed adoption cost is more than half of the net gap to the add-on, the gap to the add-on stays below the gap to convert, and the obligations add little to the gap to the add-on. Counted net of plan assets, they add \$132 to \$136 per tonne to the gap to convert, and more on the gross basis. In the specifications with a better EAF margin, the forgone profit shrinks and the fixed adoption

Table D.4: Re-estimates of the plant model

	ϕ_C ($ billion)	σ	S^X_{EAF}	S^X_{BOF}	LR	Log-lik.
Baseline estimate	0.77 [0.19, 1.97]	158	96	475	9.3	−398.9
EAF furnace replacement						
Without the furnace-replacement cost	0.77 [0.21, 1.97]	157	103	475	9.3	−399.0
Closure value						
S^X_{EAF} fixed at the median EAF deal price	0.51	108	201	480	–	−400.7
Capacity						
EAF capacity from the printed-capacity rule	0.77 [0.22, 1.93]	182	131	477	10.0	−400.0
Shutdown costs						
Gross obligation basis	1.21 [0.41, 2.90]	207	38	664	14.4	−398.6
Closure obligation lifted in Chapter 11	0.99 [0.32, 2.38]	178	68	429	12.6	−401.1
Half the obligations due on conversion	0.73 [0.21, 1.82]	151	103	478	9.4	−399.1
Obligation scale $\bar{\lambda}$ estimated	0.93 [0.24, 2.93]	176	77	573	10.1	−398.2
Margins and output						
EAF charge priced from scrap and pig iron	1.25 [0.57, 2.66]	203	80	470	26.5	−401.2
Output responds to the margin by route	0.79 [0.22, 2.00]	159	99	473	10.0	−399.1
With the largest elasticities	0.85 [0.24, 2.10]	166	104	493	11.1	−399.1
Engineering finishing cost for plate	0.96 [0.32, 2.27]	190	59	477	13.1	−399.7
Engineering finishing cost for long products	1.35 [0.58, 2.94]	245	27	468	21.7	−402.2
Engineering finishing cost for both	1.43 [0.66, >3.00]	259	24	472	23.9	−402.3
EAF flat margin +$40 per tonne	1.30 [0.61, 2.77]	207	54	471	27.5	−401.9
EAF flat margin +$80 per tonne	2.02 [1.11, >3.00]	285	−35	460	70.0	−405.0
Leave one decision out						
Without Lorain's conversion	0.98 [0.27, 2.52]	159	94	476	11.1	−391.0
Without Steubenville's add-on	0.89 [0.24, 2.33]	164	82	477	10.4	−393.1
Without Steubenville's retirement	0.72 [0.19, 1.87]	154	100	477	8.5	−396.7
Without Farrell's EAF site	0.79 [0.22, 2.02]	163	80	475	9.6	−394.6

Notes: Re-estimates of the plant model at $\beta = 0.85$, each changing one setting of the baseline, with ρ, the elasticity of the shock scale with respect to plant capacity, estimated in every run. ϕ_C in billions of dollars, with its 95% profile-likelihood interval in brackets (">3.00": still inside the interval at the grid's end). σ (shock scale at median capacity), S^X_{EAF} and S^X_{BOF} (closure values of EAF mills and integrated works, what closing is worth before shutdown costs) in dollars per tonne. $\bar{\lambda}$: scale of the shutdown obligations per tonne. LR: likelihood-ratio statistic of $\phi_C = 0$. The run with S^X_{EAF} fixed has no profile (–) and an LR against the baseline of 3.51 (p-value 0.06). Leave-one-out log likelihoods drop observations (eight for the EAF site of the Farrell works, whose one shutdown the sample also counts as an integrated closure) and are not comparable with the baseline's.

cost takes its place.

Table D.6 varies the assumed values of Table D.1 one at a time and re-estimates the plant model. The fixed adoption cost ϕ_C stays between $0.68 and $0.88 billion. The grants' spending at each re-estimate is in Appendix E.2.

Table D.5: Decomposition across re-estimates

		Gap to add-on		Share of the net gap (%)				Gap to convert	
	ϕ_C	Gap	Net	Techn.	Profit	Oblig.	Fixed	Gap	Oblig.
Baseline estimate	**0.77**	**581**	**413**	**25**	**21**	**0**	**54**	**882**	**134**
EAF charge, scrap and pig iron	1.25	680	490	21	5	1	73	1,021	135
EAF flat margin +$40	1.30	683	490	22	1	1	76	1,031	136
EAF flat margin +$80	2.02	837	604	18	−12	1	94	1,248	136
Finishing cost, long products	1.35	763	539	12	16	0	72	1,104	132
Finishing cost, both	1.43	790	558	11	16	0	73	1,142	132
Gross obligation basis	1.21	752	518	17	16	0	68	1,300	358
Obligation lifted in Chapter 11	0.99	651	464	19	19	1	61	966	136
Printed EAF capacity	0.77	569	406	28	17	1	55	875	136
Without Lorain's conversion	0.98	658	489	21	18	0	60	960	134

Notes: The decomposition of Section 5.3 re-run at each re-estimate, means over the works-years of running integrated works with an observed decision. ϕ_C in billions of dollars. Gap to add-on: the adoption gap (Gap) and the net gap (Net), the gap less the choice-set effect and the closure value, in dollars per tonne of site capacity. Shares of the net gap in percent, grouped as in Table D.3: Techn., the price of the technology (building cost, size of the shop, cap on high-end products); Profit, the forgone profit; Oblig., the obligations; Fixed, the fixed adoption cost. Gap to convert and its obligations part (Oblig.) in dollars per tonne, the obligations on the unfunded basis except in the gross-basis run. Rows as in Table D.4. The finishing costs are the engineering estimates.

Table D.6: Re-estimates with other assumed values

	ϕ_C ($ billion)	σ	S^X_{EAF}	Log-lik.
Baseline assumptions	0.77	158	96	−398.9
Cost share of idle blast-furnace capacity, α (baseline 0.5)				
0.25	0.88 [0.29, 2.12]	164	87	−399.4
0.75	0.68 [0.15, 1.84]	154	102	−398.6
Obligation levels, cutoffs for none and full ($ per tonne; baseline 5 and 50)				
2.5 and 25	0.86 [0.24, 2.16]	172	74	−400.2
10 and 100	0.81 [0.23, 2.05]	163	90	−398.8
Aging cost a year, C^A ($ per tonne; baseline 2)				
0	0.80 [0.21, 2.06]	162	92	−399.3
5	0.86 [0.27, 2.06]	166	82	−399.3
Campaign length, $\bar{v}$ (years; baseline 15)				
10	0.76 [0.22, 1.92]	156	97	−398.7
20	0.78 [0.21, 2.02]	160	93	−399.1

Notes: Each row changes one assumed value, named in its panel heading with its baseline value, and re-estimates the plant model, with the 95% profile-likelihood interval for ϕ_C in brackets, in 2005 dollars. σ and S^X_{EAF} in dollars per tonne.

Table D.7: Model fit

	Observed	Expected	
		Baseline estimate	Joint estimate
Decisions 1985–2014			
Closures of EAF mills	29	27.0	26.9
Closures of integrated works and hybrids	8	7.1	7.1
Add-ons	1	1.7	1.7
Conversions	1	0.1	0.1
Retirements of a hybrid's blast furnaces	1	1.4	1.3
Idlings	9	9.0	9.0
Restarts from idle	7	11.3	11.4
Relines	33	38.9	38.9
Held-out decisions 2016–2019			
Closures of EAF mills	2	2.3	–
Closures of integrated works and hybrids	0	0.8	–
Add-ons and conversions	1	0.3	–
Idlings	0	1.1	–
Restarts from idle	3	3.7	–

Notes: Observed: events in the data. Expected: the sum of the model's choice probabilities along the observed state paths, at the baseline estimate and at the joint estimate of entry and the plant model. Decisions 1985–2014: the estimation sample, each decision with its outcome in the next year. Idlings match by construction. Held-out decisions 2016–2019: kept out of estimation, with their outcomes in 2017–2020, expected at the baseline estimate with inputs extended to 2020 and the first-step estimates and the other parameters held at their values. Relines are not coded after 2015 and are left out of the held-out decisions. –: not computed.

D.4.6 Model fit and the holdout

Table D.7 compares the observed events with the events the model expects along the observed state paths, for the decisions of 1985–2014 and for the held-out decisions of 2016–2019. The model matches the total number of flat-product entries but spreads them over both decades, 5.9 in 1985–94 against 2 observed and 4.6 in 1995–2004 against 10, because a linear trend in the entry cost smooths the wave of mills of the 1990s that cast thin slabs and rolled them into sheet. Section 6.3 varies the entry costs across their intervals. The decisions of 2015–2019 are kept out of estimation, among them Fairfield's conversion, and Table D.7 reports those of 2016–2019. In them, the expected counts lie within about one event of the observed counts in every category.

E Policy Counterfactuals

E.1 Sources of the shift to EAFs

As Section 3.1 shows, new EAF mills did most of the decarbonizing with no climate policy. I hold each factor at its 1985 level in turn and express its contribution as the carbon price at which the industry, with that factor held at its 1985 level, emits over 1985–2015 as much CO_2 as the baseline. The factors are the EAF route's technology (non-material

Table E.1: Sources of the shift to EAFs

		Held at its 1985 level			
	Baseline	Technology	Input prices	Both	Integrated
Adoptions, 1985–2014	1.6	0.3	7.3	1.4	1.7
Closures of integrated works	7.0	1.7	12.0	3.2	8.0
Closures of EAF mills	27.8	23.6	22.6	20.2	27.3
Entries of EAF mills, change	0.0	+2.7	+20.5	+15.5	+4.5
Integrated capacity 2015, Mt	47.9	69.8	10.3	61.9	45.5
EAF share of capacity 2015, %	58.3	48.0	91.8	58.6	61.1
Flat price, mean change, \$/t	0.0	+47.1	−27.3	+24.8	+9.9
CO_2 1985–2015, Mt	3,230	3,518	2,808	3,449	2,967
Change from the baseline	0	+288	−421	+220	−277
Equivalent policy					
Carbon price (\$/tCO_2)		34.1	0	21.3	0
Adoption grant (\$/t)		542	0	333	0
Open grant (\$/t)		267	0	154	0
Obligation takeover (%)		>100	0	>100	0

Notes: Model outcomes, 1985–2015, with one factor held at its 1985 level and other inputs on their observed paths, with entry, choices, and prices responding. Technology: the EAF route's non-material cost, flat-product quality penalty, high-end cap, and utilization. Input prices: the scrap and iron the EAF route melts, and its electricity. Integrated: the integrated route's costs, with the obligations kept at the works as if the Pension Benefit Guaranty Corporation (PBGC) had not taken over the pension plans (against the baseline under the calendar-year rule, 3,244 Mt). Both: technology and input prices together. Equivalent policy: the level, interpolated, that brings CO_2 back to the baseline. Carbon price: per tonne of CO_2 on both routes. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works. Obligation takeover: a public fund pays a share of the shutdown obligations when they fall due. >: not reached at the largest level run. 0: no more CO_2 than the baseline.

cost, flat-product quality penalty, high-end cap $\bar{w}_t$, utilization), its input prices (the scrap and iron it melts, and electricity), both together, and the integrated route (costs, with the obligations kept at the works as if the PBGC had not taken over the plans).

The EAF route's technology did the work of a carbon price of \$34.1 per tonne of CO_2: held at 1985, it leaves an industry that emits 288 Mt more than the baseline. Entry changes little, because the higher flat price offsets the worse technology for new mills. With only the input prices held, the industry emits 421 Mt *less*, because the scrap price rose after 2003, while with both held it emits 220 Mt more, an equivalent carbon price of \$21.3 per tonne, 353 Mt above the sum of the single-factor cases, because cheap inputs matter only once the technology has improved. Table E.1 reports each case, and I give no additive shares. The abatement target of 311 Mt is what this equivalent carbon price of \$21.3 per tonne buys in the baseline.

E.2 Further instruments and checks

All robustness checks. Table E.2 gives the spending per tonne of CO_2 of the open, adoption, and conversion grants in the robustness checks of Section 6.3, each at the level that avoids 311 Mt, except the assumed values of the plant model, which Table E.4 gives.

The checks are grouped by the factors of equation (17). A positive gap means the adoption grant is the cheaper one. Near the upper end of the interval for ϕ_C, the largest adoption grant run, \$400 per tonne, avoids 175 Mt. The paragraphs below describe each check.

Site-retention grant. The site-retention grant pays the old site to keep running clean capacity, where the open grant pays clean capacity wherever it is built. At \$64 per tonne of EAF capacity a year, it adds 8.8 adoptions and avoids 2.6 closures of integrated works, but it pays every tonne at an integrated site in every year, \$33.8 billion in all and \$109 per tonne of CO_2, the most of the instruments in Table 4.

Takeover at fixed prices. In a check in which only the owners of existing works respond and prices are held fixed, I count steel that leaves the model's sites as made elsewhere at the blast-furnace intensity, so only a change of route avoids CO_2. Taking over half or all of the obligations then closes 2.9 and 6.5 more integrated works (7.0 without policy) and lowers gross CO_2 by 553 Mt at the full takeover, but avoids no CO_2 at unchanged output. In the main experiments, prices respond, and displaced imports count at 1.2 tonnes per tonne.

Elasticities and entry costs. Table E.3 reruns the grants at the low and high demand elasticities of Appendix C.5, at the OLS and upper instrumented import-supply elasticities, and with the flat and long entry costs together at the ends of their 95% profile intervals (\$570 to \$1204 per tonne for a flat mill). The elasticities move the open grant's budget by a few dollars and the adoption grant's by less, but at the low demand elasticity the open grant is the cheaper. The import-supply elasticities do not change the ranking. The entry cost moves the open grant through the entry that comes without support: at the upper ends of both intervals it costs \$27.5 against \$29.2 per tonne for the adoption grant, and at the lower ends it costs \$60.6 against \$26.2.

Scrap price. The main case holds the scrap price on its observed path. In this sensitivity, I multiply the scrap price, permanently and foreseen, by the ratio of the 25th or 75th percentile of the 1985–2020 real scrap price to its median, in the scenario and its baseline. At the abatement target, the adoption grant costs \$23.4 and the open grant \$36.4 per tonne of CO_2 on the 25th-percentile path, with a non-additional share of 78% for the open grant, and \$43.8 and \$45.1 on the 75th-percentile path. Baseline entry is 61 and 7 mills against 24. Entry responds strongly to the scrap price, as it does to the entry cost in Section 6.3, and that response sets how much of the open grant goes to mills that would come anyway.

Assumed values. Table E.4 re-solves the grants at each re-estimate of Appendix D.4.5 with one assumed value changed, and with an entry lag of one or three years instead of two. The adoption grant costs less than the open grant, by at most \$1.7 per tonne, in nine of the ten cases. In the tenth, an entry lag of three years, the open grant costs \$0.08 less.

Table E.2: Robustness checks of the comparison

	$ per tonne of CO_2			
	Open	Adoption	Conversion	Gap
Baseline (Table 4)	28.1	27.5	49.5	0.6
A. Entry that would come without support				
Entry costs at the lower ends	60.6	26.2	–	34.4
Entry costs at the upper ends	27.5	29.2	–	−1.7
Scrap price, 25th percentile	36.4	23.4	–	13.0
Scrap price, 75th percentile	45.1	43.8	–	1.3
Entry lag of one year	28.8	27.4	48.2	1.4
Entry lag of three years	27.6	27.7	50.9	−0.1
B. CO_2 each added tonne avoids				
Demand elasticity, low	26.5	27.7	–	−1.2
Demand elasticity, high	30.7	27.1	–	3.6
Import elasticity, low	28.4	27.5	–	0.9
Import elasticity, high	27.8	27.4	–	0.4
Iron from the blast furnaces, 10%	28.3	28.6	–	−0.3
Iron from the blast furnaces, 30%	28.7	31.2	–	−2.5
State-by-year grid factors	29.5	29.6	–	−0.1
C. Grant old works need				
Lower end of the ϕ_C interval	23.0	23.0	–	0.0
Near the upper end of the ϕ_C interval	39.4	n.r.	–	–
Joint estimate	27.8	27.2	48.9	0.5
Half the obligations due on conversion	26.6	26.4	45.1	0.2
Baseline, coarse grid of levels	29.5	28.3	49.5	1.2
EAF charge, scrap and pig iron	31.4	31.7	58.1	−0.3
EAF flat margin +$40	30.2	29.0	56.7	1.2
EAF flat margin +$80	33.9	31.4	63.6	2.5
Finishing cost, long products	36.9	33.6	59.8	3.2
Finishing cost, both	37.6	35.0	62.0	2.6
Gross obligation basis	37.8	33.5	67.5	4.3
Obligation lifted in Chapter 11	32.0	28.7	51.7	3.3
Printed EAF capacity	29.0	24.4	43.8	4.6
Without Lorain's conversion	30.8	31.9	53.7	−1.1
D. Beside a carbon price, coarse grid of levels				
No carbon price	29.5	28.3	–	1.2
Carbon price of $25	24.5	25.7	–	−1.2
Carbon price of $50	29.9	29.5	–	0.4

Notes: Public spending per tonne of CO_2 avoided, 2005 dollars, undiscounted, each grant at the level that avoids 311 Mt of CO_2 over 1985–2015, with entry and prices responding. Open grant: paid for new EAF capacity at new mills and old works. Adoption grant: paid to old works that add an EAF or convert. Conversion grant: paid to old works that convert. Gap: open less adoption grant. Entry costs: those of flat-product and long-product mills together at the ends of their 95% intervals. Scrap price: the observed path scaled to the 25th or 75th percentile of the 1985–2020 real price. Iron from the blast furnaces: share of what the add-on's EAF melts, CO_2 recounted with choices held fixed. Grid factors: EAF electricity at the state's CO_2 factor in each year, CO_2 recounted with choices held fixed. Lower end and near the upper end of the ϕ_C interval: $0.19 and $1.96 billion, the other parameters re-estimated. Indented rows: the re-estimates of Appendix D.4.5. Panel D: each grant avoids 311 Mt beyond the carbon price alone. The re-estimates and Panel D interpolate on a coarser grid of grant levels and compare with their own first row. n.r.: not reached at the levels run. –: not computed.

Table E.3: Sensitivity to elasticities and entry costs

	Adoption grant		Open grant		Conditional grant		
Case	\$/t	ι	\$/t	ι	\$/t	ι	Gap
Central	27.5	13	28.1	54	33.4	21	+0.6
Demand elasticity, low	27.7	13	26.5	56	34.3	21	−1.2
Demand elasticity, high	27.1	14	30.7	52	31.5	22	+3.6
Import elasticity, low	27.5	13	28.4	54	33.0	21	+0.9
Import elasticity, high	27.4	13	27.8	54	33.2	21	+0.4
Entry cost F^{ent}, low	26.2	14	60.6	83	27.6	23	+34.4
Entry cost F^{ent}, high	29.2	13	27.5	17	42.1	19	−1.7

Where the gap reaches zero

	Range of the input	Zero at, 311 Mt	Zero at, 150 Mt
Demand elasticity, flat	0.05–0.40	0.15	0.07
Import elasticity, flat	0.70–3.17	5.67	8.15
Entry cost F^{ent}, flat, \$/t	570–1,204	–	–

Notes: Public spending per tonne of CO_2 avoided, dollars per tonne, undiscounted, each grant at the level that avoids 311 Mt. ι: the non-additional share, percent of the payments made for investment that would happen without the grant. Gap: open less adoption grant. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works. Conditional grant: paid when an old works retires its blast furnaces. Cases: demand and import-supply elasticities at low and high values, and both entry costs at the ends of their 95% intervals. F^{ent}: entry cost of a new mill beyond the steelmaking shop, dollars per tonne. Lower panel: the input value at which the two grants cost the same, interpolated through the cases and extrapolated outside the tested range, at the target and at 150 Mt. –: with the long-product entry cost held at its estimate, the two grants do not cost the same anywhere in the tested interval.

Iron from the blast furnaces. If the add-on's EAF also melts liquid iron from the works' blast furnaces, it replaces less blast-furnace steel. I recount the CO_2 of the add-on hybrids with choices and prices as estimated, and at the lower value tested, 10% of what the EAF melts, the open grant becomes the cheaper one.

Grid intensity. The main results count EAF steel at a fixed 0.4 tonnes of CO_2 per tonne. In this check, its intensity is 0.08 tonnes of direct emissions plus 0.52 MWh of electricity per tonne times the CO_2 factor of the power sector of the plant's state in each year, as in the decomposition of Section 3.1. Without a carbon price no choice depends on emissions, so at each grant level choices, payments, and prices are those of the main runs, and only the count of CO_2 changes at unchanged grant levels. Section 6.3 reports that change and the spending after interpolation to the common abatement target.

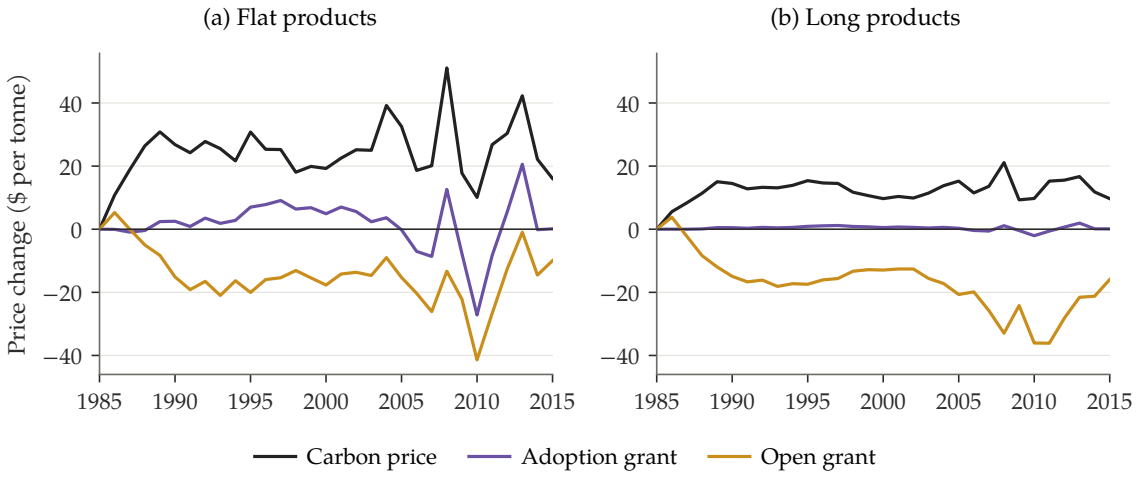
Displacement and prices. Under the open grant the part of the entrants' extra output that replaces other domestic output is $1 - \Delta X_y / \Delta X_y^{\text{ent}}$, with ΔX_y^{ent} the entrants' extra output in segment y and ΔX_y the change in the segment's domestic output, both summed over 1985–2015 against the baseline. It is 0.87 in flat and 0.76 in long products, and the rest goes to extra consumption and fewer imports. As Figure E.1 shows, the open grant lowers average steel prices over 1985–2015, while the carbon price raises them. Prices move by tens of dollars in single years because demand responds little to price (Appendix C.5).

Table E.4: Grant spending with other assumed values

	$ per tonne of CO_2		
	Adoption	Open	Conversion
Baseline assumptions	27.5	28.1	49.5
Cost share of idle blast-furnace capacity, α (baseline 0.5)			
0.25	28.2	28.5	51.9
0.75	26.9	27.7	47.3
Obligation levels, cutoffs for none and full ($ per tonne; baseline 5 and 50)			
2.5 and 25	28.4	28.9	51.3
10 and 100	27.5	29.1	49.6
Aging cost a year, C^A ($ per tonne; baseline 2)			
0	28.8	29.3	51.9
5	26.8	28.2	47.8
Campaign length, $\bar{v}$ (years; baseline 15)			
10	26.5	27.1	47.6
20	28.2	28.7	50.8
Entry lag, T^{ent} (years; baseline 2)			
1	27.4	28.8	48.2
3	27.7	27.6	50.9

Notes: Public spending per tonne of CO_2 avoided of the adoption, open, and conversion grants at the abatement target, in 2005 dollars. Each row changes one assumed value, named in its panel heading with its baseline value, re-estimates the plant model and the entry costs, and re-solves the grants. Rows compare with the first row, computed the same way. The entry lag does not enter the plant likelihood, so its rows keep the plant estimate.

Figure E.1: Steel price changes at the abatement target



Notes: Change in the domestic steel price from the baseline, 2005 dollars per tonne, 1985–2015, at the point estimate, each instrument at the level that avoids 311 Mt of CO_2. Carbon price: per tonne of CO_2 on both routes. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works.

Grants with a carbon price. Added to carbon prices of $25 and $50 per tonne, each grant set to avoid a further 311 Mt, the adoption and open grants stay close. The open grant costs less at the lower price, $24.5 against $25.7 per tonne for the adoption grant, and the adoption grant costs less at the higher, $29.5 against $29.9, while the open grant pays far more for investment that would occur under the carbon price alone: 66% and 73% against 24 and 32.

E.3 Welfare accounting and incidence

Net welfare is Equation (18) with the values of Section 6.4, and Table 4 gives the break-even carbon values. With the choice-shock term, the conditional grant has the lowest welfare cost at the one target where the open grant does not. Without that term, the takeover does well because obligations are transfers for the economy but costs for the owner, so they keep open works whose closure would raise welfare.

Table E.5 gives who gains and who pays at the abatement target: the conditional and site-retention grants raise the surplus of existing plants by $18.4 and $16.8 billion. Without the choice-shock term, the entrants' gain under the open grant turns into a loss ($8.2 billion).

Jobs at existing plants follow each site in the simulated histories. A site that closes loses all its works jobs, and a works that converts or retires its blast furnaces loses any excess of its works jobs over those of the EAF it keeps, counted at the new-mill rate below. A site's works jobs are those reported when it closed, else the drop in steel-mill employment in its county in County Business Patterns, else imputed from its capacity when it enters the panel, at 496 jobs per Mt of blast-furnace capacity and 326 per Mt of EAF capacity. Counting the jobs at new mills, the adoption grant loses 4,022 works jobs on net and the open grant 3,415. The jobs at new mills use 326 works jobs per million tonnes of capacity, the median of six headcounts in the AIST directories at five flat-product mills, which range from 227 to 480. Every instrument loses jobs on net as long as a new mill employs fewer than about 495 works jobs per million tonnes. At 480, the net change is -313 jobs under the open grant and $-1{,}863$ under the adoption grant.

The local cost is reported beside net welfare, not added to it: the earnings loss of displaced workers, $110,000 per works job lost, in present value and 2005 dollars (range $81,000 to $204,000), at 496 works jobs per Mt of capacity closed, or $55 million per Mt. The loss per job follows Davis and von Wachter (2011): the present value of earnings lost after a layoff, as a multiple of earnings before it, times average pay in steel mills. For the capacity the open grant closes, it is $0.8 billion, small beside the transfers.

E.4 Comparison with the power sector

Electricity has both features of the steel setting: new gas plants and wind farms compete with coal plants, and closing a coal plant's ash ponds and landfills with the ash in place brings at least 30 years of care after closure (EPA 2015). The decomposition of Section 3.1 on the generators of the Energy Information Administration (EIA 2025a,b), with plants as units and the intensity of each technology class fixed at its realized rate, shows the same

Table E.5: Who gains and who pays at the abatement target

		Grants			
	Carbon price	Adoption	Open	Conditional	Retention
A. Change in surplus ($ billion)					
Steel buyers	−41.9	−3.4	30.5	−17.6	1.8
Existing plants	−22.5	3.5	−41.7	18.4	16.8
Entrants	13.9	1.7	24.5	8.4	−0.5
Government	49.2	−6.5	−7.1	−8.1	−23.5
CO_2 avoided at the EPA value	31.0	30.2	30.8	31.1	30.2
Net welfare	29.7	25.5	36.9	32.2	24.8
B. Without choice shocks ($ billion)					
Existing plants	−21.4	−10.6	−39.1	6.4	2.2
Entrants	2.6	0.2	−8.2	1.2	−0.1
C. Not included in net welfare					
Earnings of displaced workers ($ billion)	−0.4	0.2	−0.8	0.3	0.3
Integrated capacity closed (Mt)	10.8	−7.2	8.7	−8.5	−8.3
EAF capacity closed (Mt)	−1.5	2.8	12.7	−0.1	−0.1

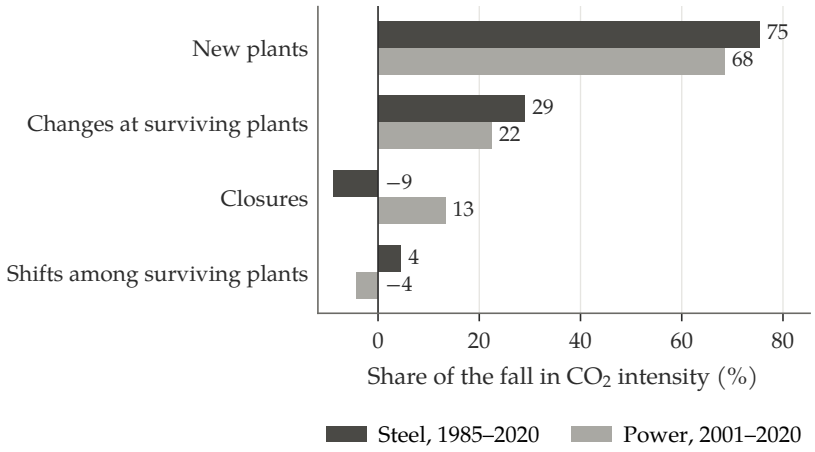
Notes: Changes from the baseline over 1985–2015, each instrument at the level that avoids 311 Mt of CO_2, billion 2005 dollars, discounted to 1985 at 2%. Existing plants and entrants: operating profit, plus grants received, less carbon paid, building and entry costs, plus closure values, less cleanup and the outlays for holding, idling, restarting, and relining, plus the expected value of the choice shocks of the chosen actions, $\sigma_i(\gamma - \log \Pr_t(a))$ for a chosen action a with model probability $\Pr_t(a)$, where γ is Euler's constant and σ_i the shock scale of the plant's spell (the entry decision of a new mill has its own scale σ_{ent}). The obligations to retirees and a fund's payments under the obligation takeover are transfers. Government: carbon revenue less grants paid, at a marginal cost of public funds of 1.0. CO_2 avoided valued at the EPA's $147 per tonne. Net welfare: the sum of the five rows above. Panel B: without the choice shocks. Earnings of displaced workers: $55 million per Mt of capacity closed, at 496 works jobs per Mt for all capacity, not added to net welfare. Capacity closed: negative where an instrument keeps capacity open. The obligation takeover, which does not reach the target, and the conversion grant are not shown. Carbon price: per tonne of CO_2 on both routes. Adoption grant: paid to old works that add an EAF or convert. Open grant: paid for new EAF capacity at new mills and old works. Conditional grant: paid when an old works retires its blast furnaces. Site-retention grant: paid each year per tonne of EAF capacity at an old site.

pattern in Figure E.2: capacity-weighted intensity fell from 0.591 to 0.424 tonnes of CO_2 per megawatt-hour between 2001 and 2020, a fall of 28%, of which entry of new plants accounts for 68%, changes at surviving plants, including conversions and new generating units, for 22%, and closures for 13%. Closures lowered intensity because the plants that closed were coal plants, while in steel, as Figure 3 shows, they raised it slightly on net, because clean EAF mills closed as well as old works. In power, sunk retirement costs delay retirement (Davis, Holladay, and Sims 2022), and rate-of-return regulated utilities keep legacy capital longer than a cost minimizer would (Gowrisankaran, Langer, and Reguant 2026).

E.5 Iron from natural gas

Governments pay for steelmaking with direct-reduced iron (DRI), iron made directly from ore, at old works and new mills alike: German aid of up to €550 million for thyssenkrupp's Duisburg works (approved July 2023 (European Commission 2023)), the selection in 2024

Figure E.2: Decomposition for steel and power



Notes: Shares of the fall in the capacity-weighted CO_2 intensity of capacity, split into new plants, closures, change at surviving plants, and shifts among them, with plants as units, adding to 100 within each sector before rounding. Steel: all plants in the panel, 1985–2020, with EAF intensity from each state's power-sector CO_2 factor and with adoption, EAF shops closed at surviving works, and cleaner power combined into changes at surviving plants. Power: generators of the Energy Information Administration grouped into plants, 2001–2020, each technology class at its realized intensity.

of the Middletown works in Ohio for negotiations over a U.S. award of up to $500 million (Cleveland-Cliffs 2024; DOE 2024a), and Swedish aid of €265 million (2024) for a new mill at Boden (European Commission 2024b). At old works, it has not always led to adoption. ArcelorMittal said it dropped an approved project at its German works (€1.3 billion in 2024) in June 2025 because it did not pay even with the support (ArcelorMittal Germany 2025; European Commission 2024a), and after Cleveland-Cliffs judged the Middletown project no longer made business sense, the U.S. Department of Energy (DOE 2026) announced in August 2026 a $500 million award to upgrade the works' blast furnace.

The gap to DRI-EAF of Section 6.5 changes two inputs of the adoption gap, the building cost of the new shop and the cost of the metal it melts. Everything else is that of the scrap EAF, and no parameter is re-estimated. Table E.6 gives the main inputs and their sources. The DRI plant adds to the steelmaking shop's $260 per tonne. The cost estimates of CRU (2024) give a low and a high building cost for a U.S. gas-based plant. Nucor's plant in Louisiana, the one reported U.S. project, cost $266 per tonne of steel capacity, between the two (AIST 2013; LED 2014). The central case uses the high value, the more recent of the two and the closer to Nucor's reported cost, and the other cases the low value and Nucor's cost. The furnace melts a little more than one tonne of DRI per tonne of liquid steel in place of scrap, at the DRI cash cost of the works and year: iron-ore pellets, natural gas at the works' state industrial price (EIA 2025c, 2026a), electricity at the model's EAF price, and other operating costs from the same cost estimates. At market pellet prices, DRI cost about as much as scrap in 2015.

U.S. Steel and ArcelorMittal USA operated their own pellet mines, so 10 of the 13 works are charged their pellets at the mines' cost, which lowers the adoption gap by $84 to $85 per tonne, to $641 in the central case. The cost is Cleveland-Cliffs' reported rate for its U.S. mines (Cleveland-Cliffs 2005–2020), which I assume for the other owners' mines too.

Table E.6: Inputs of the gap to DRI-EAF

Input	Unit	Value	Source
Building cost			
EAF steelmaking shop	$/t steel	260	U.S. replacement cost, CRU 2024
DRI plant, Nucor	$/t steel	266	Nucor: $750 million for 2.5 Mt DRI (2014)
Prices in 2015			
Captive pellets	$/t	65	Cleveland-Cliffs 10-K; assumed for others
Natural gas	$/MMBtu	3.98–8.19	EIA, state industrial prices; range over works
DRI, market pellets	$/t DRI	194–228	Cost model of CRU (2024); range over works
DRI, captive pellets	$/t DRI	148–182	As above; 10 of 13 works, own mines (USGS)

Notes: Building costs in 2005 dollars, deflated with the GDP deflator of the Bureau of Economic Analysis (BEA 2026). t: metric tonne. DRI: direct-reduced iron, made from ore with natural gas. Captive pellets: charged to the works whose owners, U.S. Steel and ArcelorMittal USA, mined their own ore, at Cleveland-Cliffs' reported cost of its U.S. mines including depreciation. The DRI cost includes electricity at the model's EAF electricity price. Nucor: the plant's reported capacity in tons read as metric tonnes. Building cost per tonne of new steel capacity: DRI plant cost per tonne of DRI capacity times the DRI per tonne of liquid steel. Prices of 2015, pellets and gas nominal, for the 13 integrated works still running blast furnaces in 2015. EIA: Energy Information Administration. USGS: U.S. Geological Survey. MMBtu: million British thermal units.

I use the parameters estimated on scrap-EAF adoptions as they are and fix the future at 2015, when the scrap price was the lowest of 2010–2015, so at the scrap prices of 2010–2014 the adoption gap would be smaller. The variant without the high-end cap in Table 5 lets the DRI-EAF sell the works' whole mix, because iron made from ore dilutes the impurities that keep scrap out of the better sheet grades (Section 2.1).