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Working Paper

Policies to Decarbonize Industry While Addressing Competitiveness and Carbon Leakage

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Policies to Decarbonize Industry While Addressing Competitiveness and Carbon Leakage*

Ian Parry, Simon Black, Danielle Minnett, and Karlygash Zhunussova

International Monetary Fund¹

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Abstract

This paper discusses the attributes and design of alternative mitigation instruments for the industrial sector, their competitiveness and emissions leakage impacts, and supplementary measures to address these effects. A quantitative analysis indicates, for selective countries, production cost increases under a \$50 per tonne unilateral CO₂ price in 2030 are 4-8 percent for steel, 20-30 percent for chemicals, and 30-35 percent for cement with leakage rates of 20-50 percent across these industries. Competitiveness and leakage impacts are however much smaller under pricing with border adjustments, other mitigation instruments like feebates and performance standards, or internationally coordinated pricing.

JEL classification: Q31, Q35, Q48, H23

Keywords: Climate mitigation, carbon pricing, competitiveness, emission leakage, border carbon adjustment, feebates

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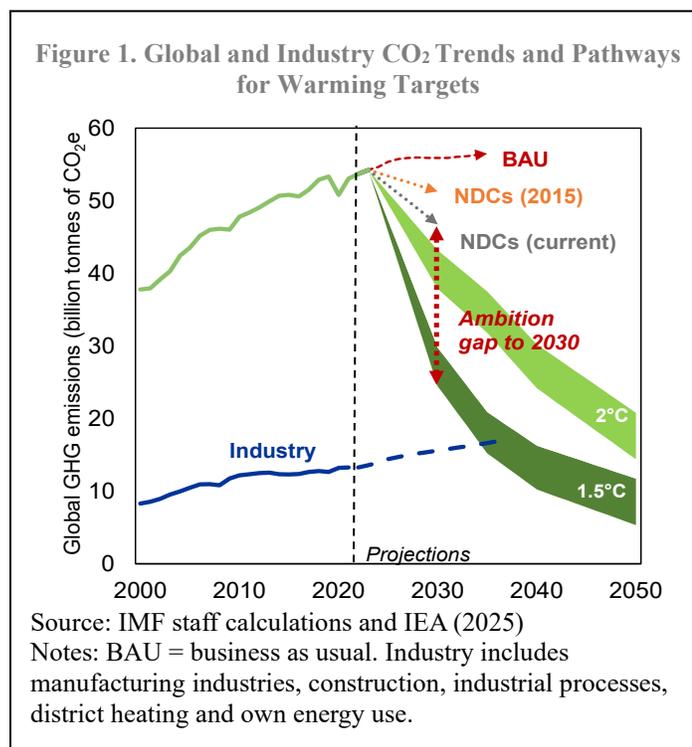
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Introduction

Transitioning the industrial sector to a low carbon pathway will be critical if the 2015 Paris Agreement goal of keeping global temperature rises below 2°C is to be achieved. Getting on track with keeping global warming to 2°C or 1.5°C would require a 25 or 50 percent reduction of global emissions of carbon dioxide (CO₂) and other greenhouse gases (GHGs) below 2019 levels by 2030. Failure to achieve the

needed emissions cuts by 2030 will likely put more ambitious temperature goals irreversibly beyond reach, adversely affecting global long term potential growth. In a business-as-usual (BAU) scenario without additional mitigation measures, global CO₂ emissions are projected to continue rising, with the industrial sector accounting for more than a quarter of the global total in 2030. See Figure 1.

Explicit carbon pricing instruments are well suited for the industrial sector but, by themselves, can have significant competitiveness and emissions leakage impacts, affecting countries' Balance of Payments (BOP). Carbon taxes or emissions trading systems (ETSs) can provide a robust carbon price, and are neutral regarding low-emission technologies, which are important given many investments (like electric furnaces) are long-lived and future uncertainties over which technologies will prove most cost effective. But carbon pricing generally imposes



larger production cost increases than other mitigation instruments because it charges firms for their unabated emissions. The resulting loss of competitiveness for energy-intensive, trade-exposed (EITE) industries can reduce their production, cause production migration to other countries, and emissions leakage—increases in foreign emissions that partially offset emissions reductions in domestic industries. Responses to these concerns might include using mitigation instruments like feebates and tradable performance standards (TPSs) that do not charge for unabated emissions (or alternatively recycling revenues from pricing within the industrial sector), combining unilateral carbon pricing with measures like border carbon adjustments (BCAs) which charge for embodied carbon in imports, or by international coordination over carbon pricing.

This paper provides conceptual, and cross-country quantitative, analyses to inform debate about choosing between, and designing, mitigation strategies for the industrial sector, and the implications of different choices for emissions, competitiveness, and leakage. After some background on the industrial sector, the Note discusses how different mitigation policies affect production costs, the underlying determinants of competitiveness and leakage impacts, and the attributes of different policy responses to them. The quantitative analysis uses a basic model of trading between countries and their major partners for key EITE industries—trade impacts of mitigation policies depend on increases in domestic and foreign production costs, as well as the slopes of domestic demand, supply, and foreign supply curves. Results are provided for alternative mitigation policy regimes for the steel, cement, and chemical (mostly ammonia) industries, implemented on a unilateral or multilateral basis, with and without BCAs, and for selected members of the Group of Twenty (G20) large economies. The paper is largely an academic exercise to help policymakers understand underlying economic factors that determine

competitiveness and leakage effects and to what extent they may differ by industry, country, and illustrative policy regimes—it is a logical first step to a more ambitious analysis that would account for differences in countries’ emissions commitments and preferred mitigation instruments to implement them.

Some notable points from the discussion include:

- Steel, cement, and chemicals combined account for three-quarters of global CO₂ emissions from the industrial sector (though these industries have modest shares in the total value of traded products).
- Non-trade measures (partial carbon tax exemptions, free allowance allocation, within-sector revenue recycling), or using feebates/TPSs instead of explicit carbon pricing, can mostly address competitiveness and leakage effects in the earlier stages of energy transitions, but are less robust for deeper decarbonization. They also undermine some mitigation incentives and forgo revenues. BCAs are a more robust and fine-tuned instrument for addressing competitiveness and leakage, but require careful design to address administrative, legal, and equity concerns. Similar concerns apply to coordinated carbon pricing regimes.
- Production cost increases under a \$50 carbon price in 2030 are typically around 4-8 percent for steel across different countries (which is modest relative to 25 percent steel tariffs recently introduced by the US), 20-30 percent for chemicals (ammonia), and 30-35 percent for cement, with charges on unabated emissions accounting for most of the cost increases.
- Under unilateral carbon pricing, with no accompanying measures (which provides an upper bound for competitiveness/leakage effects), reductions in domestic production are mostly 4-8 percent for steel and 15-20 percent for chemicals and cement, with much of the domestic reductions reflecting production migration to other countries (rather than reductions in domestic demand). Emissions leakage rates are mostly around 20-40 percent for steel, 40-50 percent for cement, and 30-50 percent for chemicals.
- Under unilateral feebates/TPSs (achieving the same domestic emissions reduction as the \$50 carbon price) emission leakage is far more limited due to the relatively modest impacts on domestic production costs and output (at least for more moderate levels of decarbonization). Carbon pricing with BCAs are generally an intermediate case with larger losses in domestic production than under feebates/TPS, but smaller impacts on domestic production and foreign emissions as under unilateral carbon pricing. Results in the latter case are largely equivalent under coordinated carbon pricing, as both regimes price domestic and foreign emissions at the same level.

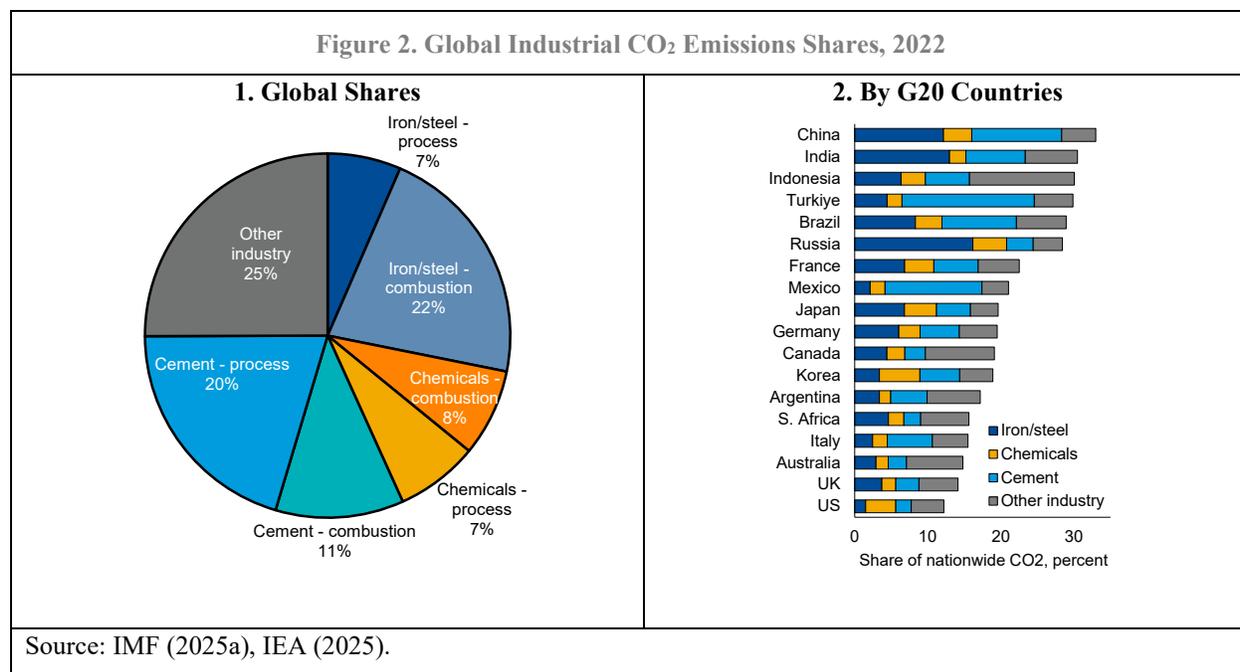
In short, competitiveness and leakage should not be major concerns if countries adopt one of the alternative regimes—feebates/TPSs (or revenues retained within the industrial sector), carbon

pricing with BCAs, or coordinated carbon pricing. Which regime countries prefer will depend on national circumstances. For example, the robust domestic carbon price enabled by BCAs may be appealing for countries with high fiscal needs, but it requires them to have adequate administrative capacity. Coordination over carbon pricing may be promising in regions (for example, Asia-Pacific) with multiple countries progressing on carbon pricing or in monetary unions progressing towards fiscal unions, though there are significant costs to formalizing and monitoring such coordination agreements. Feebates/TPSs may be reasonable options in other cases where industries have significant scope for cutting the emissions intensity of production.

Industrial Emissions Sources: A Closer Look

Collectively, steel, cement, and chemicals accounted for 75 percent of global industrial CO₂ emissions in 2022. Across G20 countries, industry accounted for between about 15 and 30 percent of nationwide (non-land use) CO₂ emissions. Within industry, and taking a simple average across G20 countries, (iron and) steel, cement, and chemicals accounted for 29, 31, and 15 percent of CO₂ emissions respectively and all other industries combined (for example, aluminum, textiles, pulp/paper) 25 percent, though with significant cross-country variation in these shares. About 75 percent of global CO₂ emissions from steel are from fuel combustion, 35 percent for cement, and 50 percent for chemicals—the remainder is from processes to decompose feedstocks (for example, coke, limestone, and fossil fuels in steel, cement, and chemical production, respectively). See Figure 2. The industrial sector also produces non-CO₂ GHGs, but these emissions are small or are not relevant for the analysis below (see Annex I). Globally (see Figure 1), industrial CO₂ emissions grew 60 percent between 2000 and 2015, reflecting rapid expansion of demand for vehicles, construction, and other sectors (especially in

large industrializing nations like China) though future baseline emissions growth is less rapid (for example, with some saturation of demand and greater supply of recycled steel).



Presently about 70 percent of global steel production is from traditional blast furnaces usually fed by coal and 30 percent from electric arc furnaces. Blast furnaces commonly use coal to heat iron ore with coke and limestone and then inject it with oxygen to reduce the carbon content and remove impurities, while electric furnaces use electrical currents to melt recycled steel. The former are concentrated in Asia and eastern Europe and the latter in western Europe and the US (for example, in China, only about 10 percent of steel production is from electric furnaces)—see Figure AII.1 in Annex II for the location of steel plants worldwide.

Approximately 45 percent of global steel is used for buildings, 20 percent for industrial equipment, 18 percent for consumer products, 13 percent for infrastructure, and 10 percent for vehicles.²

² Bataille (2020).

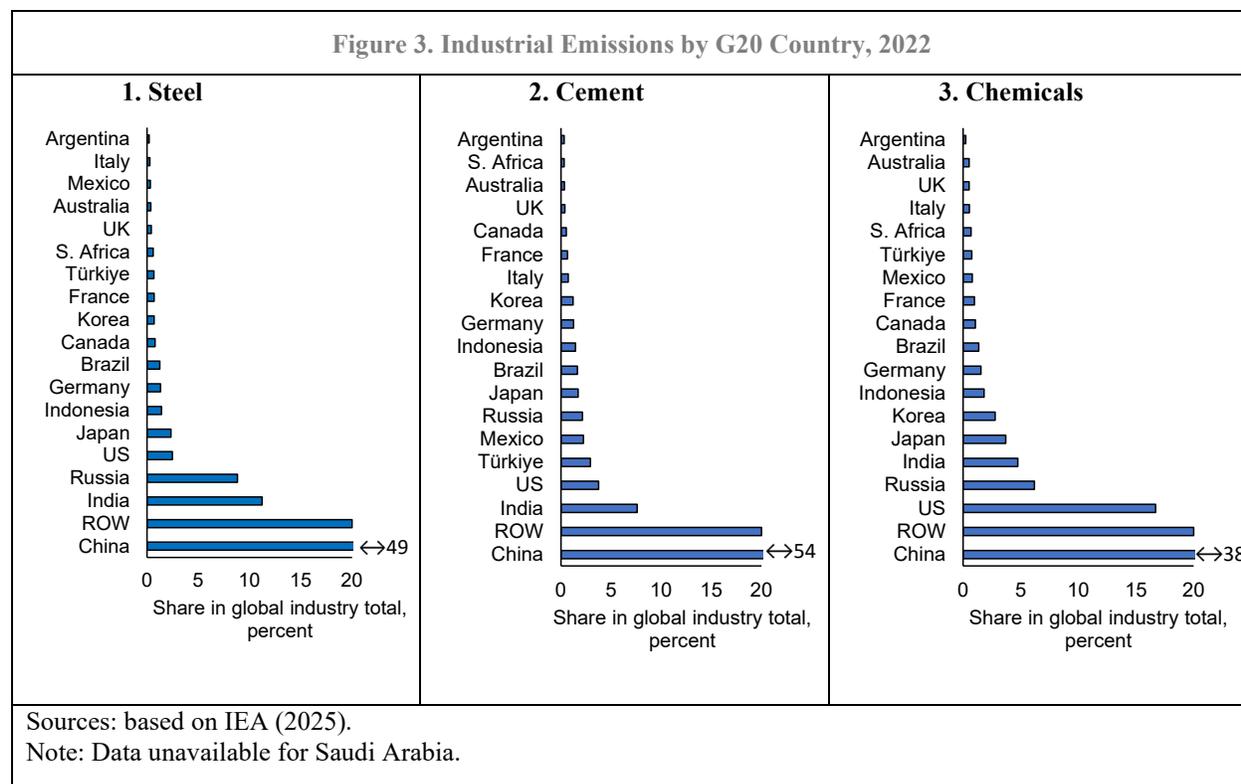
Cement is produced using kilns to decompose limestone into clinker and CO₂ and grinding mills mixing clinker with other minerals like gypsum. Cement recycling is not generally practical as demolition waste is of low value. Cement kilns are predominantly heated by coal (globally and in China and India) or natural gas (in western Europe and the US). Cement plants are heavily concentrated in Asia, Europe, and Middle East, and to some extent North and South America and Africa—see Figure AII.1. in Annex II. Cement is used as the glue to hold together sand, gravel, and stone aggregates to make concrete, the most consumed manufactured substance globally.

The chemical sector typically uses fuels as feedstock and for basic processes, such as thermal cracking and distillation. Ammonia makes up 45 percent of global chemical emissions, followed by methanol (28 percent), and other high-value chemicals like ethylene.³ Ammonia is usually produced by transforming natural gas into hydrogen, leaving CO₂ as a by-product, and then catalyzing nitrogen and hydrogen at high temperature, while methanol and ethylene are produced from breaking down natural gas and petroleum or natural gas, respectively. About 80 percent of ammonia is used in fertilizers; methanol and its derivatives are used to produce plastics, fabrics, adhesives, paint, plywood, pharmaceuticals, and agrichemicals; and ethylene is used, for example, to produce fibers, bins, buckets, crates, bottles, piping, food packaging films, trash liners, and bags.

China is by far the top emitter for steel, cement, and chemicals. In 2022, China produced 49, 54, and 38 percent of global steel, cement, and chemical emissions respectively. The next five largest emitters combined produced 26 percent of global steel emissions (India, Russia, US,

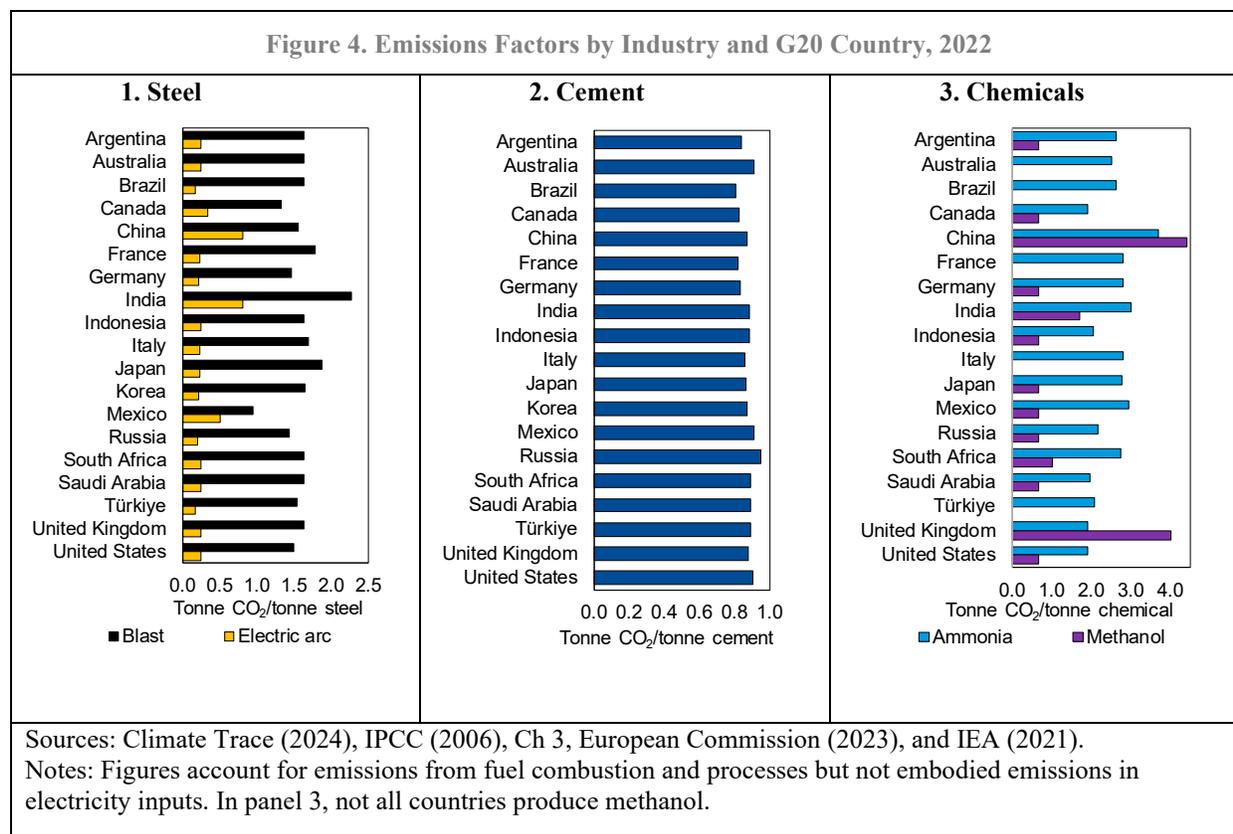
³ www.iea.org/energy-system/industry/chemicals

Japan, Indonesia), 19 percent of cement emissions (India, US, Türkiye, Mexico, Russia), and 34 percent of chemical emissions (US, Russia, India, Japan, Korea). See Figure 3.



Within industries, there is generally limited variation in emission intensities across countries, aside from differences in used technologies. See Figure 4 which includes emissions from heating fuels and processes, but not indirect emissions embedded in on-grid electricity inputs. For steel, emissions factors for blast furnaces are typically about 1.6 tonnes CO₂ per ton of production (though emission rates are lower in Mexico where natural gas is the heating source). For electrically produced steel, emissions factors are much lower, averaging 0.3 tonnes CO₂ per tonne of steel (reflecting use of coal/coke for chemical purposes and on-site power generation from fossil fuels). For cement, emissions factors are about 0.9 tonnes CO₂ per ton of output with little cross-country variation. And for chemicals emissions factors are typically around 2.5 tonnes CO₂ per tonne of output for ammonia and 1.1 for methanol—a notable exception is China where

emissions factors are higher (especially for methanol) because coal is commonly used as a feedstock.



There is a diverse range of potential mitigation technologies for the industrial sector, though their future costs and viability are uncertain. Opportunities include electrification of heating, which is well-established for scrap steel (through constrained by availability of scrap) and a future possibility for primary steel (from iron ore), cement, and chemicals; input switching (for example, using heating from gas rather than coal, or from green hydrogen or biomass, or partially replacing limestone with other materials); installing carbon capture and storage technologies; improving production efficiency; and reducing demand (for example, switching from chemical to organic fertilizers). See Annex III, Table AIII.1. for more details.

Conceptual Discussion: Attributes of Alternative Mitigation Instruments and their Design

Potential mitigation instruments for the industrial sector can be classified as follows (see Table 1):

	Market-based/technology neutral		Technology-specific
	Explicit pricing (charges for remaining emissions)	Implicit pricing	
Price-based	Carbon tax	Feebate	Subsidies
Quantity-based	Emissions trading system	Tradable performance standard	Mandates

Source: IMF staff.

- *Market based, explicit pricing*—including carbon taxes and ETSs which impose charges on firms' unabated emissions in the form of taxes or allowance purchases (or foregone sales when firms use freely received allowances for their own emissions).
- *Market-based, implicit pricing*—including (i) feebates, which apply a sliding scale of fees/rebates to firms with emission rates above/below a pivot point rate for their industry; and (ii) TPSs where firms comply with an emission rate standard per unit of output for their industry, but credit trading provisions accommodate firms exceeding or falling short of the standard. Feebates/TPSs do not charge the average firm for their unabated emissions.
- *Technology-specific*—subsidies or mandates for specific, identified technologies. In contrast, market-based instruments are neutral with respect to low-carbon technologies.

The remainder of this section takes a closer look at the above instruments.⁴

Explicit Carbon Pricing

Industrial emissions are currently subject to explicit carbon pricing in 46 countries. This includes 30 countries participating in the EU ETS, which prices industrial and power generation emissions—allowance prices in 2024 were around €50-75 per tonne of CO₂ (though prices should rise in future with a tighter cap). Industrial emissions are also subject to pricing in six other ETSs (for example, California, Korea, New Zealand, UK), and by carbon taxes in seven

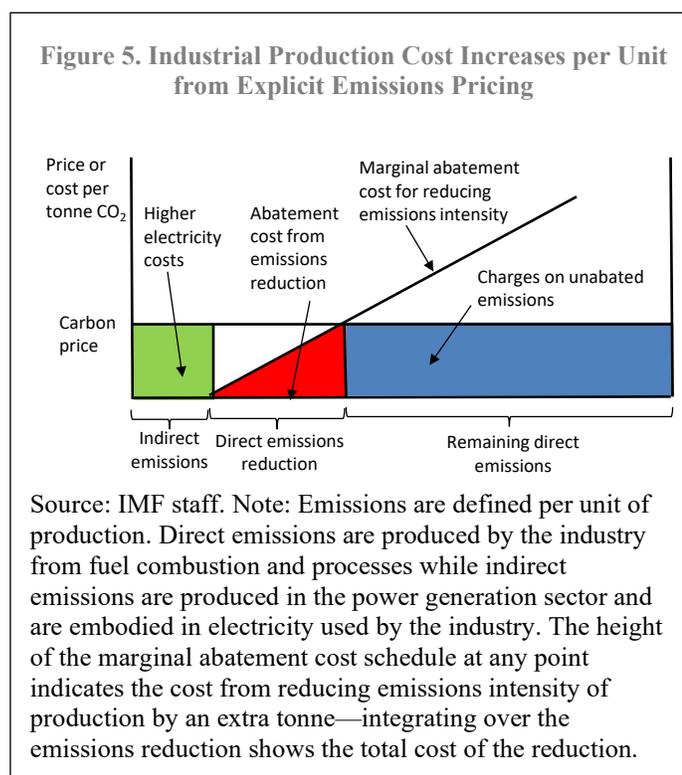
⁴ For further discussion on broader climate mitigation policies and their emissions and other impacts see Black and others (2022) on existing policies (for G20 countries) and Black and others (2023b) on fossil fuel subsidies and energy taxes (for all countries).

cases (for example, Colombia, Chile, Singapore, South Africa). See Annex IV, Table AIV.1., for details on these schemes including their coverage, prices, point of regulation, price stability measures, use of revenues, and accompanying competitiveness measures.

Explicit carbon pricing increases production costs through three channels.

These include (see Figure 5):

- *Abatement costs*—costs of reducing the emissions intensity of production, which are measured by the red triangle or integral under the marginal abatement cost schedule for reducing emissions intensity.
- *Charges on unabated emissions*—tax payments or allowance purchases paid on remaining emissions per unit of output, indicated by the blue rectangle; and
- *Higher electricity input costs*—these reflect the impact of policies to mitigate indirect emissions in the power generation sector which raises electricity prices, and the costs of electricity inputs used by the industry. To an approximation, these costs, indicated by the green rectangle, are the product of emissions per unit of power generation (tonnes of CO₂ per kWh of electricity), electricity usage per unit of industrial production (for example, kWh per ton of steel production), and the price on power sector emissions.



Charges on unabated emissions are generally large relative to abatement costs, though their relative size declines with deeper decarbonization.

The pros and cons of carbon taxes and ETSs in their pure forms have been discussed extensively.⁵ To summarize:

⁵ For example, Parry and others (2022), Stavins (2022).

Carbon taxes: These are usually implemented by finance ministries midstream on fossil fuel supply. They provide price certainty (which helps to mobilize private investment), raise revenue, and are administratively straightforward as an extension of fuel taxes (which are well established in most countries). However, they leave emissions uncertain, do not reduce process emissions from non-fossil feedstocks or promote carbon capture, and do not compensate adversely affected firms.

ETSs: These are usually implemented by environment ministries downstream to smokestack emissions. They provide certainty over emissions, reward all mitigation responses, and can compensate firms through free allowance allocations. However, they require new capacity for monitoring downstream emissions and trading markets, omit small emitting firms (to contain administrative costs), require fluid credit trading markets to be cost effective, leave uncertainty over emissions prices, and may forgo revenue opportunities (if allowances are freely allocated rather than auctioned).

Design features can, and often do, blur some distinctions between taxes and ETSs:

- *Certainty:* ETSs affecting industry often include provisions to limit price volatility like price floors or allowance withdrawals/injections to counteract market developments (see Annex IV, Table AIV.1)—a more novel mechanism is carbon contracts for difference (CCfDs) which help to transfer price risk from investors to the government (see Annex V). Conversely, in carbon tax schemes, rates can be adjusted according to progress on emissions goals.
- *Revenue:* Most ETSs envision a progressive transition from free allowances to allowance auctions, while in some cases (for example, California) allowances have been fully auctioned from the start, though revenues have been, at least partially, earmarked for environmental spending in several cases (Annex IV, Table AIV.1). In principle, carbon tax revenues collected on fuel inputs used by the industrial sector could be remitted in compensation to the sector (making the impacts on production closer to feebates – discussed below), though this would require additional administrative capacity and could be distortive (for example, if it takes the form of firm-specific reductions in corporate tax).
- *Administration:* To promote downstream mitigation, a midstream carbon tax could, with additional capacity, be combined with supplementary taxes on CO₂ emissions for non-

fossil fuel feedstocks, such as limestone or clinker input and payment schemes to reward emissions capture technologies.

In short, carbon taxes and ETSs work well in countries with adequate capacity and enough firms for viable trading markets while in other cases, carbon taxes are more practical options.

Implicit Carbon Pricing

Experiences with implicit pricing for industry are limited but this may change. Canada applies a TPS for the industrial sector, China has introduced a restricted variant of a TPS for the power sector and extended it in 2025 to the steel, cement, and aluminum sectors, while the Netherlands implemented a feebate variant for the industrial sector. See Annex VI. These implicit schemes were motivated by the need to price emissions while also containing production cost increases to limit competitiveness/leakage concerns—conceivably other countries will adopt similar schemes in combination with, or in place of, explicit carbon pricing.

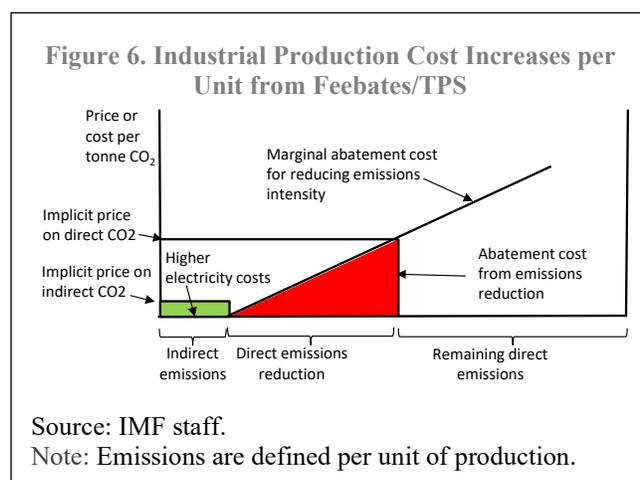
Feebates and TPSs can cost effectively reduce the emissions intensity of production, with harmonization of emissions prices across industries.

- *Feebate*: under a feebate scheme, firms would pay a fee or receive a rebate equal to the product of: (i) a carbon price; (ii) the difference between the firm's emission rate and a pivot point emission rate; and (iii) the firm's production level. All firms face the same reward (reduced fees or increased rebates) for reducing emission by an extra tonne—the carbon price. One scheme is needed for each major industry with, for revenue-neutrality, the pivot point given by the recent average emission rate for that industry (and updated over time)—a common carbon price across schemes promotes cost-effectiveness across industries.
- *TPS*: under this scheme, firms incur credit purchases or receive payments from credit sales equal to the product of: (i) the market price of credits; (ii) the difference between their emission rate and an industry benchmark rate; and (iii) their production levels. Emissions reductions are cost effective across industries if credit trading within and across industries establishes a common carbon price.⁶

⁶ According to ClimateTrace datasets, individual G20 countries have more than 20 emission sources across steel, cement, and chemicals (with petrochemicals) combined (except for Australia with 11 sources) which should allow fluid credit trading.

In cases with few firms, emissions benchmarks in feebates and TPSs need to be set exogenously (perhaps declining by a fixed annual percent each year)⁷ to avoid individual firm incentives to deliberately keep emission rates high to influence future standards.

For the same total emissions reduction, feebates/TPSs have generally smaller impacts on production costs than explicit carbon pricing, though the difference declines with deeper abatement. Abatement costs under feebates/TPSs are larger than under explicit carbon pricing for the same total emissions reduction, as the former instruments need to push harder on reducing emissions intensity of production to compensate for the smaller impact on reducing production levels. But for the average firm they do not charge for remaining emissions, while increases in electricity input costs, for the same reason, are also smaller if feebates or TPSs are



applied to the power sector rather than explicit pricing. See Figure 6.

Feebates share some similarities with carbon taxes, but also have pros and cons.

- *Similarities:* Feebates provide price predictability, as the government specifies the future emissions price trajectory.
- *Pros:* Their (generally) smaller impact on production costs limits competitiveness/leakage concerns and enhances acceptability.
- *Cons:* Feebates do little to reduce production, do not raise revenue, and require capacity to monitor firm emission rates.

⁷ The benchmark might, for example, be based on the average emissions intensity of relatively clean firms in the industry.

Prices in feebates can be adjusted over time if needed to keep on track with emissions goals.

TPSs share some similarities with ETSs, but again have pros and cons.

- *Similarities:* TPSs provide more certainty over emissions as the government specifies emission rate standards.
- *Pros:* Competitiveness/leakage concerns are less acute for TPSs than ETSs. The same applies for price volatility, as under TPSs volatility depends on market swings in emissions intensity—in contrast, ETSs are also subject to price volatility from shifts in demand for electricity, steel, cement, and so on over the business cycle.
- *Cons:* These are the same as for feebates.

To further limit price volatility, TPSs can be combined with price collars (on the price of credits in trading markets), explicit fees/subsidies for falling short/going beyond standards, or CCfDs.

Technology-Specific Instruments

Technology mandates specify how firms must reduce emissions. For example, steel firms might be required to use electric furnaces when constructing new factories. These approaches can be easier to administer than market-based policies as they only require one-off inspections (rather than continuous monitoring of emissions/trading markets and application of financial incentives). However, this approach does not exploit all technological and other behavioral responses for reducing emissions and is not cost-effective (for example, it may not specify the least-cost technologies and costs of meeting mandates may differ significantly across firms).

Clean technology subsidies are more flexible, but they need careful design. Subsidies do not force specific technologies regardless of their costs, may have political appeal as they benefit a compact constituency, and do not require emissions monitoring capacity.⁸ Ideally, subsidies

⁸ Clean technology subsidies have been common for other sectors (for example to promote renewable power generation or electric vehicles) and have recently been applied to the industrial sector—for example the 2022 US

would provide broad incentives across firms and behavioral responses, avoid excessive fiscal costs (where the government pays for emissions reductions that would have occurred anyway) and avoid conferring trade-distorting, competitiveness advantages that might provoke retaliation or legal challenge among trading partners.⁹ One possibility to allocate subsidies is to use auction mechanisms where industrial firms bid for subsidies to cover the extra production costs from adopting clean technologies with subsidies from a fixed government budget allocated to firms with the lowest bids per ton of CO₂ reduced—this promotes cost-effective investments while largely neutralizing competitiveness impacts. Annex VII provides a conceptual discussion of how abatement subsidies reduce production costs along with calculations suggesting the cost reductions across industries and countries are modest.

More broadly, governments may also use subsidies or related incentives to address possible impediments to the development and deployment of clean technologies or to foster domestic production of low carbon technologies. These instruments need different design features however—for example, deployment subsidies to address learning-by-doing spillovers from new immature technologies should be technology-specific and phase out progressively over time as new technologies move down the learning curve. Governments may also provide incentives to develop domestic industries for batteries, solar panels, and so on, perhaps for security reasons. See Annex VIII for more discussion of both types of measures.

Summary

Inflation Reduction Act provided federally funded tax credits to clean industrial technologies (like green hydrogen) with many of the tax incentives containing domestic production requirements.

⁹ Subsidy approaches may have limited effectiveness in cases where firms have much better information about the costs of alternative mitigation technologies than the government (Christos and Pugh 2016).

In short, choosing among mitigation instruments will trade off different attributes. Table 2 summarizes how instruments compare against key metrics. Explicit pricing instruments provide the widest mitigation incentives, and technology subsidies/regulations the narrowest, while taxes and feebates have some attractions over ETS and TPS respectively, though the case for the former instruments is nuanced. A hybrid approach, involving both explicit pricing and implicit market-based instruments, may balance efficiency and acceptability, though instruments should be compatible. In this regard, carbon taxes and feebates are compatible with overlapping mitigation instruments as the latter instruments further reduce emissions without affecting prices for the former instruments. A pure ETS or TPS is not compatible with overlapping instruments as the latter lower allowance/credit prices but not emissions or emission rates—underpinning the former instruments with price floors (or appropriate tightening of the emissions cap or emission rate standards) can however improve compatibility.

Table 2. Comparing Attributes of Mitigation Instruments

Instrument	Carbon tax	ETS	Feebates	TPS	Technology mandates	Technology subsidies
Effectiveness	Cost effectively promotes all mitigation responses	Cost effectively promotes all mitigation responses	Cost effectively promotes all responses for reducing emissions intensity	With fluid trading cost effectively promotes all responses for reducing emissions intensity	Promotes narrower range of responses	Promotes narrower range of responses
Revenue mobilization	Raises revenues for general budget (but some may be needed for compensation)	Can raise revenues if allowances auctioned	Recommended design is revenue neutral	Revenue neutral	Revenue neutral	Loses revenue
Administrative practicality	Can be levied on fuels and feedstocks with rebates for downstream mitigation	Requires capacity for monitoring emissions and trading markets	Requires capacity for monitoring emissions	Requires capacity for monitoring emissions and trading markets	Monitoring compliance is straightforward	Monitoring compliance is straightforward
Political acceptability: burdens on firms	Politically difficult but keeping revenue in sector can help	Can be difficult but free allowances can help	Revenue neutrality helps with acceptability	Revenue neutrality helps with acceptability	Revenue neutrality helps with acceptability	Can be popular with benefiting firms
Competitiveness/leakage	Additional measures needed	Additional measures needed	Revenue neutrality helps but not robust for deep decarbonization	Revenue neutrality helps but not robust for deep decarbonization	Revenue neutrality helps but not robust for deep decarbonization	Competitiveness impact neutralized as subsidy compensates for abatement cost
Uncertainty over emission prices	Announced trajectory for tax rates provides price certainty	Potentially volatile but price stability measures can help	Announced trajectory for feebate price provides price certainty	Less volatility than ETS and price stability measures can help	Not applicable	Announced trajectory for subsidy rates provides price certainty
Uncertainty over emission/emission rates	Uncertain but discretionary tax adjustment can help	Emission cap can be aligned with emissions targets	Uncertain but pivot point can be updated with emission rate targets	Emissions standard can be aligned with emission rate targets	Leaves some uncertainty over emissions	Emissions uncertain
Compatibility with other instruments	Compatible	Not compatible but price floors can help	Compatible	Not compatible but price floors can help	Not compatible	Compatible

Source. IMF staff.

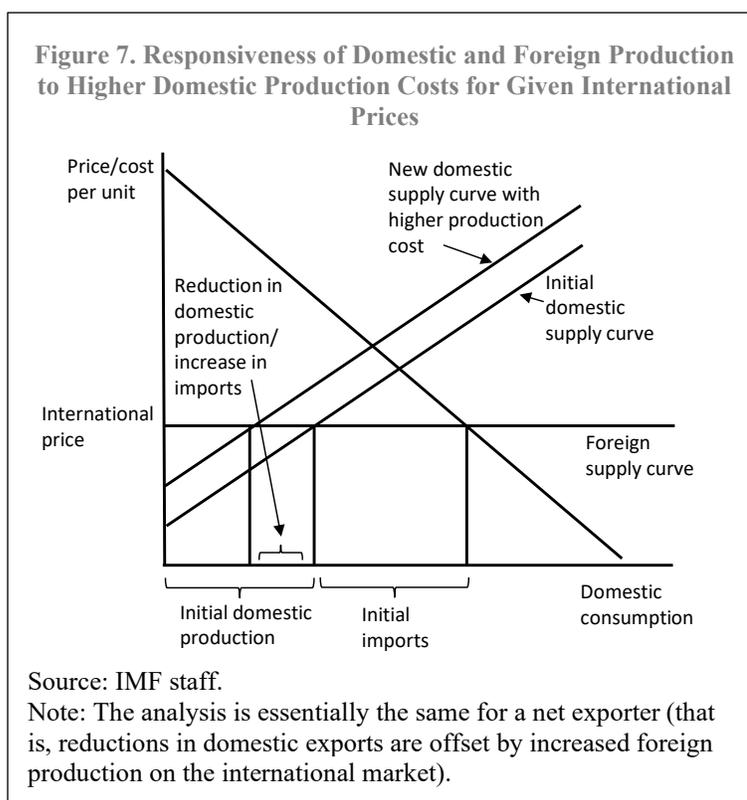
Note. Green indicates an advantage, orange a partial advantage or neither an advantage or disadvantage, and red a disadvantage of an instrument respectively.

Competitiveness and Leakage: Conceptual Issues and Policy Responses

The Determinants of Competitiveness and Leakage Impacts

Competitiveness concerns revolve around risks of reductions in domestic production in key industries, not least due to production migration abroad. Production losses are also a political concern as they affect potentially influential firms, workers, and regions. Risks of production losses are determined by both increases in domestic production costs from mitigation policies relative to production costs in trading partners (see below) and the responsiveness of domestic and foreign production to changes in relative production costs.

The responsiveness of domestic and foreign production depends on the slope of domestic demand, domestic supply, and foreign supply curves. Figure 7 illustrates the simplest case of an integrated international market where domestic demand is met through both domestic and foreign production and domestic producers take international prices as given.



Domestic mitigation costs are fully

passed backwards in lower producer prices and all the reduction in domestic production is offset by increased foreign production, resulting in higher net imports in the BOP (negative impact on trade balance). The same analysis applies if the domestic economy is a net exporter.¹⁰ The resulting reductions in domestic production are larger the flatter the domestic supply curve, that is, the easier it is to reallocate productive resources to other sectors of the domestic economy. More generally, foreign supply curves slope upwards (due, for example, to product heterogeneity, imperfect competition, rising unit transport costs, and investment lead times) in

¹⁰ In fact, countries are commonly both importers and exporters of the same product (perhaps, for example, because producers located in one part of a country are close to consumers across the border, while domestic consumers located elsewhere in the country may be closer to producers across the border than domestic producers).

which case a portion of production cost increases are passed forward to consumer prices and some of the reduction in domestic production reflects reduced domestic demand.

The emissions leakage rate (expressed relative to domestic industry emissions reductions) is the product of three factors:

- *The fraction of the policy-induced CO₂ reduction due to reduced domestic production (rather than reductions in the emissions intensity of production).* This fraction will be larger the larger the production cost increases from a given mitigation policy and the flatter the domestic supply curve.
- *The fraction of the reduction in domestic production due to production migration (rather than reduced domestic demand).* This fraction will be larger the flatter the domestic demand curve (that is, the easier for consumers to shift to other products in response to higher prices) and the flatter the foreign supply curve.
- *The relative carbon intensities of foreign and domestic production.*

Leakage rates are usually measured at the industry level as this is relevant for gauging the need for targeted competitiveness/leakage measures—leakage rates expressed relative to economywide emissions reductions are much smaller.

Leakage might also result from increased fossil fuel demand in foreign countries in response to downward pressure on international fuel prices from a group of large countries taking mitigation action.¹¹ However, as this form of leakage depends on the reduction in aggregate consumption of fossil fuels in mitigating countries, it is essentially unaffected by both the type of mitigation instrument and any accompanying measures to address competitiveness. Leakage either from production migration or changes in fuel prices would not be relevant if all countries were meeting binding absolute emissions constraints for the Paris Agreement—in this case, countries would need to offset any extra emissions from inward production migration or extra fuel demand by emissions reductions in other sectors. Many countries, including key emitters

¹¹ See for example Fischer and Fox (2012).

like China, India, and (since January 2025) the US do not however have binding absolute emissions targets.

Supplementary Measures to Address Competitiveness and Leakage

Non-trade measures for addressing competitiveness and leakage concerns include combining carbon taxes with emissions exemptions, ETSs with free allowance allocations, or recycling of revenues to the sector.

- *Exemptions*: industrial firms might be charged for their emissions above a threshold level (in a downstream system) or receive partial (lump-sum) rebates for carbon charges on fuel inputs (in a midstream system). These exemptions, however, reduce abatement incentives: for example, savings from adopting a zero-carbon technology are smaller when charges apply to a portion, rather than all, emissions.
- *Free allowances*: EITE industries in the EU, Korea, and New Zealand ETSs have been granted free allowances which are cancelled if firms shut down or move abroad. These allocations are largely equivalent to lump sum payments but, since they benefit incumbents, may deter entry of newer, cleaner, and possibly more innovative firms.
- *Within-sector recycling*: carbon charges collected from EITE industries can be returned to firms in output-based rebates (that is, proportionate to firm output)—such charging/recycling schemes are operationally similar to feebates and TPSs, as they approximately neutralize, for the average firm, payments on remaining emissions and dampen production reductions. Revenues might also be recycled in general business tax relief for the sector which would preserve incentives both to reduce production and emissions intensity but would distort the allocation of investment between the EITE and other sectors.

These approaches—along with using feebates/TPS in place of explicit carbon pricing—may be manageable from an administrative perspective and have little impact on consumer prices (which can be politically difficult). At the same time, they divert revenue from general purposes and are less robust for addressing competitiveness/leakage at deeper levels of decarbonization—they (partially or fully) compensate the average firm for charges on unabated emissions but not

abatement costs, which rise disproportionately with abatement levels. Table 3 provides a summary of how these measures compare against metrics of concern to policymakers.

Table 3. Attributes of Policy Instruments for Addressing Competitiveness and Leakage

Metric	Non-trade measures				Trade measures
	Exemptions under carbon tax	Free allowances under ETS	Recycling (in output-based rebates)	Feebate/performance standard	Border adjustments
Preserve EITE competitiveness	Mostly	Mostly	Mostly	Mostly	Yes (if foreign emissions intensity \geq domestic intensity)
Limit carbon leakage	Mostly	Mostly	Mostly	Mostly	Yes
Mitigation incentives	Reduced incentives for zero-emission investments	Can slow exit of polluting firms (as they lose free allowances)	Dampens production responses	Dampens production responses	Dampens production responses
Revenue implications	Forgoes carbon pricing revenue	Forgoes carbon pricing revenue	Forgoes carbon pricing revenue	Forgoes carbon pricing revenue	Preserves carbon pricing revenue
Extra administrative burden	Modest	Modest	Modest	Modest	Significant
Risk of WTO challenge	No	Could be challenged as subsidy but has not happened yet	No	No	Significant
Equity principles of the Paris Agreement	na	na	na	na	Significant if advanced countries impose measure
Reduction in global emissions	Not effective	Not effective	Not effective	Not effective	May encourage pricing in trading partners

Source. IMF staff.
Note: Green indicates an advantage of an instrument, red a disadvantage, and amber neither an advantage nor a disadvantage.

BCAs can be a more robust instrument for addressing competitiveness and leakage. A BCA—termed carbon border adjustment mechanism (CBAM) in the case of the EU—imposes charges on embodied carbon in products imported into a jurisdiction with carbon charging, possibly matched by rebates for embodied carbon in domestic exports. If the BCA raises import costs by the same amount as carbon pricing raises domestic production costs, then the competitiveness effects of domestic pricing are neutralized. In addition, in the extreme case where the domestic country is a price taker in world markets, domestic mitigation costs would be fully passed forward in higher consumer prices—the reduction in domestic demand comes at the expense of foreign production with no effect on domestic production (see Figure 8), so that the

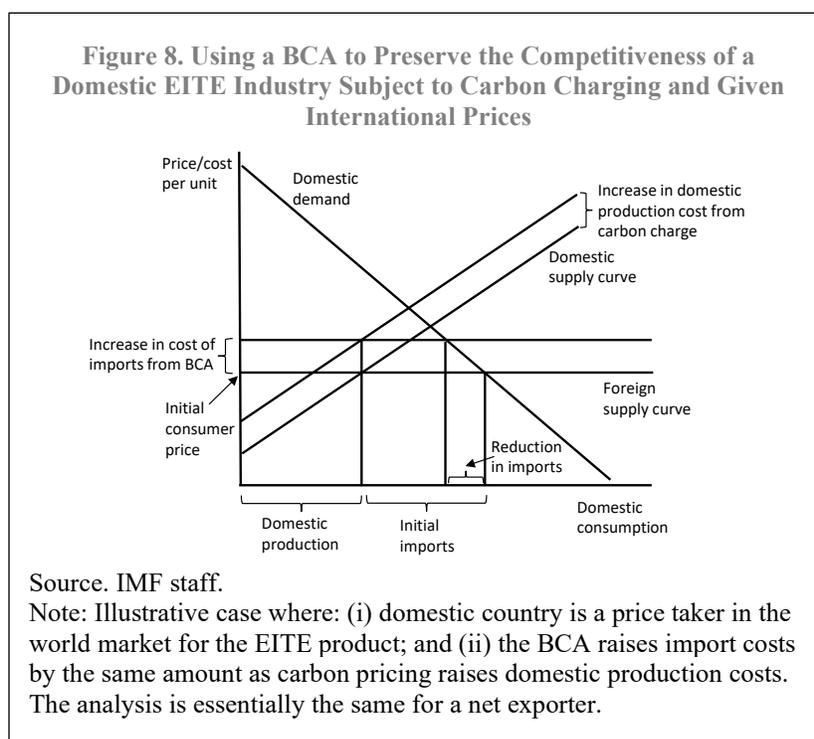
trade balance is positively impacted. More generally, the jurisdiction imposing the BCA will face an upward sloping foreign supply curve and some portion of the burden of carbon pricing will be passed backwards in lower producer prices with adverse impacts on domestic production (still, the BOP impact will be lower than in case of mitigation policies without competitiveness measures). BCAs are also a more fine-tuned instrument for addressing emissions leakage than

non-trade measures if they vary across foreign suppliers according to their emissions intensity. BCAs might also incentivize other countries to consider or increase their own mitigation policies. In addition, BCAs preserve incentives to cut emissions intensity (but not domestic production levels) and (by

addressing competitiveness concerns) they may facilitate a more robust domestic carbon price. BCAs can also have a fiscal benefit, though this is modest relative to that raised from domestic, economywide carbon pricing. Again, see Table 3 on pros and cons of BCAs.¹²

But BCAs need careful design to address administrative, legal, equity, and other concerns.

For example:



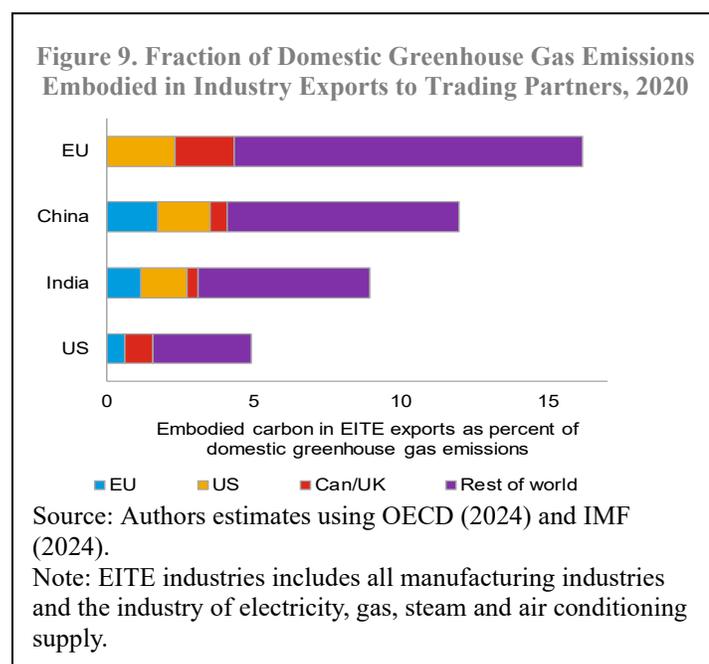
¹² For further discussion see Cosbey and others (2019) and Parry and others (2021a).

- *Coverage*: Limiting coverage of the BCA to EITE industries can limit administrative burdens (as embodied emissions and charges need to be assessed on a narrower range of products) and risks of challenge at the World Trade Organization (as the BCA is more likely to be interpreted as an environmental measure for which border adjustments are allowed, rather than a revenue-raising or protectionist measure, for which they are not);
- *Emissions factors*: Benchmarks for assessing embodied carbon in imports could be based on domestic industry emission rates or, for foreign exporters, either industry-average or firm/plant level emission rates. The last option (which is the benchmark in the EU CBAM) provides incentives for foreign firms to cut emission rates but is more burdensome administratively as each exporter must measure and report their emissions (though default emissions factors can be used where reporting requirements are onerous).¹³
- *Export rebates*: These are warranted to preserve international competitiveness for domestic exporters, but rebates should be tied to industry-level benchmarks to avoid undermining firm-level incentives to cut emission rates. WTO rules permit export rebates for domestic taxes but not for regulations—as ETSS might be viewed as regulations, the EU CBAM does not include export rebates.
- *Revenue use*: BCAs might be viewed as being at odds with the Paris Agreement principle of differentiated responsibilities for developing countries as they impose the same price on emissions for advanced and developing countries alike. Remitting some revenues collected from carbon charges on imports to developing country governments to support their clean energy transitions might help to address equity concerns, while again increasing likelihood of the BCA being viewed as an environmental measure at the WTO.¹⁴ However, announced BCA schemes either plan to use revenues mostly for general budget (EU CBAM) or do not have a decision on revenue use yet (the UK CBAM).
- *Adjusting import charges for mitigation policies abroad*: Charges on imports should in principle be net of any carbon pricing on embodied emissions imposed by foreign governments (though this is less clear if the foreign government compensates domestic exporters for competitiveness effects, for example, through free allowance allocations). Adjustments for implicit pricing policies, like performance standards, that do not charge for unabated emissions, do not seem warranted from a competitiveness perspective.

¹³ If reporting is at the plant level, the BCA could induce firms to switch production from their cleaner plants for export to the BCA-imposing jurisdiction while redirecting products from their dirtier plants to other countries. This perverse incentive is avoided under a firm-level scheme where embodied emissions are based on an average across all their plants.

¹⁴ See Elkerbout and others (2025) for further discussion of options for making BCAs more equitable internationally.

International or regional coordination mechanisms, such as carbon price floor agreements, are more effective than BCAs for countries seeking to scale up global mitigation but are more challenging to implement. BCAs might encourage trading partners to adopt or scale up carbon pricing, though the fraction of nationwide emissions embodied in traded products is not large—only 9 and 12 percent of nationwide GHGs in India and China are embodied in their



exports respectively, and only 1 percent in their exports to the EU (see Figure 9). International or regional agreements on more comprehensive pricing (beyond industry) are more efficient for coordination, while also addressing competitiveness and leakage concerns. But there is much to agree, including which countries participate (for example, large emitters); the pricing requirements and how they vary across high-, middle-, and low-income countries; sectors to be covered (ideally power and industry, at least to start with); procedures for monitoring compliance; assistance for low-income countries; and whether BCAs against non-participants are applied.¹⁵

¹⁵ For further discussion of internationally coordinated price floors, see Parry and others (2021b) and Chateau and others (2024) who recommend pricing initially focuses on emissions from power and industry, and industry only, respectively.

Lastly, sector and product-specific clubs can overcome technical as well as incentive-related hurdles. For example, climate clubs could be set up on steel and include agreements on ‘carrots’ such as agreements of zero-carbon steel in public procurement in addition to the ‘sticks’ of carbon charging. These efforts could build off the pre-existing sectoral global agreements, such as the ‘Breakthrough Agenda’ to accelerate decarbonization in steel, hydrogen, and power.¹⁶

Quantitative Assessment of Mitigation Policies for Industry

Methodology and Policy Scenarios

The quantitative analysis is based on merging a basic trade model with the IMF-World Bank Climate Policy Assessment Tool (CPAT). CPAT is a spreadsheet-based model providing, on a country-level, projections of fuel use and emissions by major energy sector and the environmental, fiscal, economic, and distributional impacts of a wide range of alternative mitigation instruments.¹⁷ For the purposes of this paper, CPAT was modified in two regards. First, detailed country-level data on emissions rates, production levels, electricity consumption, and prices (or supply costs) for the steel, cement, and chemicals (ammonia and methanol) industries was compiled along with marginal abatement cost schedules for the industries from the literature. Second, CPAT was linked to a basic trade model between individual countries and their top ten trading partners (in terms of import) for each industry. Mitigation policies increase production costs in the domestic economy and (for scenarios with BCAs), in trading partners, through emissions abatement costs, charges on remaining emissions, and on emissions embodied in electricity inputs. The pass through of domestic production costs in domestic consumer prices,

¹⁶ See IEA and others (2022), Hermwille and others (2022).

¹⁷ See Black and others (2023a) for details on the model and its parameterization. CPAT is available to policymakers upon request.

domestic production impacts, and production migration to other countries also depend on assumptions about domestic demand, domestic supply, and foreign supply elasticities (which vary by industry). Annex IX discusses the mathematical representation of the trade model, the data and parameter values underlying it, and limitations (which do not seem too restrictive) such as abstracting from general equilibrium effects, feedback effects on international prices and exchange rates, and recent US tariffs.

Three policy regimes are considered that broadly span the range of possibilities:

- (1) *Unilateral carbon pricing*: one country unilaterally applies explicit carbon pricing to power and industry emissions with no competitiveness measures (and baseline emissions in other countries).
- (2) *Unilateral feebate/TPS*: one country unilaterally applies a feebate/TPS to power and industry emissions with no competitiveness measures (and baseline emissions in other countries).
- (3) *Unilateral carbon pricing with BCA*: same as (1) except that a BCA is also imposed on imported products based on country-specific emissions factors for trading partners.¹⁸

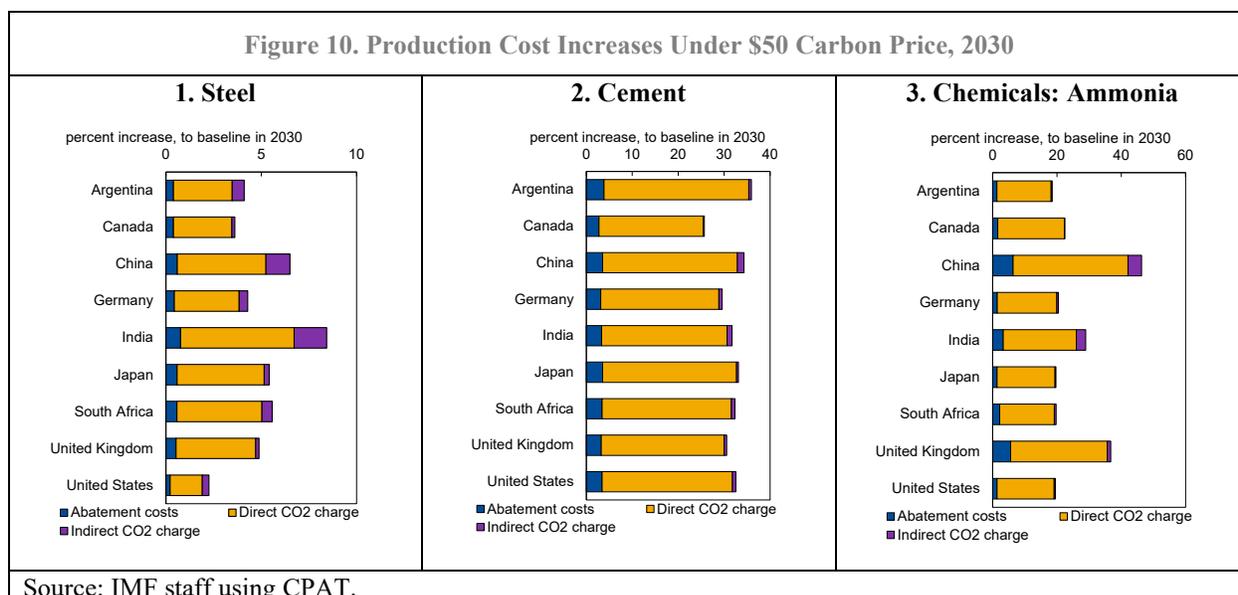
As noted above, regime (2) is operationally equivalent to a unilateral carbon tax with revenues returned to firms in output-based rebates. And an ETS with free allowance allocations lies somewhere between cases (1) and (2) as it dampens some production losses (from domestic firms shutting down and moving abroad) but not others (domestic firms staying in business but cutting production levels). From an individual country perspective, regime (3) is equivalent to coordinated carbon pricing in the sense that domestic and foreign emissions are priced at the same level.

¹⁸ The BCA scenario does not apply export rebates, which would be consistent with satisfying legal requirements at WTO under ETs (which are viewed as a regulation). Allowing for export rebates (which could be legally permissible under carbon taxes) would further limit domestic production losses and moderately reduce leakage compared with BCA without export rebates scenario.

Results are shown for a selection of ten G20 countries. Most of the focus is on scenario (1), as it provides an upper bound for competitiveness/leakage impacts. To provide a clean comparison across countries and industries the pricing scenario assumes a uniform charge of \$50 per tonne of CO₂ in 2030 (prices in the feebate/TPS case are higher as they are chosen to match the absolute domestic emissions reductions in scenario (1)). In practice, countries have differentiated responsibilities for mitigation, but using different country-specific policies in the exercise below would obscure to what extent competitiveness/leakage effects may differ across countries for economic reasons rather than policy stringency. The chemicals sector is represented by ammonia—Annex X discusses the case of methanol, which is somewhat different due to lower emissions price responsiveness.

Results: Uniform Carbon Pricing

Costs: Production cost increases are smallest for steel, largest for cement, and intermediate for ammonia and (with the odd outlier) differ only moderately across countries (see Figure 10). For steel, proportionate production cost increases are typically around 4-8 percent across countries—cost increases are largest in India and lowest for the US mainly reflecting differences in emission rates (including the larger share of electrified production in the latter case). For cement, production cost increases are around 30-35 percent. These increases are large (given the high emissions intensity per unit value) and similar across countries (given similar emissions intensities), as could be anticipated from Figure 4. Production cost increases for ammonia are around 20-30 percent in most cases, though somewhat higher for China (given its higher emissions intensity and low baseline supply cost). For each industry, direct charges on unabated CO₂ emissions contribute most of the cost increase.



Production: Reductions in domestic production are typically about 4-8 percent for steel and 15-20 percent for cement and ammonia with migration (rather than domestic demand reductions) accounting for the bulk of the domestic production losses. See Figure 11. For steel and ammonia, most (typically 75 percent or more) of the production cost increases are passed back in lower domestic producer prices and, with domestic supply elasticities for the industries of around unity, each 1 percent reduction in producer prices reduces domestic output about 1 percent. The low pass-through rate also implies domestic demand reductions are limited and most of the domestic production losses are offset by increased foreign production. Cement is less mobile internationally (due to high transport costs per unit of value) implying less of the production cost is passed back in lower producer prices, which dampens the reduction in domestic production. At the same time, consumer demand is relatively less responsive to higher prices (due to limited substitutes for the product) which limits the demand reduction and again implies that most of the domestic production loss is offset by increased foreign production.

Figure 11. Production Impacts Relative to Baseline Under \$50 Carbon Price, 2030

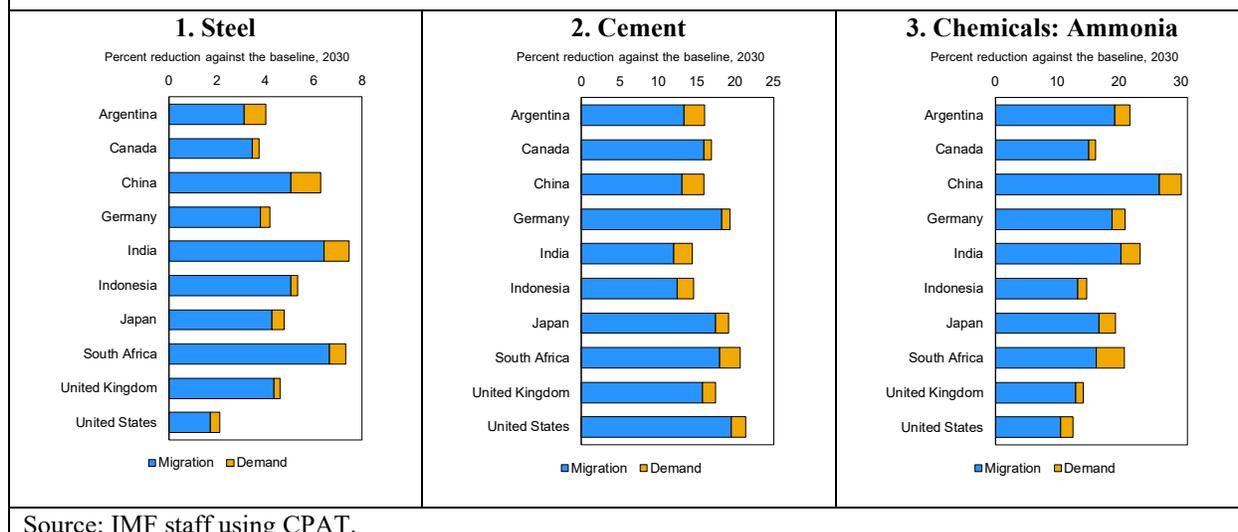
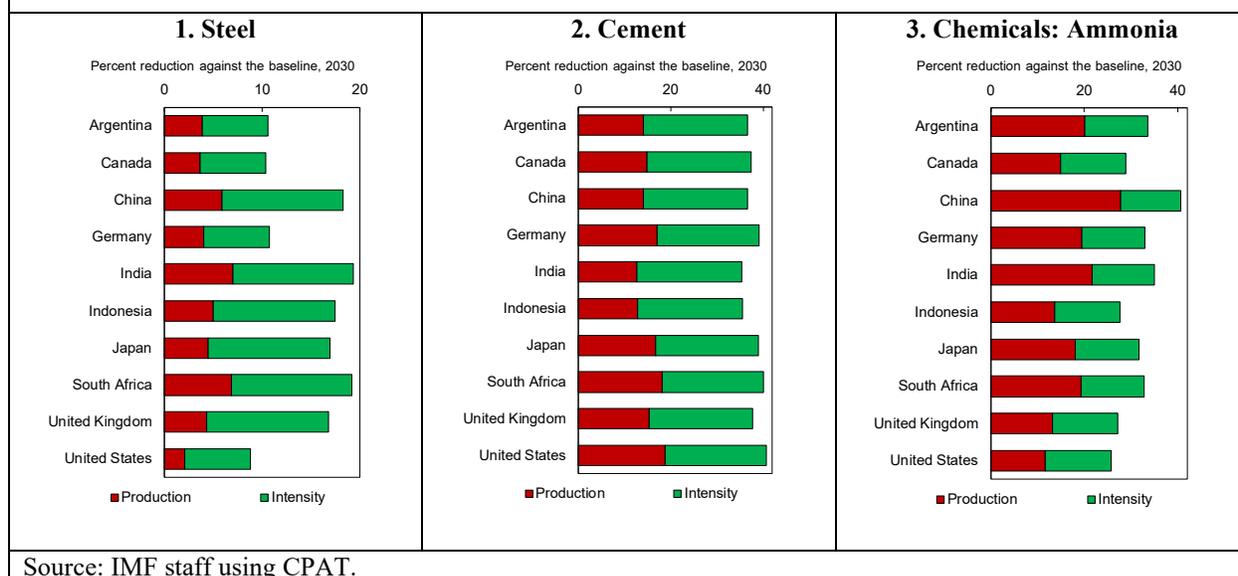


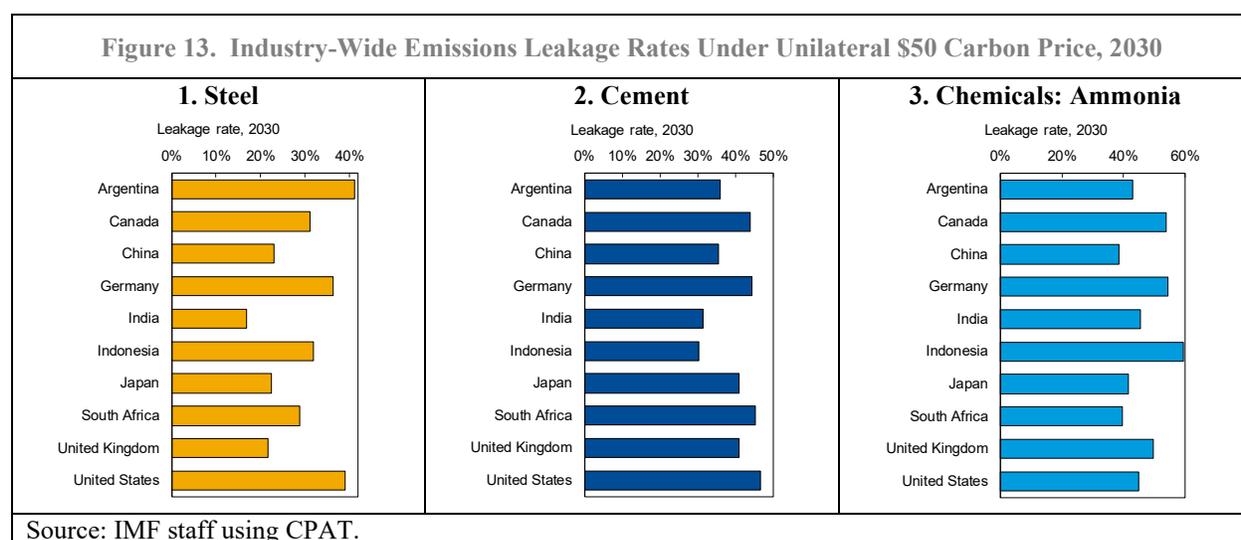
Figure 12. Emissions Reductions and their Breakdown Under Unilateral \$50 Carbon Price, 2030



Emissions: Emissions reductions below 2030 baseline levels are around 20-40 percent across countries and industries with production reductions accounting for a larger share of emissions reductions for cement and chemicals than steel (see Figure 12). Reductions in emissions intensity account for a larger share in total emissions reductions in steel (about 70 percent on average) than in cement (about 60 percent) and ammonia (about 45 percent) due to a

wider range of low-cost mitigation opportunities in steel (more so for countries where production is primarily from blast furnaces). The emissions reductions from reduced production are similar to the proportionate reductions in production (from Figure 11).

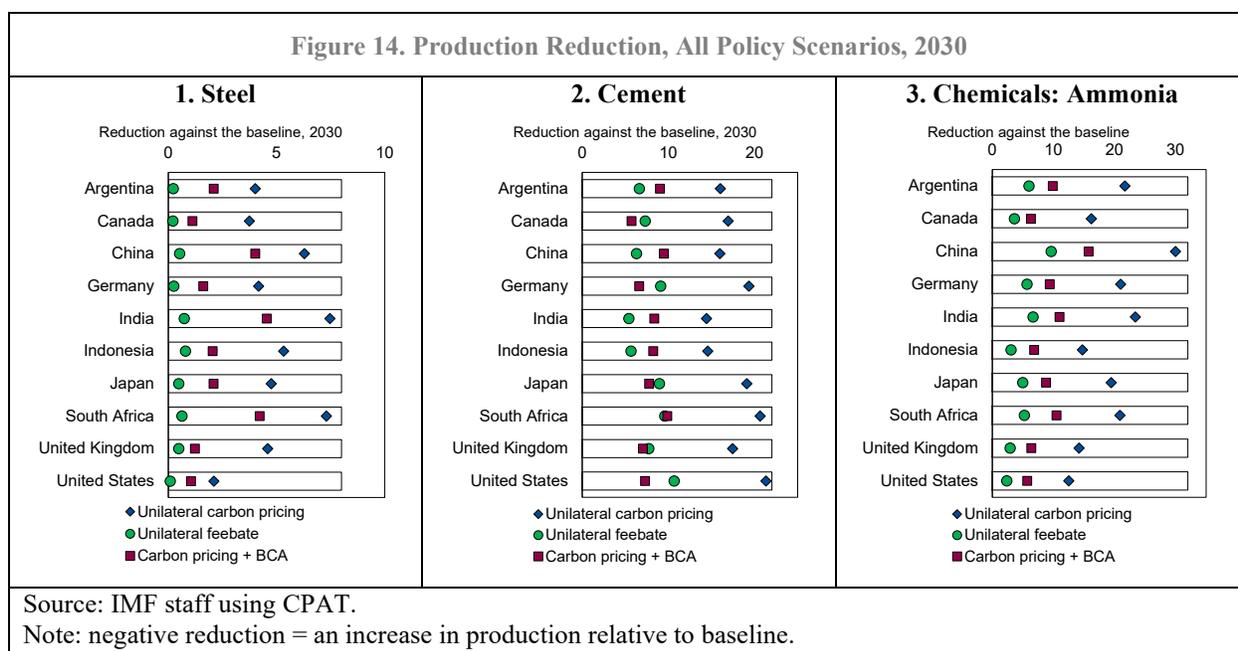
Leakage: Industry-wide leakage rates are mostly around 20-40 percent for steel, 40-50 percent for cement, and 30-50 percent for ammonia (see Figure 13). The differences in leakage rates across industries mainly reflects differences in the portion of emissions reductions that comes from production losses. Across countries, differences in leakage rates are most pronounced for steel, where cross-country differences in emission rates are more significant due to differing shares of electric arc versus blast furnace production. Estimated leakage rates are broadly within those found in the literature (see Annex XI).



Other Policy Regimes

Production: Using feebates/TPSs eliminates much of the domestic production losses under (equivalently scaled) explicit pricing, while combining pricing with a BCA has a similar effect though not as strong (see Figure 14). For steel, feebates/TPSs approximately neutralize domestic production losses, while for cement and chemicals they typically reduce production losses by about two thirds relative to unilateral carbon pricing. In the latter cases, mitigation

costs are relatively higher than for steel (due to more limited technologies to cut emissions intensity), implying feebates/TPS have relatively more impact on raising production costs than for steel (though the impact is still much smaller than for explicit carbon pricing). Under carbon pricing with BCAs, although a smaller portion of production cost increases are passed back in lower producer prices, this is more than offset by the larger increase in production costs (due to pricing of unabated emissions)—hence domestic production losses are somewhat larger than under feebates/TPS (though well below losses under unilateral pricing).

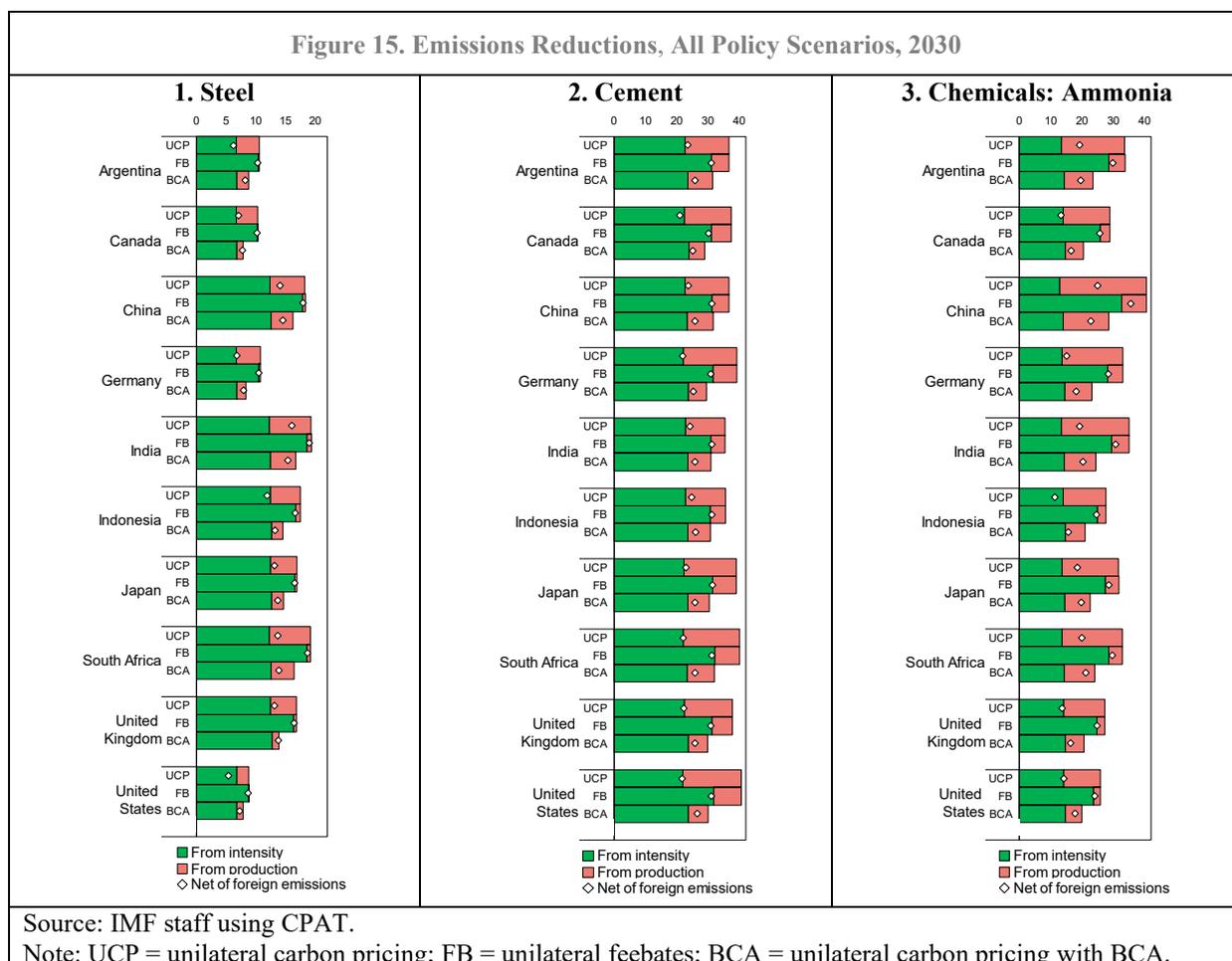


Emissions: Domestic emissions reductions, net of increased emissions in trading partners, are largest under feebates/TPSs, and smallest under unilateral carbon pricing, with carbon pricing with BCAs an intermediate case (see Figure 15). Under unilateral carbon pricing, emissions reductions from reductions in domestic production are approximately offset by increased emissions in trading partners in (most) cases where domestic and foreign industries have similar emissions intensities—they are less than offset in odd cases where domestic industries are more emissions intensive than in trading partners (for example, China and India for steel and

chemicals) and vice versa where domestic industries are relatively less emissions intensive (for example, US steel). For feebates/TPSs there is minimal impact on domestic or foreign production for steel, while for cement and chemicals there is a modest reduction in emissions from reduced domestic production which (for the most part) is offset by increased foreign emissions—on net emissions reductions are larger than under unilateral carbon pricing, due to the larger reduction in emissions intensity. However, although net emissions reductions are larger, they also come at substantially higher price levels needed in feebates/TPS scenarios, compared with \$50 per tonne carbon price.¹⁹ Under carbon pricing with BCAs, the emissions reduction from reduced domestic production is larger than under feebates/TPS but smaller than under unilateral carbon pricing (as there is less pass back of mitigation costs in lower producer prices) but the increase in foreign emissions (to make up for reduced domestic production) is smaller than under unilateral carbon pricing (and can be negative if the reduction in domestic demand exceeds the reduction in domestic supply). Net emissions reductions are larger with BCAs than under unilateral carbon pricing but smaller than under feebates/TPS (though the latter result could reverse at deeper levels of decarbonization).

¹⁹ For steel \$60-100 per tonne of CO₂, for cement \$110-140 per tonne, and for ammonia \$75-100 per tonne.

Figure 15. Emissions Reductions, All Policy Scenarios, 2030



Conclusion

Carbon pricing can lead to significant production cost increases and, by itself, production reductions, emissions leakage in EITE industries, and more general Balance of Payments concerns. Cost and production effects are more modest for steel, but leakage rates (which depend in part on the share of emissions reductions coming from reductions in production) are still significant (20-40 percent). For cement and chemicals, production cost increases and domestic production reductions are more substantial, and leakage is more severe than for steel. Differences in these effects across countries are generally less pronounced than the differences across industries.

All these effects, however, are largely ameliorated when countries offset, or do not impose, charges on firms' unabated emissions, combine pricing with BCAs, or trading partners coordinate over carbon pricing—which approach is appropriate will vary with country circumstances. For example, the EU and UK are phasing in BCAs for EITE industries as a replacement for free allowance allocations as this will facilitate a high and rising carbon price and capacity needs for them are manageable. Canada has addressed competitiveness concerns through a TPS at federal level for industrial emissions, while China is extending this approach (currently applying to its power sector) to industry and India is considering the same approach. In due course, price coordination may well emerge in Asia-Pacific given many countries have already implemented pricing systems for the industrial sector (for example, Indonesia, Korea, New Zealand, Singapore), while others (beyond China and India) are considering or are in the process of implementing it (for example Japan, Malaysia, Pakistan, Thailand, and Vietnam).

Annex I. Industrial Emissions on Non-CO₂ GHGs

There are three sources of non-CO₂ GHGs associated with industrial production.

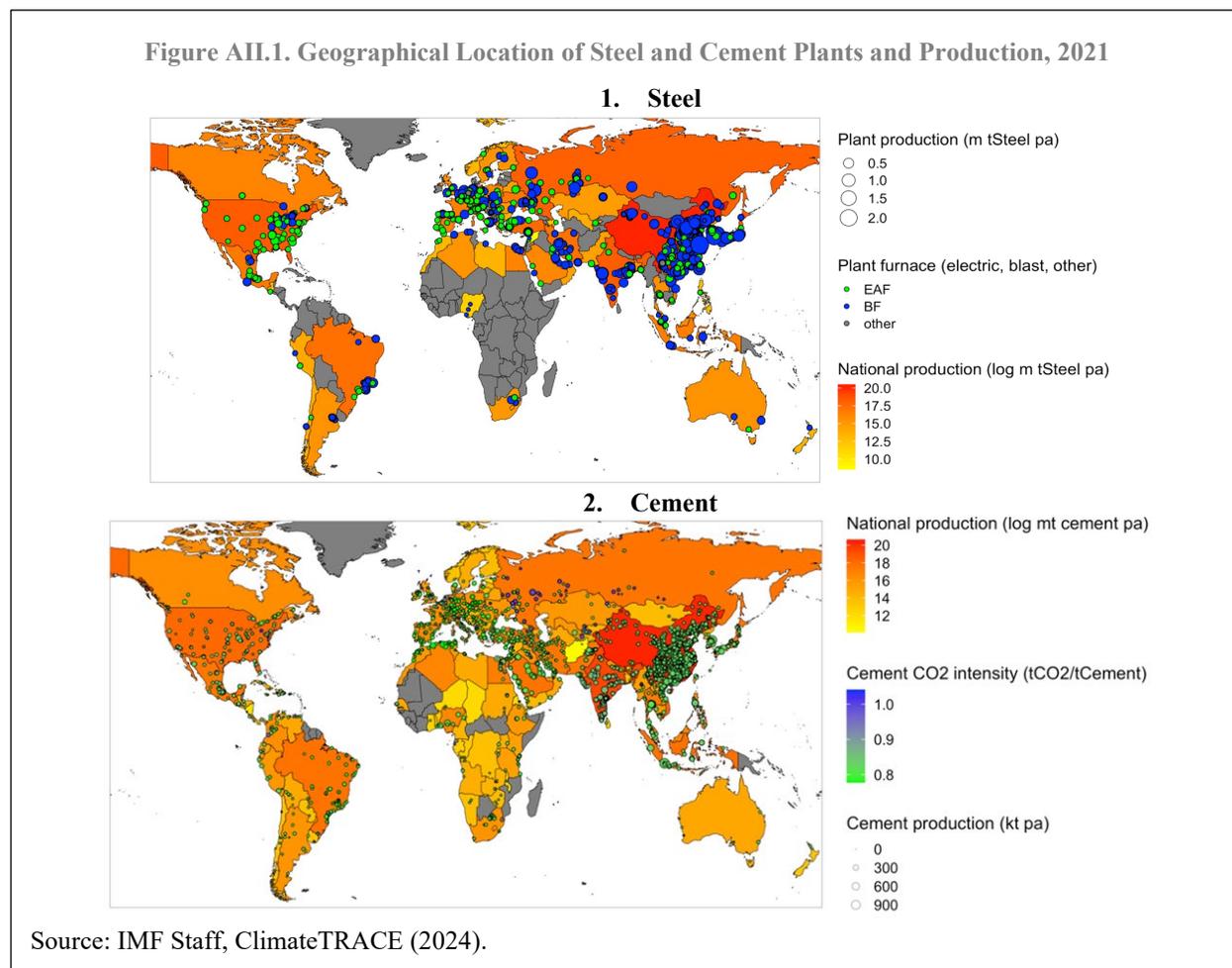
- First, combusting fossil fuels produces nitrogen oxide emissions. When expressed in terms of CO₂ equivalents however, this is less than 1 percent compared to direct CO₂ emissions from fuel combustion in industrial sectors.²⁰
- Second, fluorinated (F-) gases, most importantly hydrofluorocarbons (HFCs), are used to manufacture products like foams, aerosols, and fire extinguishers and ultimately leak into the atmosphere. These gases were largely developed in response to the phase out of ozone-depleting chemicals under the 1987 Montreal Protocol. F-gases are ozone friendly but trap heat and can reside in the atmosphere for centuries—indeed they accounted for 10 percent of industrial GHGs in 2019.²¹ Unlike other GHGs in the Paris Agreement, however, HFCs have other international negotiations. Under the 2016 Kigali Agreement, advanced countries are required to reduce use of HFCs by 85 percent relative to 2011-2013 levels by 2036 and developing countries by 80-85 percent by 2045-2047. Given these gases are being addressed by other policies like taxes,²² they are not considered in the above discussion.
- Third, waste materials generated by industrial processes (for example, chemicals, trash, oils, solvents, dirt) eventually leak GHGs as they decompose. To a large extent however, the appropriate response should be focused on waste management like methane capture at landfills.

²⁰ IMF (2025a).

²¹ IPCC (2022), Table 11.1.

²² See Brack (2015) and Sastre (2016).

Annex II. Location of Steel and Cement Plants Across the World



Annex III. Mitigation Opportunities in the Industrial Sector

These include (see Table AIII.1.):

Electrification (for heating): Electric arc furnaces are well established for scrap steel. For primary steel from iron ore, cement, and chemicals, all of which require intense heat (of around 1,000-1,500°C) electric furnaces are coming closer to market but are not yet viable—and electrification of heating (even if renewably generated) does not reduce process emissions. Electrolysis of material inputs might also be a possibility for lowering cement emissions.

Input switching: For heating fuels, input switching might include shifting from coal to gas (for cement) or from fossil fuels to green hydrogen (or possibly other fuels like biofuels)—green hydrogen is produced by water electrolysis using renewable electricity. Input switching might also include, for cement, partial substitution away from clinker (currently around 75-85 percent of cement) to other feedstocks (like volcanic ash, ground limestone, broken glass).

Emissions capture: In principle technologies could be applied to (new or existing) coal blast furnaces, cement kilns, and chemical processes, to separate CO₂ from waste gases (or also during production in cement kilns) but remains a rarity due to its expense, not least due to the infrastructure and geological sites required for transporting and disposing of CO₂.

Production efficiency: Using state-of-the-art technologies or, in cement, shifting from wet to dry kilns with preheaters feeding off the kilns, can reduce fuel and feedstock requirements per unit of production.

Demand reductions: Steel might be partially substituted with wood or polymers in buildings or plastic in cars; wood or stone might be used in place of concrete in buildings; greater use of fillers (like burnt clay or wastes from fly ash and slag) might partially substitute

for cement in concrete production; and chemical demand might be reduced through, for example, more use of organic fertilizers or reusable shopping bags.

Table AIII.1. Classification of Behavioral Responses to Reduce Emissions by Industry

Type of response	Examples		
	Steel	Cement	Chemicals
Electrification (for heating)	Blast furnace → electric furnace using recycled steel or iron ore as feedstocks	Electric kilns and electrolysis of material inputs are future possibilities	Fossil fuels → electric furnaces
Input switching	Heating: fossil fuels → green hydrogen	Heating: fossil fuels → green hydrogen, coal → gas. Feedstock: partially substituting volcanic ash, ground limestone, other materials for clinker	Heating: fossil fuels → green hydrogen
Emissions capture	Potentially applicable to new/existing blast furnaces	Potentially applied during or after combustion to extract CO ₂ from exhaust gases	Using organic compounds to separate CO ₂ from the gas stream
Production efficiency	State-of-the art technology	State-of-the-art technology; wet → dry kilns with preheaters feeding off the kilns	State-of-the art technology
Demand reduction	Buildings: steel → wood, fiber-reinforced polymer; cars: steel → plastics for trunk lids, body panels, floor panels, fuel tanks	Concrete → wood, stone; optimizing mix of cement/fillers in concrete	Fertilizers: chemical → organic; shopping bags: single use plastic → reusable

Source: Compiled from various websites. Note: Unlike for steel, cement recycling is not generally practical as demolition waste is of low value (and is mostly used as gravel for roads and other infrastructure).

Annex IV. Explicit Carbon Pricing Schemes Applying to Industry

Table AIV.1. Details of National or Regional Explicit Carbon Pricing Schemes Covering Industry, 2024

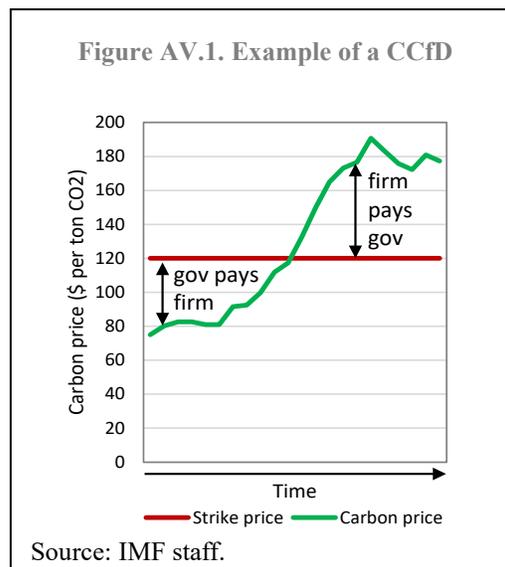
Country/ Region	Year Introduced	Coverage Beyond Industry			Coverage Rate, all GHGs (percent)	Price, \$/tonne	Point of Tax/ Regulation	Price Stability Measures (for ETS)	Revenue/ Rent		Competitiveness measures
		Power	Transport	Buildings					Percent GDP	Use	
Carbon Taxes											
Argentina	2018	✓	✓	✓	38	1	Upstream		0.03	General	
Colombia	2017	✓	✓	✓	20	7	Upstream		0.03	Environmental	
Chile	2017	✓			55	5	Downstream		0.06	General	
Japan	2010	✓	✓	✓	80	2	Upstream		0.04	Environmental	
Singapore	2019	✓			79	18	Point Source		0.03	General	
South Africa	2019	✓	✓	✓	82	10	Point Source		0.03	General	
Ukraine	2011	✓			32	1	Point Source		0.05	General	
Uruguay	2022	✓	✓	✓	5	167	Upstream		0.36	General, environmental	
ETSs											
China*	2021	✓					Point Source	Market stability provisions (buy-back, auctioning), price range			Free allowances
EU	2005	✓			38	61	Point Source	Allowance injection/withdrawals	0.25	General, environmental	Free allowances, transition to BCA
Kazakhstan	2013	✓			47	1	Point Source	Allowance cap/ reserve		General	Free allowances
Korea	2015	✓	✓	✓	89	6	Downstream/ Point Source	Price floor--related to previous prices	0.00	Environmental	Free allowances
New Zealand	2008	✓	✓		48	35	Upstream/Point Source	Price floor and ceiling	0.01	General, environmental	Free allowances
US: California	2009	✓	✓	✓	76	39	Upstream/Point Source/Downst ream	Price floor ramping up exogenously	1.22	General, environmental	Free allowances, BCA for electricity
Hybrid											
Canada	2019	✓	✓	✓	32	59	Upstream/Point Source	The price of carbon pollution increases annually	0.45	Tax cuts, environmental	Free allowances
Mexico	2014	✓	✓	✓	29	4	Upstream		0.03	General	Free allowances initially
Switzerland	2008	✓		✓	47	113	Midstream	Threshold based on previous year's cap	0.33	Tax cuts, transfers, environmental	Free allowances (phase out gradually)
UK	2005	✓			28	45	Point source	Price floor	0.18	General, tax cuts	Free allowances, compensation scheme

Note: China's intensity-based ETS, covering the power sector, is planned to cover 2024 emissions from cement, steel, and aluminum by the end of 2025. Data in the table does not include industry addition (shows as of April 1, 2024).

Sources: Updated from Parry and others (2022).

Annex V. Carbon Contracts for Difference (CCfDs)

An increasing number of countries are considering CCfDs in their industrial decarbonization strategies. For example, the EU and Norway plan to implement them to support the rollout of hydrogen in industries such as steel. Many needed low-carbon technologies are not currently cost-competitive with high-carbon incumbents at current or expected future carbon



price levels. Though cost-effective decarbonization requires least-cost abatement, the longevity of certain capital assets means early deployment may be economically efficient (Vogt-Schilb and others 2018). Additionally, carbon price uncertainty may hold back investment where industrial emissions are covered by ETSs.

CCfDs can address these problems by offering to pay investors in targeted sectors for the difference between an agreed ‘strike price’ and the prevailing carbon price while if the price rises above the strike price firm pays the government the difference. In this way, the investor is insured against the risk of low carbon prices while the government and public benefits at times of high prices.

CCfDs are drawn up as follows:

- Firms estimate additional costs (discounted capital and operational expenditure) from investments in expensive low technologies divided by the expected CO₂ emissions reductions compared with investments in high carbon technologies;
- The government auctions carbon contracts for projects (for example, ten years for hydrogen-based steel), with firms bidding down the strike price based on projects’ additional costs;
- CCfD-winning projects are bankable and face lower market and political risk; and

- Following investment, governments and CCfD-holding firms remunerate each other for the difference between the strike and carbon price.

In the example shown in Figure AV.1., a firm wins a carbon contract with a strike price of \$120 per tonne of CO₂ for investing in hydrogen-based steel. The carbon price begins at \$80 per tonne so the government pays the firm \$40 per ton of CO₂ reduced. But as the carbon price rises to \$180, the firm pays the government \$60 per ton. Though the firm ends up paying, at the point of investment it faces lower risks that future carbon prices will decline (and hence the competitiveness of the steel it produces with it). As a result, it can more easily finance the project.

The benefits of CCfDs include a reduction in price uncertainty faced by firms in targeted sectors. This lowers capital costs in part by allowing a larger share of (cheaper) debt relative to (more expensive) equity financing. Reducing uncertainty can lower overall expected mitigation costs.²³ In addition, the regulator is disincentivized from lowering future carbon prices as it would then need to fund additional CCfD transfers.

The main drawback is that CCfDs are—unlike revenue-raising carbon taxes or revenue-neutral feebates—a revenue-costing instrument.²⁴ They also create uncertain liabilities equal to the difference between future carbon prices and the strike price (when the latter is below the former). If carbon prices decline (for example, due to a recession) then the liability to CCfD holders rises, creating additional fiscal pressure. Lastly, as with other policies overlapping ETSs,

²³ For example by 27 percent in steel according to Richstein and Neuhoff (2022).

²⁴ Even if the government receives revenues in the case of the carbon price rising above the strike price, the government still foregoes revenues equal to the strike price times emissions reductions (assuming permits are fully auctioned).

CCfDs are subject to the so-called ‘waterbed effect’, and so impact on overlapping instruments needs to be considered (as with other policies in ETSs).²⁵

²⁵ Any additional policy that cuts emissions in sectors covered by an ETS will reduce demand for and hence prices of permits. This then raises emissions in other sectors, negating the impact on total emissions (under the waterbed analogy, one side of the bed goes up while the other goes down, with no net impact on volume). To ensure overlapping policies yield additional cuts in emissions – and don’t simply change the composition of emissions – requires removing permits from the ETS equal to the expected emissions cuts, though such a procedure is rarely observed in practice.

Annex VI. Examples of Industrial TPSs and Feebates²⁶

Canada. Provinces and territories in Canada had been required to have a carbon charging system, with the carbon price ramping up from CAN\$10 per tonne CO₂ in 2019 to CAN\$50 in 2023 and prospectively up to CAN\$170 by 2030. A federal carbon pricing backstop system applied in provinces/territories that requested it or that did not meet the federal standard. The backstop had two components: (i) a fuel charge; and (ii) a TPS for facilities in EITE industries (with annual emissions exceeding 50 kilo tonnes of CO₂ equivalent), known as the Output-Based Pricing System (OBPS). The fuel charge was however scrapped in 2025, but the OBPS was kept in place applying in Manitoba, Prince Edward Island, Yukon, Nunavut, and partially in Saskatchewan (Ontario and New Brunswick recently transitioned from the OBPS to regional versions). The OBPS sets an annual emissions-intensity standard for each facility based on (70 percent of) the production-weighted average emissions intensity of all large emitting facilities producing similar products across Canada. Facilities exceeding the standard are subject to fees on their excess emissions (in line with federal pricing) while those emitting less than their standard earn credits they can sell or bank for future use.

China. In January 2021 China launched a nationwide TPS (building off pilot carbon market programs in eight regions) applying to over 2,100 power generators with annual CO₂ emissions 26 kilo tonnes and covering nearly 40 percent of nationwide GHGs. Allowances are allocated freely to covered entities according to production levels of coal- and gas-fired power plants and predetermined emissions intensity benchmarks (in tonnes of CO₂ per megawatt hour

²⁶ This Annex draws from: www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/overview.html; IEA (2022); <https://carbonmarketwatch.org/2020/12/21/what-can-we-learn-from-the-dutch-national-carbon-tax>.

for electricity and or per gigajoule of heat generation) covering only coal- and gas-fired power plants and with no cap on total emissions. The current allowance allocation plan defines four benchmark categories, three for coal-fired and one for gas power plants. Trading prices remain relatively low at the equivalent of around US \$8 per tonne with low liquidity and volume. This scheme has been extended to industry, including steel, cement, and aluminum, with the first deadline for meeting emissions rate requirements scheduled for the end of 2025.

Netherlands. In January 2021, Netherlands introduced a levy on industrial CO₂ emissions equal to any positive difference between an escalating target price (rising to €125 per tonne by 2030) and the prevailing EU ETS price. The levy applies to emissions over and above a pivot point emission rate based on the cleanest ten percent of firms in the industry at the EU-level. Companies with emission rates below the pivot points can sell credits to other firms where the levy is binding.

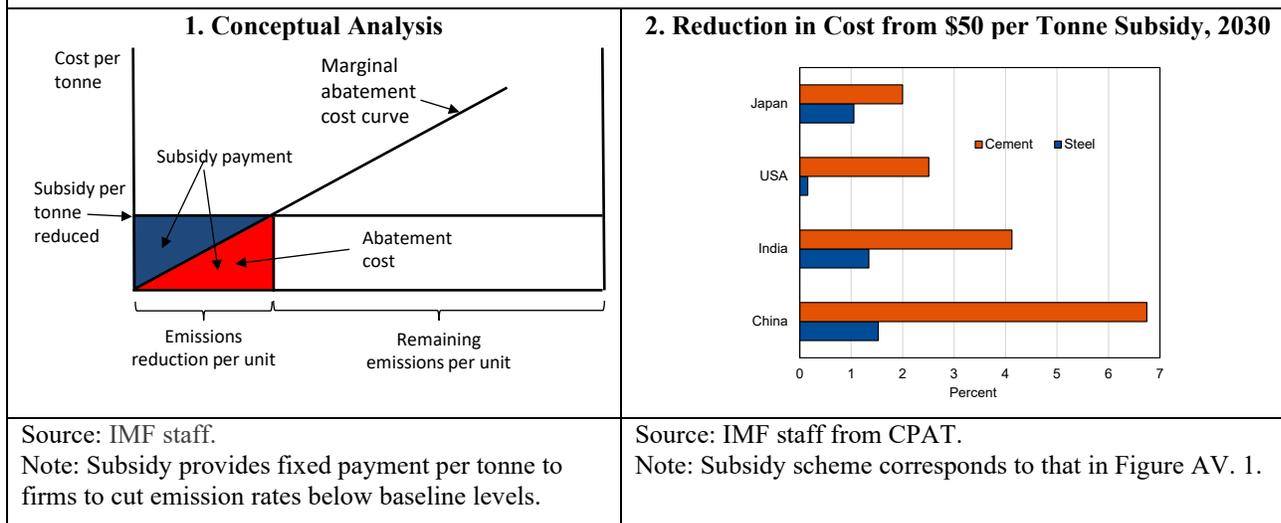
Annex VII. Implications of Subsidy-Based Approaches for Production Costs

This Annex provides a brief conceptual and quantitative sense of the implications for production costs from subsidy-based approaches for reducing emissions. For this purpose, a stylized scheme is considered where firms receive a fixed payment per tonne of CO₂ reduced below their baseline emission rate.

As indicated in Figure AVII.1. Panel 1, this stylized scheme will induce emissions reductions up to the point where the cost of the last tonne reduced equals the subsidy per tonne. Firms incur costs indicated by the integral under the marginal abatement cost curve and receive payments equal to the product of the emissions price and the emissions reduction—on net, firms are better off by the blue triangle. The subsidy scheme is far from the mirror image of explicit carbon pricing—the base of the subsidy is the emissions reduction (rather than remaining emissions as with pricing) and the subsidy payment is partly offset by abatement costs (while underpricing schemes charges on remaining emissions add to the increase in production costs).

Figure AVII.1. indicates the reduction in production costs implied by this stylized scheme with a payment of \$50 per tonne in 2021. For the steel industry, production costs on net are reduced by only around 1 percent or less. For cement, cost reductions are more significant at 4-7 percent in India and China, though international trading markets are less integrated than for steel.

Figure AVII.1. Impacts of Subsidies on Production Costs: Conceptual and Quantitative Illustrations



Annex VIII. Broader Green Policies for the Industrial Sector

Beyond the emissions mitigation instruments discussed above, policies may also be needed to address impediments or market failures at different stages during the development and diffusion of low carbon technologies for the industry.

A further issue is that governments may choose (through procurement policies, domestic content requirements, to foster the development of domestic industries for low-carbon technologies for use across all sectors of the economy (not just industry) and export, for example, electric vehicles, solar panels, batteries, fuel cells. Done well, such policies could help countries diversify, increase energy security, develop comparative advantage in a fast-growing sector, while supporting domestic decarbonization efforts but done poorly, they could distort the economy through inefficient use of scarce resources.^{27,28}

These green industrial policies have resurged in popularity in recent years²⁹ as global trade in low carbon technologies has grown from around \$220 billion (3.5 percent of total trade)

²⁷ The economic rationale for targeting industrial sectors (especially manufacturing) is potential for large positive spillovers and hence for raising overall productivity in the economy ('Kaldor's growth laws'; Kaldor 1966). There is a debate in development economics on this, with some evidence finding in favour (Marconi and others 2016). However, many developing countries have decreased industrial sector size ('premature deindustrialization') as manufacturing has become increasingly concentrated globally (Haraguchi and others 2017). LCT production is also concentrated: developed countries account for 70 percent of LCT exports in 2021 (down from 92 percent in 1998) with most of the remainder attributable to China (Howell and others 2023).

²⁸ Some argue there is a difference between 'old' and 'new' industrial policies. Old policies emphasized import-substitution which may have hindered competition, dampened market signals, and incentivized cronyism. New industrial policies emphasize export-orientation, incentives for steady improvement through competition, investment in complementary infrastructure (Yulek 2018; Cherif and Hasanov 2019), and an 'entrepreneurial' willingness to take risks by policymakers (Mazzucato 2015).

²⁹ For example, with the Sustainable Development Goals (SDGs), countries committed to "build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation." (SDG9; UN 2015)

in 2000 to \$1.2 trillion (4.9 percent) in 2021.³⁰ But these policies have a mixed track record.³¹ Indeed designing these policies is difficult as low carbon technologies have distinctive features, such as requiring high-skilled labor, possible reliance on new supporting infrastructure (such as smart grids), and high up-front costs.³² And importing, adopting, producing, and exporting these technologies requires an ever-increasing set of national, firm-level, and human capabilities.³³ The current pattern of LCT production and trade is also highly concentrated in a small number of countries, and others may find it difficult to compete given their current capabilities and production structures and various barriers to entry across LCT value chains. If countries choose to adopt green industrial policies to target growth in LCT, they should seek to minimize risks, avoid protectionist approaches, and manage fiscal costs.³⁴

³⁰ Howell and others (2023).

³¹ Cherif and others (2022). In a database which tracks government interventions which are likely to affect global trade, investments, and migration, industrial policy measures grew from 20 percent in 2009 to nearly of all policies in 2019 (Global Trade Alert 2023).

³² Pigato and others (2020a).

³³ Empirical evidence suggests that human capital (i.e. skills and educational performance) matter for accelerating LCT adoption and production/export (proxied by RE trade), along with physical capital. This appears is consistent with the larger reliance on human capital and pre-existing infrastructure LCT mentioned above (Pigato and others 2020b).

³⁴ See Hallegatte and others (2013).

Annex IX. Modeling of the Industrial Sector

Mathematical Representation

The industrial sector distinguishes steel, cement, and chemicals (ammonia and methanol) production with equations below applying to each industry. The model contains a reduced form representation of each industry competing in international markets, where the domestic economy can be a net importer or exporter, and foreign production represents a composite of a countries largest trading partners for each industry. Domestic mitigation costs are partly passed through in higher prices to domestic consumers and partly passed back in lower domestic producer prices where the pass-through fraction depends on the price elasticity of domestic demand, domestic supply, and foreign supply. Mitigation costs in trading partners, as well as costs from possible BCAs, are partly passed forward into higher international, and hence domestic consumer prices.

Demand

Domestic demand in a future period t for a product from an EITE industry, denoted Q_t^D , depends positively on expansion in the domestic economy and negatively on domestic consumer prices as follows:

$$(1) Q_t^D = Q_0^D \cdot \left(\frac{GDP_t}{GDP_0}\right)^v \cdot \left(\frac{p_t^D}{p_0^D}\right)^\eta$$

where 0 is the current (starting) period. In addition:

GDP_t = gross domestic product;

$v > 0$ = the income elasticity of demand for the industrial product;

p_t^D = the domestic consumer price (see below); and

$\eta < 0$ = price elasticity of domestic demand, which governs the percent reduction in domestic demand per 1 percent increase in the domestic consumer price.

Production

Domestic supply for an EITE industry, denoted Q_t^S , also depends on expansion in the domestic economy as well as domestic producer prices as follows:

$$(2) Q_t^S = Q_0^S \cdot \left(\frac{GDP_t}{GDP_0}\right)^\phi \cdot \left(\frac{p_t^S}{p_0^S}\right)^\varepsilon$$

Where:

$\phi > 0$ is the elasticity of domestic production with respect to GDP (due to greater availability of labor, capital, and other inputs)—in the default case $\phi = \nu$, that is, supply expands in proportion to domestic demand with growth in the domestic economy;

p_t^S = price received by domestic suppliers, defined net of any costs incurred by firms from mitigation policies; and

ε = price elasticity of domestic supply, which governs the percent increase (decrease) in domestic production per 1 percent increase (decrease) in the domestic supply price.

Net imports (which could be negative) is the difference between domestic demand and production, $Q_t^D - Q_t^S$.

Supply Price

The domestic supply price, net of the costs of mitigation policy, is determined by

$$(3) p_t^S = p_t^M - (1 - \alpha) \cdot Z_t$$

$$(4) Z_t = \left\{ \tau_t \cdot \bar{\beta}_t \cdot \frac{\Delta e_t}{2} \right\} + \{ \Omega \cdot \tau_t \cdot \beta_t \} + \{ \theta_t^E \cdot \Delta p_t^E \}$$

Where a bar denotes a value in the baseline and

p_t^M = the market price (price as determined on international markets)

Z_t = domestic mitigation costs per unit of production;

$0 \leq \alpha \leq 1$ = the fraction of domestic mitigation costs that are passed forward in higher domestic consumer prices and $1 - \alpha$ is the fraction that is passed backwards in lower domestic producer prices;

τ_t = a price per tonne on CO₂ emissions from explicit or implicit carbon pricing;

β_t = CO₂ emission factor (emissions per unit of output) from direct use of fuels or processes;

Δe_t = proportionate change in emissions intensity of production induced by domestic mitigation policy relative to baseline intensity (see below);

Ω = a dummy variable equal to 1 under domestic (explicit) carbon pricing (when firms are subject to charges on remaining emissions) or 0 under a feebate/TPS (when the average firm is not subject to charges on remaining emissions);

θ_t^E = electricity input per unit of domestic production in the baseline;

Δp_t^E = proportionate increase in (domestic industrial) electricity prices caused by mitigation policies in the power sector (the electricity price increase will be smaller if implicit rather than explicit carbon pricing is applied to the power sector).

According to equations (3) and (4), the supply price received by domestic producers is the international market price less three potential private costs from mitigation policies, all scaled by the pass back fraction:

- Abatement costs per unit of output from induced reductions in emissions intensity based on a second order approximation, corresponding the red triangle in Figure 5 and Figure 6;
- Any charges applying to unabated emissions, corresponding the blue rectangle in Figure 5; and
- Increases in electricity input costs per unit, caused by higher electricity input prices, here approximated ignoring policy-induced changes in industrial electricity use per unit of output, and corresponding to the green rectangles in Figure 5 and Figure 6.

Domestic Demand Price

The domestic demand price is determined by the international market price and the pass through of domestic mitigation costs into domestic consumer prices as follows:

$$(5) p_t^D = p_t^M + \alpha \cdot Z_t$$

International Market Price

The international market price is determined by the baseline regional price plus mitigation costs or BCAs for foreign producers that are passed forward into international prices.

That is, international prices are determined by:

$$(6) p_t^M = \bar{p}_t^M + \alpha^F \cdot \{BCA_t + Z_t^F\}$$

$$(7) Z_t^F = \Omega^F \cdot \tau_t^F \cdot \beta_t^F + \tau_t^F \cdot \bar{\beta}_t^F \cdot \frac{\Delta e^F}{2} + \theta_t^{FE} \cdot \Delta p_t^{FE}$$

Where:

BCA_t = a possible BCA imposed on foreign producers;

$0 \leq \alpha^F \leq 1$ = the fraction of foreign mitigation costs or BCA payments that is passed forward to domestic consumers;

And

Z_t^F = foreign mitigation costs where all the terms are analogous to those in equation (4) and are relevant only for the internationally coordinated policy scenarios when trading partners also implement mitigation policies.

Emissions

CO₂ emissions from fuel combustion or industrial processes from a domestic industry, E_t , depend on emission factors and production as follows:

$$(8) E_t = \beta_t \cdot Q_t^S$$

$$(9) \beta_t = \bar{\beta}_t \cdot (1 - \Delta e_t)$$

$$(10) \bar{\beta}_t = \beta_0 \cdot (1 - \delta)^t$$

Where:

δ = an autonomous rate at which the emission factor declines over time in the baseline (for example, as state-of-the-art factories with higher energy efficiency gradually replace less efficient plants).

The reduction in emissions intensity induced by mitigation policy is given by

$$(11) \Delta e_t = \Gamma \cdot (\tau_t)^\gamma$$

In this equation:

$0 < \gamma < 1$ = a parameter that determines the degree of concavity of the emission rate/emissions price relation, or conversely, or the degree of convexity in the marginal abatement cost schedule for reducing emissions intensity below baseline levels.

Γ = a scalar which, for a given γ , is parameterized to ensure absolute values of Δe_t for specific values of τ_t are consistent with estimated marginal abatement cost curves in the literature.

Parameterization

Countries: The domestic economy in model is parameterized for each individual country member of the G20. The foreign economy is defined by the top ten import partners and rest of the world for each G20 country and each industrial subsector. Industry-specific indicators of foreign economy (electricity consumption per unit, emission factor, etc.) calculated as a weighted average by share of each trading partner in import.

GDP: Projections of country GDP are taken from the latest IMF World Economic Outlook.³⁵

Domestic consumption and production: For the starting year (2021), production data comes from Climate Trace datasets (Climate Trace, 2024) for iron and steel, cement, ammonia, and methanol. Data from US Geological Survey Mineral Commodity Summaries (USGA, 2024) were added on ammonia production, and open sources were used to add data points for methanol production. Trade data comes from UN Comtrade database (2024), with following commodity codes: 72 for iron and steel, 2523 for cement, 2814 for ammonia, and 290511 for methanol. Production and demand then projected forward using the above equations.

Income elasticities: On the demand and supply side (for both v and ϕ), unitary values were used. These are typical values for the income elasticity broadly consistent with other studies.³⁶

Demand/supply elasticities and pass through fractions: We adopt a demand elasticity η for steel and chemicals of -0.5 and for cement (where substitutes for the product are more limited) -0.2. The domestic supply elasticity ε_d is assumed to be unitary. All these assumptions are based on empirical studies and other models.³⁷ Foreign supply elasticities depend on (i) the international mobility of products (foreign supply elasticities are greater for steel and chemicals than for cement as the former have lower transport costs relative to value per ton shipped product); and (ii) openness (foreign supply elasticities are greater for countries with higher trade

³⁵ See IMF (2025b), which projections for five years. After five years, we assume gradual GDP growth rates conversion. See details in Black and others (2023a).

³⁶ See Black and others (2023a), Fernandez (2018).

³⁷ For example, see Fernandez (2018), Labandeira et al. (2017), NERA Economic consulting (2016), Demailly and Quirion (2006).

shares due, for example, to closer proximity to international markets). Foreign supply elasticities are therefore based on a benchmark value for each industry, a multiplier reflecting the relative size of trade.

For steel and chemicals (where international markets are reasonably well integrated) the benchmark value is assumed to be 3 and for cement 1. The multipliers are 50, 66 or 100 percent for cases where trade is less than 40 percent, 40-70 percent, and 7—200 percent of domestic production. See Table AIX.1. The pass-through coefficients (fraction of domestic or foreign mitigation costs or BCA payments that is passed forward to domestic consumers) are calculated based on the following formulas:

For domestic pass-through (PT_d):

$$PT_d = \frac{\varepsilon_d * \frac{\varepsilon_d}{\varepsilon_d + \varepsilon_f}}{\varepsilon_d + |\eta|}$$

For foreign pass-through (PT_f):

$$PT_f = \frac{\varepsilon_f * \frac{\varepsilon_f}{\varepsilon_d + \varepsilon_f}}{\varepsilon_f + |\eta|}$$

For example,

Prices: In the baseline, market prices p_t^M for each industry are based on the weighted average of recently observed prices for each country's trading partners (from open sources and databases, including Statista, UN Comtrade Database, news reports) and these prices are assumed to be growing at the average compound growth rate for industry, based on data from FRED database (2024). For selected ten countries, prices vary from \$897 (Argentina) to \$1109 (South Africa) per tonne for steel; \$76 (Argentina) to \$104 (Canada) per tonne for cement; \$427 (Argentina) to \$540 (United States) per tonne for ammonia, and \$329 (Canada) to \$430 (Argentina) per tonne for methanol.

CO₂ (direct) emission factors: For cement and ammonia, baseline emissions factors $\bar{\beta}_t$ mainly come from Climate Trace datasets (other sources include IPCC (2006), default CBAM values from the European Commission (2023), and IEA (2021)), based on averaging over emissions factor data at the plant level by country, while for steel and methanol baseline emissions factors are obtained by the respective technology (blast furnaces and electric arc furnaces for steel, steam methane reforming and coal gasification for methanol) by the respective steel output for these technologies. The autonomous rate of reduction in emissions factor δ is taken to be 0.2 for steel, and none for cement and chemicals, based on historical data.³⁸

Table AIX.1. Demand/Supply Elasticities

Industry	Elasticity assumptions		
	Domestic demand	Domestic supply	Foreign supply
Steel	-0.5	1	3 x multiplier
Cement	-0.2	1	1 x multiplier
Chemicals	-0.5	1	3 x multiplier

Multipliers:

Total trade to dom. production, percent	Less than 40%	40-70%	70-200%
Multiplier for foreign supply elasticity	50%	66%	100%

Sources: See text.

³⁸ See IEA: <https://www.iea.org/energy-system/industry>

Parameters of emissions/price relation: For each industry, marginal abatement cost curves scalar and concavity (Γ and γ) are chosen based on the abatement costs and abatement potential of available and possible technologies, parameterized to Blok et al. (2021), Scott et al. (2023), and McKinsey (2013) for iron and steel and cement. For ammonia and methanol, parameters were based on Woodall et al (2022), which also quantifies abatement costs and abatement potential of available and possible technologies for chemicals. See Table AIX.2.

Electricity parameters: The ratio of electricity inputs to production θ_t^E is obtained from several sources and depends on the technological processes in each industry. Electricity consumption data for steel comes from Climate Trace datasets based on plant-level data. For cement, the main source is IEA (2018b), which provides country-specific and regional per unit electricity consumption. For ammonia, per-unit electricity consumption was chosen based on default values for different types of production processes from IEA (2021).

For methanol, per-unit electricity consumption was based on default values for each technology process from Woodall et al (2022). Electricity inputs are assumed to change if there is a shift in technology over time. The proportionate increase in electricity prices Δp_t^E is calculated endogenously in CPAT under carbon pricing or feebates/TPS.

Industry	Reduction in emissions intensity relative to baseline from carbon price	
	\$20	\$50
Steel: blast furnace	6%	16%
Steel: electric arc furnace	3%	9%
Cement	18%	25%
Ammonia	13%	35%
Methanol: coal gasification	26%	35%
Methanol: steam methane reforming	3%	8%

Source: IMF staff calculations based on studies cited in the text.

Fuel taxes and baseline fuel use: Pre-existing fuel taxes τ_t^i are included in the CPAT model.³⁹ \bar{F}_t^i is based on current and projected future fuel use by country/industry in CPAT.

Limitations

The model treats trading partners as a group, and therefore does not decompose the increase in production in individual trading partners in response to production migration from the domestic economy. It seems reasonable, however, to assume production increases are proportional to the share of the trading partner in imports to the domestic economy—relaxing this assumption will likely have little effect given the limited cross-country differences in emissions rates for given industries.

The model does not account for possible feedback effects from induced changes in exchange rates as countries trade balances change in response to mitigation policy, though these effects are likely modest given the modest size of EITE industries in overall trade balances (and effects will depend on whether the monetary authorities in different countries respond, for example, by changing interest rates). The model also abstracts from possible feedback effects on international prices for EITE products that might result in a regime where countries coordinate over carbon pricing. This effect is difficult to accurately pin down, not least as it depends on the share of global production for EITE industries covered by the pricing regime but is likely modest unless the regime covers both a large portion of global production and substantially reduces aggregate production by the coordinating countries.

The model also abstracts from future technological progress for clean technologies that might be induced by carbon pricing. This effect is difficult to estimate *ex ante*, but it is important

³⁹ See Black and others (2023a) for details on their estimation.

to update the type of analysis presented here over time, as mitigation cost schedule are refined over time. The model also does not explicitly consider general equilibrium effects, though some of these effects are implicitly included. For example, to the extent that mitigation policies reduce GDP this may have some feedback effect on reducing consumer demand for EITE products, though this effect should be modest (given both modest effects on GDP and the small shares of derivative products from EITE industries in consumer budgets) and in any case is typically accounted for in empirical estimates of consumer demand elasticities. More generally, higher prices for critical materials like steel and cement could have macroeconomic implications in fast-growing economies, but this is beyond the focus of the paper on competitiveness/leakage issues.

The parameterization does not account for recent tariffs imposed by the US on its trading partners, which are typically 25 percent for steel (and other imports) though they do not apply to cement and most chemicals. Including the steel tariff would raise baseline steel prices in the US and dampen the demand and production responses to domestic carbon pricing (as such pricing would have a smaller proportionate impact on raising prices relative to baseline levels) but these effects would be modest.

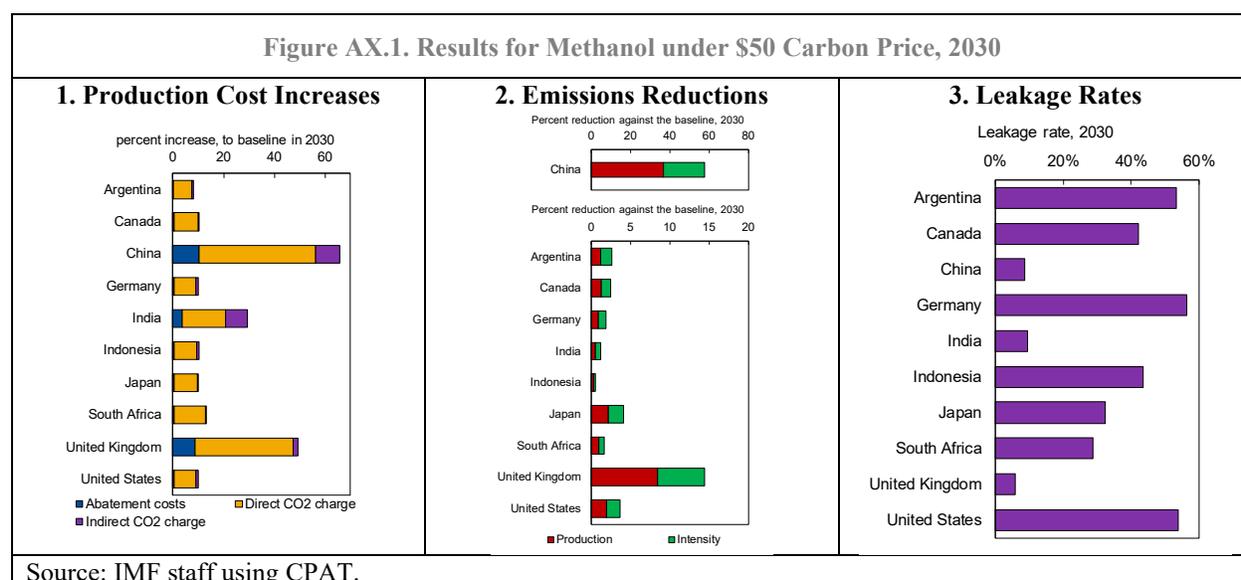
In modeling BCAs, some second-order effects are ignored. They include the (likely small) increases in imports of primary energy due to the change in relative prices of products covered by the BCA (cement, steel, chemicals) relative to primary energy sources (not covered by the BCA). They also include potential diversion of trade flows away from the countries applying BCAs to countries without BCAs, though this might be hard to gauge due to non-price trade barriers.⁴⁰

⁴⁰ See Naegele and Zaklan (2019) for further discussion.

Annex X. Additional Results from Quantitative Analysis

This annex shows quantitative results for methanol sector (see Figure AX.1).

- Production costs increases are around 10 percent for countries with steam methane reforming (SMR) as the main technology, and more than 50 percent where coal gasification (China, India, UK) dominates.
- Emissions reductions vary based on technology as well. Mitigation potential is higher for countries using mainly coal gasification (decrease in emissions between 15 and 50 percent), while abatement opportunities are limited where methanol is main producer via SMR (less than 2 percent).
- Leakage rates vary significantly across countries (between 10 and 55 percent), with “dirtier” coal gasification production process leading to lower leakages, as there offsetting increase in foreign emissions is limited (due to foreign production being cleaner).



Annex XI. Comparing Emission Leakage Rates to Other Studies

In other literature, ex-ante modeling studies usually find significant leakage rates, while ex-post empirical studies do not. Estimates in the modeling studies vary significantly, from a relatively modest 5 to 25 percent (Branger and Quirion 2014) up to 130 percent (Babiker 2005). Most of the empirical studies find leakage effects to be small or statistically insignificant (see extensive reviews by Dechezlepretre and Sato 2017, Venmans and others 2020, and Verde 2020 for EU ETS specifically), although Misch and Wingender 2024 find higher leakage rates of 15 to 45 percent. Differences in ex-ante estimates can be explained by scenario (size of coalition, level of pricing) and modeling assumptions (Armington elasticities), while factors like low levels of carbon pricing and measures to address competitiveness in existing pricing schemes help to explain low leakage rates found in the ex-post empirical studies. Naegele and Zaklan (2019) also suggest various non-price barriers (like market power, transportation costs, political risks, concerns over exchange rates and availability of qualified labor) may help explain the small leakage rate estimates. At the same time, some studies suggest leakage may be *negative* if mitigation policy in one country catalyzes similar policies in other countries (for example, Bogmans 2015, Ferguson and Sanctuary 2019, Aydemir and Zeren 2017).

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