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The Economics of Border Carbon Adjustment: Rationale and Impacts of Compensating for Carbon at the Border

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Abstract

International trade contributes directly to global greenhouse gas emissions, as the carbon content of high-emission products is priced differently in different countries. This phenomenon is termed carbon leakage. Thus, not putting a price on carbon is theoretically equivalent to an export subsidy, although that would be difficult to challenge in the context of multilateral trade law. Leakage can be alleviated by pricing the carbon embedded in imported products through a border carbon adjustment (BCA), be it a tax, a carbon tariff, or a regulation requiring the purchase of emissions allowances. The design of a BCA is a compromise between environmental effectiveness in preventing leakage, economic effectiveness in preserving competitiveness and ensuring acceptability, technical feasibility of the implementation, and World Trade Organization compatibility. An import-limited BCA is more effective than free emissions allowances in reducing leakage, but it does not preserve the export competitiveness of the country imposing it.

1. INTRODUCTION

International trade increases CO_2 emissions through the shipment and production of traded goods (Cristea et al. 2013), although the gains of international trade exceed the associated environmental cost by two orders of magnitude (Shapiro 2016). But international trade also contributes to global emissions insofar as it directly or indirectly undermines some of the decarbonization efforts undertaken in an uncoordinated way at the international level: directly, if the carbon content of certain products does not have the same price in different countries because of the shift of production to countries where this price is lower (direct carbon leakage), or indirectly, if the effort to reduce the use of fossil fuels by certain large countries lowers the world price of these fuels and leads to an increase in consumption in countries not participating in the effort (indirect leakage through energy markets).

Not pricing the externality of fossil fuel burning theoretically amounts to an export subsidy (Stiglitz 2006). Although it is generally impossible for one government to interfere with the public policies of another—in this case, to impose an equivalent taxation of carbon—such a subsidy can be corrected by a border tax (Markusen 1975). Whether such a subsidy is actionable is uncertain in the context of multilateral trade law (Mehling et al. 2019, Pauwelyn 2013). Actually, in contrast to this clear-cut theoretical result, there are few examples of the implementation of border carbon adjustments (BCAs). The well-known exception is California's emissions trading system, which since 2013 has imposed a BCA for electricity imports from states without an emissions trading system linked to California's. Suppliers of imported electricity are held responsible for the emissions associated with electricity generated outside California. A default carbon intensity is used as a benchmark for emissions embodied in imported electricity. Importers who can justify that the imported electricity is less emitting than this default value escape compensation. The prohibition on resource reshuffling by suppliers—a potential source of leakage—has proven to be unworkable in practice (Fowlie et al. 2021). At the federal level, a bicameral Democratic proposal (the FAIR Transition and Competition Act of 2021) aims to compensate for carbon at the US border for carbon-intensive industries exposed to trade competition, and Congress has examined the pros and cons of such an adjustment (Ramseur et al. 2022). Another example is the border adjustment embedded in the Fit for 55 package of the European Commission, dubbed the Carbon Border Adjustment Mechanism (CBAM). Announced by European Commission President Ursula von der Leyen in September 2020 as part of the European cap-and-trade market reform, the CBAM followed the usual institutional track. Negotiations on the design of the CBAM, beyond their political economic foundations (Sapir & Horn 2020), illustrate the economic analysis of the instrument made in this review.

At first glance, the principle of such compensation is simple. The externality can be corrected by putting a price on the carbon embedded in imported products. This price can take the form of a tax, a customs duty, or a regulation requiring importers to purchase emissions allowances on a cap-and-trade market. If the reference price is the one imposed on domestic producers and the reference tax base is the actual carbon content of the product, then a level playing field is restored in the domestic market between domestic and imported products. In third markets, the competitiveness of exporters can be partially restored by exempting them from carbon pricing—partially only, because domestic exporters, who also sell on the domestic market, have invested in reducing their carbon footprint anyway, unlike their foreign competitors.

In reality, many additional elements make the implementation of this compensation challenging. The first set of issues relates to equity considerations. Should the different levels of development between countries, the history of emissions, or the importance of the efforts made in decarbonization be taken into account in the reference carbon price? Another set of issues relates to commitments made at the multilateral level within the framework of the World Trade

Organization (WTO). How can we reconcile a new trade barrier with these commitments? A third set of issues relates to the distinction between the objective and the means. The objective of abating emissions can be achieved with regulations or subsidies, even though these tools are less effective than a carbon price. Shouldn't the country imposing a compensation at the border take into account the implicit carbon price of these policies? A final set of considerations relates to cooperation, free riding, and incentives. The compensation mechanism at the border can indeed be viewed as a permissive condition for the implementation of ambitious policies by a group of countries and as an incentive to join the cooperation for countries that have not yet implemented such policies.

The objective of this article is to review the burgeoning literature on border carbon offsetting by placing it within a broad perspective of economic theory addressing the collective action problem of reducing global emissions (other recent surveys include Aldy 2017, Bellora & Fontagné 2020, Bierbrauer et al. 2021, Böhringer et al. 2022, Cosbey et al. 2019, Felbermayr & Peterson 2020, Keen et al. 2021, Mehling et al. 2019, Parry et al. 2021b, Sato 2014, and Timilsina 2018). Section 2 examines why a global carbon price is out of reach and what the second best solutions to address climate change are. Section 3 sets the stage and documents the distinction to be made between carbon footprint and territorial emissions. Section 4 surveys the ex post and ex ante empirical evidence of carbon leakage. Section 5 reviews the arguments for and against carbon compensation at the border, sketches a simple theoretical framework, and surveys the impacts of such a mechanism. Section 6 concludes.

2. CLIMATE CHANGE WILL NOT BE ADDRESSED BY A GLOBAL CARBON PRICE

2.1. The First Best Solution: The Same Carbon Price Worldwide

Climate is a global public good. Each molecule of greenhouse gas (GHG) emitted increases the atmospheric concentration of the gas, whatever the emitter, and generates the same marginal damage. While command-and-control instruments (e.g., regulation of emissions of power plants) can be considered, market-based instruments should in theory be preferred (Gollier & Tirole 2015). The most efficient response to the deterioration of this global common is to put in place a uniform price on GHG emissions at the world level, in the form of a carbon tax or a worldwide emission permits market (below, we use carbon as shorthand for GHGs). This uniform carbon price, reflecting the social cost of emissions, leads to the equalization of marginal abatement costs worldwide and therefore minimizes the global cost of abatement.

However, the implementation of this uniform carbon price is clearly out of reach at the moment. Contrary to what happens with local public goods, there is no jurisdiction at the international level regarding who is responsible for providing, and paying for, the global public good. Therefore, countries must resort to negotiations to try to reach an international agreement on climate policy. They started to negotiate at COP1 in 1995 and have met again each year since, with limited success. The task is proving to be extraordinarily difficult for at least three reasons. First, free-riding incentives are very strong. Second, the temporal dimension of the climate change problem requires the international community to decide how to allocate the efforts over a long time horizon. Third, justice cannot be separated from efficiency in the design of climate policy.

2.2. Obstacles

Free-riding incentives are pervasive in environmental policy in general and in climate policy in particular. Countries that do not make any mitigation efforts still benefit from the efforts of others. Nordhaus (2015) attributes to free riding the failure of the first climate treaty, the Kyoto

Protocol, and the impossibility of designing an international climate agreement on a basis other than voluntary.

The temporal dimension of the problem makes the fight against climate change even more difficult. Indeed, present generations have to pay the costs of climate policy, but the benefits will go mainly to future generations. There is an intertemporal free-riding issue: Each generation is tempted to enjoy the benefits of high carbon emissions while postponing costly abatement efforts. At the core of the intergenerational equity question is the much-debated choice of a social discount rate (Arrow et al. 2013).

Different countries bear different historical responsibilities for climate change. Advanced countries are responsible for much of the cumulative GHG emissions since the Industrial Revolution. For that, they owe a climate debt to the least developed countries.[1] However, some emerging countries now emit more GHGs than industrialized countries, in absolute terms if not per capita. These asymmetries are obviously a strong handicap for a global climate policy. On the one hand, developing countries posit that they should not pay to reduce their emissions but rather should be compensated for the historical emissions of advanced countries, especially because damages are very unevenly distributed across the globe and are much higher at low latitudes. On the other hand, advanced countries are clearly reluctant to pay developing countries to make the investments necessary to decrease their emissions and to adapt to the changing climate.

Countries at different levels of development face different constraints and have different abilities to pay for abatement. In poorer countries, the marginal utility of consumption and the discount rate are higher than in richer ones. Increasing short-run income and wealth is a priority, while investing in abatement for the long run does not seem as urgent. At the same time, developing countries will be the most affected by climate change not only because of geography but also because of lower resilience and higher vulnerability. The main question is whether it is possible to grow cleaner without growing slower (World Bank 2012).

Several theoretical arguments, revolving around equity considerations, support the international differentiation of carbon prices. Chichilnisky & Heal (1994) and Sandmo (2005) show, from a public economics perspective, that equalizing marginal abatement costs across countries through a uniform carbon price is optimal only if distributional issues are neglected or if lump-sum transfers between countries can be freely implemented. In the realistic case where transfers between governments are impossible to implement or are too small, international differentiation of carbon prices is the only way to take care of equity concerns. Pottier et al. (2017) survey the literature on intergenerational and intragenerational climate justice and discuss the principles that could guide fair sharing of the remaining carbon budget. They show that no consensus emerges from the diversity of opinions and arguments. However, Article 3.1 of the United Nations Framework Convention on Climate Change (UNFCCC 1992) has laid down the principle of "common but differentiated responsibility and respective capabilities," stating unambiguously that historical responsibilities and differences in levels of development must be taken into account for the burden to be shared fairly.

Moreover, climate change is not the only externality at play in the economy, and several imperfections interact with climate policy: households' behavioral biases, constraints of all sorts (credit constraints, lock-in due to past decisions regarding equipment and location, etc.), and potentially stranded assets. The multiplicity of imperfections implies that direct carbon pricing is necessary

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[1] Several objections to the notion of climate debt have been raised. The two main ones are that ignorance of the harm caused by emissions is a sufficient reason for lack of responsibility of advanced economies and that present generations cannot be held responsible for the behavior of past generations (for a discussion from the ethical, moral, and legal points of view, see Kolstad et al. 2014 and references therein).

but not sufficient, and that it needs to be complemented by other instruments that can address these issues, among them regulations, standards, and subsidies. Political economy considerations are also paramount: Even though economists massively favor carbon taxes to combat climate change, virtually nobody else shares this view. Households, firms, and consequently governments favor command-and-control instruments, even though they are more costly and generally more regressive than carbon pricing for a given environmental result (Bruegge et al. 2019, Davis & Knittel 2019, Levinson 2019).

2.3. Solutions

Various ways to overcome obstacles to the first-best solution have been considered. The first international agreement on climate change, the Kyoto Protocol (1997), was adopted at COP3 in December 1997 and entered into force in February 2005. It consists of a legally binding commitment by some countries to reduce their GHG emissions. According to the UNFCCC principle of common but differentiated responsibility and respective capabilities, Annex B of the Kyoto Protocol lists the countries for which binding emissions reduction targets are set: all the developed countries in the OECD, plus the European Union and economies in transition. Non–Annex B countries do not commit to decrease their emissions. Annex B countries have to enact domestic policies to achieve their emissions reductions and can resort to flexible market mechanisms, including an international cap-and-trade system.

The Kyoto Protocol can be credited with a small success: The regulations put in place have had some effect on emissions (Aichele & Felbermayr 2013, Grunewald & Martinez-Zarzoso 2016). However, its ambition has been weak, and the cap-and-trade market has been a failure. The facts that major emitters (e.g., China, India) were not included in Annex B and that the USA chose to withdraw from the Kyoto Protocol have been detrimental. According to Barrett (2002), the two main flaws of the Kyoto Protocol were that it focused on the short term and that it did not create incentives for broad participation and full compliance.

This failure has led to a more comprehensive approach, the Paris Agreement (2015). It requires all countries to set emissions reduction pledges, known as nationally determined contributions (NDCs). The important point is that these contributions are voluntary. They have to be reviewed and strengthened every 5 years. The goals are to limit the increase in temperature, compared with the preindustrial level, to well below 2°C and to pursue efforts to keep it below 1.5°C. As each country decides its own contribution, nothing ensures that the sum of these contributions will allow countries to reach this goal, and the theory of voluntary contributions to public goods tells us that it will not (Bergstrom et al. 1986, Cornes & Sandler 1984). Furthermore, there is no mechanism ensuring that each individual country meets its target, absent penalties for noncompliance.

Whether the Paris Agreement is a success or a failure is debatable. On the one hand, the vast majority of countries have joined the Agreement and provided NDCs. On the other hand, the Agreement does not fix the problem of cooperation because national commitments cannot be enforced, and it does not address the problem of coordination, either, because the sum of NDCs is not sufficient to reach the objective.

International institutions are considering alternative solutions. The core issue is the comparison of decarbonization efforts, given the multiple instruments that can be mobilized. The first approach, termed effective average carbon prices, is a summation of the different modalities of explicit carbon pricing (fuel excise taxes, carbon taxes, and tradable emission permits). The carbon price score then measures to what extent a country prices all energy-related carbon emissions at a certain benchmark value [e.g., €60 in the 2021 release of the OECD Effective Carbon Rates

(OECD 2021)]. The second, more ambitious approach aims to compute implicit carbon prices, a research avenue initiated by McKibbin et al. (2010), followed by a series of tentative international comparisons (Aust. Product. Comm. 2011, OECD 2013). The International Monetary Fund (IMF) and the OECD embarked on a systematic comparison of economy-wide carbon price equivalents (ECPEs) (IMF & OECD 2022). Based on granular policy information and using the IMF Climate Policy Assessment Tool (a combination of partial equilibrium models developed jointly by the IMF and the World Bank), this approach aims to calculate the price equivalent of the emissions reduction policies of G20 countries. The criterion used for this comparison is the ECPE, namely the carbon price that would achieve the same emissions reductions as the policies actually in place. Black et al. (2022) take into account electricity generation, industry, road transport, and buildings, which lead to rather low ECPEs compared with the orders of magnitude used for high-emission industries or electricity generation only. This comparison is intended as a first step toward a more ambitious international policy that would aim for a carbon price floor differentiated by development level (Parry et al. 2021a). Lastly, Chateau et al. (2022) use a dynamic and global computable general equilibrium (CGE) model (IMF-ENV) and conclude that command-and-control or indifferently market-based instruments are effective in reducing emissions from power generation; in contrast, in high-emission industries with limited opportunities for technical substitution, price instruments are more effective and less costly. Unlike the IMF–OECD initiative mentioned above, the objective of this exercise is methodological: The approach is less granular, but it takes into account the interactions between instruments and countries.

The proposal to create a climate club is an additional layer of complexity in international negotiations. Initially suggested as a solution to the limitations inherent in the uncoordinated approach to voluntary commitments at the international level (Nordhaus 2015), this approach was revisited as a forum for cooperation under the German G7 presidency. The main difference between the two approaches, however, is that the Nordhaus Club would impose a punitive flat tariff on all imports from nonparticipating countries, while the German presidency's proposal would impose a carbon compensation only at the club border.[2]

Currently, carbon pricing (through carbon taxes or emissions trading systems) is increasing worldwide in an uncoordinated manner. As of 2022, 68 carbon pricing instruments are in operation, covering around 23% of global GHG emissions (World Bank 2022). Carbon prices and the share of emissions covered are far from being harmonized. The risk of leakage is therefore real and will probably increase over time as carbon prices diverge further.

3. SETTING THE STAGE

3.1. Territorial Emissions Versus Footprint

The EU27 is a perfect example of the challenges to be overcome by an ambitious and rather isolated climate policy. EU27 emissions of GHGs (excluding emissions or removals from land use, land use change, and forestry) have continuously decreased since 1990. Territorial emissions

[2]For a discussion of the difference between the two proposals, see Bierbrauer et al. (2021). Bekkers & Cariola (2022) use the WTO's dynamic general equilibrium model to simulate alternative policies that aim to incentivize nonparticipating countries to join the mitigation effort: a BCA, the Nordhaus Club, a differentiated carbon price floor, a global fund redistributing the revenue of global carbon pricing on a per capita basis, and finally global emissions trading. They conclude that emissions trading fulfills all the desired conditions, whereas the BCA can hardly incentivize nonparticipating countries to adopt mitigation policies, the Nordhaus Club is unfair to developing economies, the minimum carbon price is unable to prevent income losses from decarbonization in low-income economies, and the carbon fund is inefficient in terms of incentives.

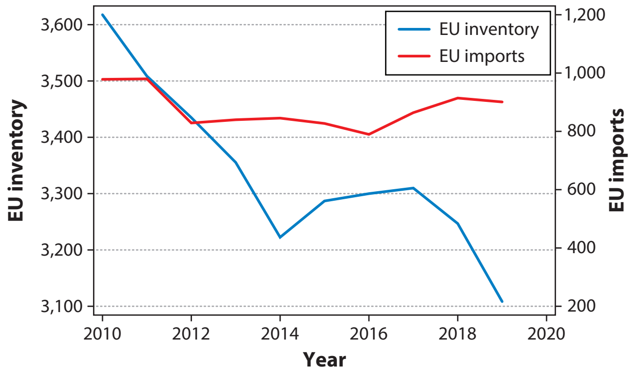

Figure 1

EU27 greenhouse gas (GHG) inventory and carbon embodied in EU imports, 2010–2019. Data are from Eurostat (data set available at **https://ec.europa.eu/eurostat/databrowser/view/ENV_AIR_GGE/default/table?lang=en**). Emissions were computed with the FIGARO multiregional input–output model (million ton CO_2 equivalent of all GHGs).

amount to 3,125 Mt CO_2eq in 2020, down from 4,687 Mt in 1990. According to Eurostat data,[3] direct emissions by households were 753 Mt CO_2eq in 2019, and emissions by EU industries and services for domestic consumption amounted to 2,353 Mt. Were foreign producers to use EU technology, the CO_2 content of imported goods and services for EU consumption would be 609 Mt, which is slightly lower than the EU emissions involved in the export of goods and services (697 Mt). But imports are produced with less carbon-efficient technologies. These international differences in technology can be taken into account using a multiregional input–output (MRIO) model. In 2019, EU consumption was responsible for 3,438 Mt CO_2eq, above the 3,108 Mt of EU inventories. The difference between the two figures is the net of 901 Mt embodied in EU imports and 571 Mt in EU exports. As illustrated in **Figure 1**, the GHG content of net EU imports has barely decreased since 2010, as opposed to EU inventories, leading to an increasing wedge between the two. In 2019, imported GHGs originated mostly in China (27.1%), Russia (11.9%), the USA (8.1%), and India (5.8%).

3.2. Correlation Between Energy Intensity and Trade Openness

Energy intensity of economic activities and trade openness are related, although the relationship is rather complex. Copeland et al. (2022) argue that dirty industries are more exposed to trade. **Figure 2** plots the trade openness of the five most-emitting and five least-emitting industries against the log of emission intensity, as selected by Copeland et al. (2022) using the World Input–Output Database (WIOD) MRIO table. With the exception of transport, services are among the least-emitting sectors. Fuels; other nonmetallic mineral products; and electricity, gas, and water supply are the most-emitting ones. With the exception of electricity, which is not frequently traded directly, the positive relationship between emissions and openness is illustrated in the figure.[4] This relationship can be explained by (nontransport) services being intrinsically less traded than goods;

[3]The Eurostat workbook can be downloaded at **https://ec.europa.eu/eurostat/documents/4187653/14185648/CO2_footprints_overview_2022-05-11.xlsx/af2f0f90-1143-8777-35b8-3843e211e6e4?t=1652880014532**.

[4]Indeed, electricity used as intermediate consumption is indirectly traded, and its emissions are embodied in the total (direct and indirect) emissions of other sectors.

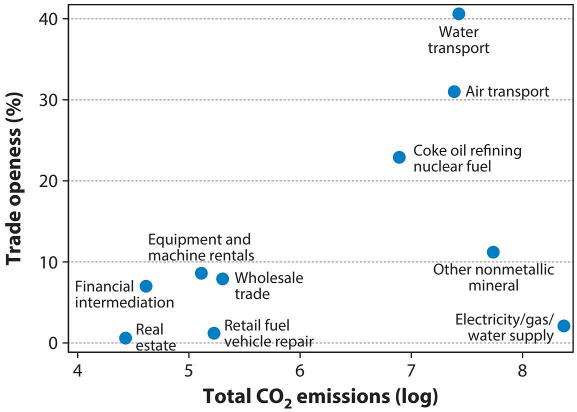

Figure 2

Total CO_2 emission intensity and trade openness (defined as international trade divided by gross output) from the five most-emitting and five least-emitting industries. Emission rates are (log) metric tons of CO_2 per million dollars of output in 2009, after inverting the World Input–Output Database multiregional input–output table. Figure adapted from Copeland et al. (2022).

that a large proportion of emissions are concentrated in upstream industrial activities related to extraction or transformation of fuels and minerals; that tariffs are lower for upstream activities (Corden 1966, Shapiro 2016); and, last but not least, that the most-emitting industries may have tentatively escaped carbon taxation or regulations aiming to curb emissions. The last determinant is the basic justification for a BCA.

3.3. Indirect Emissions

An important pattern that must be taken into account in the design of a BCA is the relative contribution of direct and indirect emissions to the total emissions of each sector. Direct emissions (or scope 1) include all emissions generated directly by firms (factories, offices, vehicle fleets, etc.). Indirect emissions are emissions associated with the firm's consumption of electricity, heat, or steam (scope 2) and other emissions taking place upstream and downstream in the firm's value chain (scope 3).[5] Visual inspection of **Figure 3** confirms the intuition that the least-emitting sectors are those for which most emissions are indirect. This stylized fact provides clear guidance for policies aiming to abate emissions as well as for the design of a carbon adjustment mechanism. Targeting the most-emitting sectors is efficient because most of their emissions are direct.

Let us now look in more detail at the energy intensity and emission intensity of these sectors from an international and temporal perspective. To proceed, we use EXIOBASE data to compute the average intensity (weighted by output) of 161 sectors for the EU27, China, and the USA in 2015.[6] A total of 99 sectors have an energy intensity below 5%, 144 sectors below 10%, and 8 sectors above 20%. Such a concentration of emissions on a limited number of sectors might suggest that a possible border offset mechanism should be limited to the perimeter of these sectors. More systematic coverage of industry would increase the complexity of implementing the

[5] Scope 1 and scope 2 emissions are relatively easy to measure and often are already monitored by firms. That is not the case for scope 3 emissions. An appropriate framework for measuring these emissions in a harmonized way has yet to be designed.

[6] We are grateful to Youssef Salib for preparing the EXIOBASE data set.

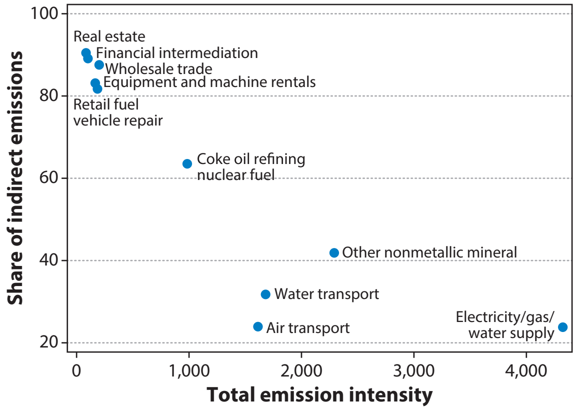

Figure 3

Total CO_2 emission intensity and share of indirect emissions from the five most-emitting and the five least-emitting industries. Emission rates are metric tons of CO_2 per million dollars of output in 2009, after inverting the World Input–Output Database multiregional input–output table. Figure adapted from Copeland et al. (2022).

mechanism for a limited environmental gain. However, expanding the coverage would probably bring significant gains in terms of competitiveness for some manufacturing industries. The emblematic example is the automobile industry, whose products would not be subject to a BCA limited to a narrow perimeter, whereas its inputs (like steel) would. As a result, this industry would be incentivized to delocalize its production and reimport the finished products.

3.4. International Differences in Emission Intensities

Emission intensities differ at the international level for the same sector because of the difference in taxation or regulation of GHG emissions among countries. We illustrate this difference in **Figure 4** by selecting five high-emitting sectors and by considering all GHGs, not only CO_2 (not surprisingly, once methane is included, livestock appears to be among the high-emitting sectors). These international differences, within the panel considered, narrow over time. At the same time,

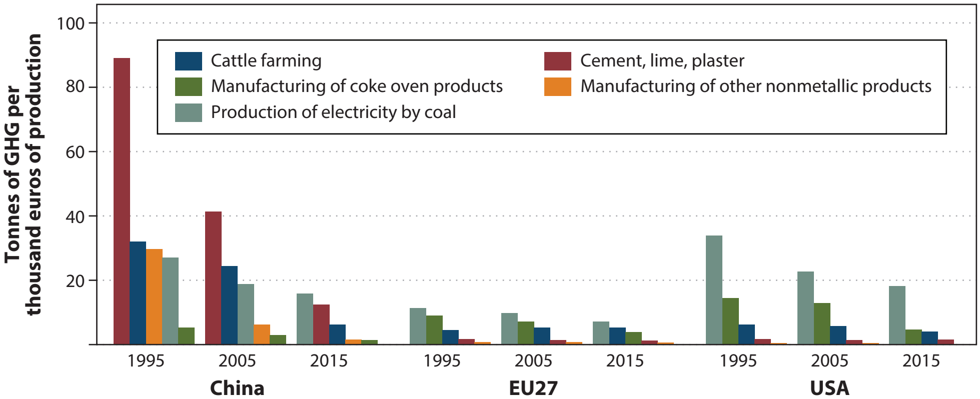

Figure 4

Direct emission intensity (all greenhouse gases) of five selected sectors in China, the EU27, and the USA in 1995, 2005, and 2015. Data are from EXIOBASE.

the relative importance of emissions embodied in the production of electricity (here produced by coal) increases over time, while electricity is barely traded directly internationally. These developments reduce the effectiveness of carbon tariffs in mitigating leakages and in abating emissions globally (Böhringer et al. 2021).

4. IS THERE SUCH THING AS A LEAKAGE?

Direct leakage occurs through a competitiveness effect. Indirect leakage occurs through energy prices: A unilateral climate policy reduces the domestic demand for fossil energy, inducing a decrease of fossil energy prices on the international markets and, therefore, an increase in foreign demand, which at least partially cancels the beneficial effect of domestic climate policy (Daubanes et al. 2021, Harstad 2012, Hoel 1994, Keen & Kotsogiannis 2014). We focus here on direct leakage.

4.1. Theoretical Mechanism

Let us consider two zones, Home (H) and Foreign (F), and denote by D_i, Y_i, M_i, and X_i ($i = H, F$) the aggregate carbon content of domestic demand, production, imports, and exports, respectively. Home puts in place a climate policy in the form of a carbon price τ, whereas Foreign does not. The equilibrium in terms of carbon content reads $D_i + X_i = Y_i + M_i$ ($i = H, F$) (Misch & Wingender 2021). Because $X_F = M_H$, the Foreign equilibrium reads $D_F + M_H = Y_F + X_H$. Following a (marginal) carbon price increase at Home $\mathrm{d}\tau$, and under the plausible assumption that this increase does not affect the carbon content of Foreign domestic demand, we obtain

$$\frac{\partial Y_F}{\partial \tau}\mathrm{d}\tau = \frac{\partial M_H}{\partial \tau}\mathrm{d}\tau - \frac{\partial X_H}{\partial \tau}\mathrm{d}\tau.$$

The leakage rate, introducing price elasticities at Home [defined as $\zeta_x = (\partial x/\partial \tau)/(x/\tau)$], is therefore

$$L = -\frac{\partial Y_F/\partial \tau}{\partial Y_H/\partial \tau} = \frac{\partial X_H/\partial \tau - \partial M_H/\partial \tau}{\partial Y_H/\partial \tau} = \frac{\zeta_X X_H - \zeta_M M_H}{\zeta_Y Y_H}. \quad 1.$$

The leakage rate depends on the price elasticities of the carbon content of exports, imports, and production to the carbon price at Home and on Home's openness in trading carbon at the initial equilibrium. It may theoretically exceed 100%, meaning that Home's climate policy increases global emissions. This is the trade equivalent of Sinn's (2008) Green Paradox (Long 2015).

On the domestic production side, climate policy reduces by construction carbon emissions from production: $\zeta_Y < 0$. In the production process, carbon is embodied in energy and in intermediate inputs. In absolute value, ζ_Y is an increasing function of the elasticity of substitution between the bundle composed of energy and intermediate inputs on the one hand and the bundle composed of the other inputs (capital and labor) on the other hand, of the possibilities of substitution between fossil and decarbonized energy, of the possibilities of substitution between dirty and clean (decarbonized) inputs in the complex value chains leading to the aggregate intermediate inputs, and of the share of the energy cost in the total production cost.

On the trade side, leakage (the numerator in Equation 1) is caused by a change in the relative competitiveness of Home compared with Foreign following the increase of the carbon price at Home: $\zeta_M > 0$ and $\zeta_X < 0$. Two channels are potentially at work: The loss of competitiveness induces a loss of Home's market shares in the domestic and international markets, and it may also trigger a relocation of firms out of Home. The magnitude of the market shares effect depends mainly on the value of the Armington elasticity between domestic production and imports.

Introducing explicitly intermediate inputs (dirty and clean) conveys further insights. When there is trade in intermediate inputs, Baylis et al. (2014) show that a negative leakage can occur if climate policy at Home makes producers substitute the dirty input with the clean one, reducing the amount of clean input that Foreign can use, which in turn can reduce Foreign output to some extent. Negative leakage can also occur when Home climate policy spurs innovation directed toward the clean input and this clean innovation is also adopted by Foreign (Di Maria & Van der Werf 2008, Gerlagh & Kuik 2014). In any case, this clean technology effect reduces leakage (Hémous 2016, Van den Bijgaart 2017). On the export side, leakage is reduced if exporting firms refrain from passing the cost increase through to consumers.

Reasoning at the aggregate level hides effects that may be very different across sectors (energy-intensive, trade-exposed sectors in particular are the most vulnerable to leakage) and ignores cross-sectoral substitutions and the propagation of climate policy along value chains. The purpose of CGE models is precisely to extend the analysis in this direction, by introducing a sectoral disaggregation and an input–output table and by putting numbers on the parameters to obtain a quantitative evaluation of the effects (see Section 4.3).

The recent literature goes further by recognizing that complex mechanisms may take place within each sector, at the firm level. There is evidence that, within an industry, the most efficient firms are also the ones with the lowest emission intensity (Copeland et al. 2022). Therefore, a carbon tax can reallocate resources toward more productive firms in the regulated zone (Cherniwchan et al. 2017, Kreickemeier & Richter 2014), amplifying the comparative advantage of the sector rather than penalizing it.

4.2. Ex Post Empirical Studies

Carbon leakage is a special case of the pollution haven effect that has been much studied in the literature, especially for local pollution. The pollution haven hypothesis predicts that pollution-intensive activities shift to countries with weak or no environmental regulations to avoid the additional costs imposed by those regulations at Home (Levinson & Taylor 2008). The Porter hypothesis goes in the opposite direction: It predicts that environmental policy spurs clean innovation, which in turn improves nonprice competitiveness and potentially price competitiveness as well, if the effect is strong enough to offset the extra cost of compliance with environmental regulations (Porter & van der Linde 1995).

Levinson (2016) reviews the literature on the pollution haven hypothesis and highlights two important issues this literature faces: the difficulty of measuring regulatory stringency and the fact that stringency and pollution are determined simultaneously. He reports that the most recent studies, which are technically better than the older ones at addressing these issues, do find statistically significant effects.

Dechezleprêtre & Sato (2017) review the empirical literature on the impacts of asymmetric environmental regulations on competitiveness, along several dimensions: trade, industry location, employment, productivity, and innovation. They report that the competitiveness effects are generally small, even very small, because the cost increase due to environmental policy is frequently negligible when compared with the other determinants of trade and firms' location choices: labor cost and quality of labor, transport costs, proximity to demand, agglomeration, and so forth. When the regulations concern energy, the adverse effects are concentrated in energy-intensive sectors, where the additional cost is substantial. The authors also report the presence of a weak form of the Porter hypothesis. Here, environmental policy significantly spurs clean innovation; however, the effect is not strong enough to actually increase firms' competitiveness.

The literature focusing more specifically on the consequences of unilateral climate policies is very much in line with these results. Most papers estimate the competitiveness effect of carbon pricing, using various metrics (for two recent surveys, see Ellis et al. 2019, Verde 2020): net imports, bilateral trade flows, economic outcomes (turnover, value added, investment, employment, productivity, profit), and innovation. A few papers look at the effect of regulations. Very few attempts have been made to estimate a carbon leakage rate as such.

An important question is how to measure the stringency of climate policy. For regulations, the relevant measure is the abatement cost that the firms incur for compliance. For price policies—tax, cap-and-trade—the total cost is composed of two parts: the abatement cost and the emissions cost (the price paid on unabated emissions). The emissions cost may be known from administrative data, whereas the abatement cost is unobservable, which explains why studies estimating the effect of price policies usually rely on the emissions cost whereas studies estimating the effect of regulations have to use additional information sources, like surveys or other measures of climate policy stringency.

Estimating the effect of unilateral carbon pricing on competitiveness has to tackle two challenges. First, carbon pricing around the world has until recently been nonexistent or very lenient (with a few notable exceptions). Second, countries that have enacted nonnegligible carbon pricing have simultaneously taken measures to prevent competitiveness losses, such as giving free allowances under the European Union Emissions Trading Scheme (EU-ETS) or granting exemptions to carbon taxes to industry, as in the case of Sweden. These features explain why most of this literature finds no effect (Ellis et al. 2019, Joltreau & Sommerfeld 2019, Verde 2020). To overcome the first difficulty, some studies look at the effect of changes in relative energy prices, which provide the desired source of variation, and infer from the results what the effect of a carbon price of similar magnitude would be.

4.2.1. Effects of carbon pricing within the European Union Emissions Trading Scheme. The EU-ETS is a cap-and-trade system put in place in 2005 as the central building block of European climate policy. It limits GHG emissions from more than 11,000 installations, mainly power stations and large industrial plants. In phases I (2005–2007) and II (2008–2012), most allowances were given for free by grandfathering.[7] In phase III (2013–2020), the default allocation method was auctioning, but installations in sectors at risk of carbon leakage still received most of their allowances for free. The leakage risk can be appreciated by considering two criteria: the carbon intensity of the sector, defined as the sum of direct and indirect emissions (valued at €30/t CO_2) divided by the value added of the sector, and the trade exposure, defined as the sum of imports from and exports to third countries divided by production. A sector is at risk if its carbon intensity or trade exposure is higher than 30%, or if its carbon intensity is higher than 5% and its trade exposure is higher than 10%. The emissions-intensive and trade-exposed (EITE) industries thus defined are mining and quarrying; coke and refined petroleum products; chemicals and chemical products; rubber and plastic products; other nonmetallic mineral products; basic metals; and electricity, gas, steam, and air conditioning supply. In phase III, the EITE industries accounted for 95% of industry emissions. Industrial installations in sectors at risk receive a free allowance of up to 100% of their efficient level of emissions, defined as a benchmark multiplied by their previous level of output (Eur. Commission 2011). The benchmark is the average emission coefficient of the 10% best producers in the sector. In phase IV (2021–2030), a stricter criterion is applied to identify the sectors at risk (the product of carbon intensity and trade exposure has to be higher than 0.2), and the benchmarks are updated to take into account technical progress. The overall message is that, at least in the first three phases, there has been a vast overallocation of allowances,

[7] In grandfathering, the free allowances are allocated before the emissions are generated, on the basis of historical emissions as opposed to an ex post output–based allocation.

most of them given for free. It is not surprising, then, that the studies we review here struggle to find any leakage effect of the EU-ETS.

Naegele & Zaklan (2019) use gravity equations to study the impact of the EU-ETS on net imports and bilateral trade flows at the firm level. They investigate both the market shares channel and the relocation channel. Trade flows and CO_2 emissions come from the Global Trade Analysis Project (GTAP), and emissions cost comes from the EU Transaction Log (EUTL). GTAP enables the computation of embodied carbon using input–output tables, accounting for global supply-chain linkages. The authors obtained CO_2 emissions embodied in the traded goods for 3 years (2004, 2007 and 2011), that is, one year prior to the policy and two after. They find no evidence of carbon leakage in European manufacturing sectors.

Garnadt et al. (2021) extend the analysis of Naegele & Zaklan (2019) by including phase III of the EU-ETS and by estimating delayed effects. Introducing phase III into the analysis is potentially important because the policy in this phase has been more stringent than in the two previous ones. However, the authors do not find strong evidence of leakage: Carbon embedded in imports slightly increases in industries covered by the EU-ETS, but the policy has no effect on carbon embedded in exports. Interestingly, the authors identify phasing-in effects as carbon leakage increases over time, which they interpret as resulting from costly adjustment of production capacity.

Colmer et al. (2022) use French firm-level data, which allow them to compare, using a difference-in-difference design, regulated and unregulated firms within each sector. They find no evidence that the EU-ETS shifted production and emissions to unregulated firms or out of the regulated zone through trade.

Dechezleprêtre et al. (2022) investigate the relocation channel. They look at the behavior of multinational companies, which are the most likely to relocate to avoid climate policy. Using the Carbon Disclosure Project (CDP) database (composed of 1,122 companies, of which 216 are subject to the EU-ETS), they find no significant effect of the EU-ETS in the period 2007–2014.

Aus dem Moore et al. (2019) also investigate the relocation channel, focusing on the European asset base as an early indicator of relocation: Multinational firms contemplating relocation do not invest in the regulated zone. They find evidence that contradicts the idea of an erosion of the tangible fixed asset base of regulated firms.

Borghesi et al. (2020) and Koch & Basse Mama (2019) study the impact of the EU-ETS on outward foreign direct investments by multinational companies in the cases of Italy and Germany, respectively. They do not find any evidence.

Studies limited to one EITE sector do not exhibit larger effects. For primary aluminum, see Sartor (2013), and for cement and steel, see Branger et al. (2017).

Finally, some studies have investigated the effect of the EU-ETS on clean innovation as a crucial determinant of long-term competitiveness. Using Italian firm-level data, Borghesi et al. (2015) find that EU-ETS sectors are more likely to innovate than non-EU-ETS ones. Calel & Dechezleprêtre (2016) estimate the causal impact of the EU-ETS on firms' patenting. They find that innovation in low-carbon technologies increased by 10% in regulated firms compared with a control group. Calel (2020) also finds a positive effect of the EU-ETS on the clean patenting activity of British firms.

4.2.2. Effects of variations in energy prices. Sato & Dechezleprêtre (2015) look at the response of bilateral trade flows to differences in energy prices across countries and sectors (42 countries, 62 manufacturing sectors) in the period 1996–2011, in a gravity framework. They find no effect on exports and a small but significant effect on imports.

A study by Misch & Wingender (2021) is an exception in the literature. These authors use sector-country-specific data on policy-induced changes in energy prices and country-sector data on carbon embodied in trade flows (the Trade in Embodied CO_2 database of the OECD). They estimate elasticities of the carbon content of production, imports, and exports and retrieve leakage rates using Equation 1. They find very significant leakage rates, with an average of 25% over their sample of countries and an average of around 15% for 14 European countries plus the United Kingdom. Their results tend to confirm that the weakness of the leakage obtained in previous studies is at least partially due to the weakness of the carbon price in the EU-ETS.

4.2.3. Effects of environmental regulations. In a series of papers, Aichele & Felbermayr (2012, 2013, 2015) look at the effect of the Kyoto Protocol on carbon emissions. They find much more evidence of adverse effects of environmental policy on competitiveness, though they did not clearly investigate the channel through which these effects materialize.

Aichele & Felbermayr (2012) evaluate the effects of commitments made by some countries under the Kyoto Protocol. These commitments are supposed to take effect on the date of ratification of the Kyoto Protocol by the national parliament. The authors build a panel database on carbon embodied in trade and carbon footprints, using MRIO tables. Their sample of countries covers more than 80% of world carbon emissions over the period 1995–2007. Using a first-difference instrumental variables estimation strategy, they find that domestic emissions have decreased by 7% in committed countries but that carbon footprints have increased, providing evidence of carbon leakage.

Aichele & Felbermayr (2013) use a different methodology (difference-in-difference estimation combined with matching techniques) to account for the endogeneity of the Kyoto Protocol commitment. Their sample is composed of 117 exporters, of which 34 have Kyoto commitments. The average treatment effect for a Kyoto country is a 13–14% reduction in bilateral exports. They also find that energy-intensive sectors and sectors producing homogeneous goods have been the most affected by the Kyoto commitments.

Aichele & Felbermayr (2015) look at the impact of the Kyoto Protocol on carbon embodied in bilateral trade flows in a gravity framework, accounting for the endogeneity of Kyoto. They find that Kyoto commitments have increased the carbon imports of committed countries from noncommitted ones by around 8% and that the carbon intensity of those imports is 3% higher. The most affected industries are basic metals, other nonmetallic mineral products, and paper and pulp, where the evidence of carbon leakage is robust. Using a similar methodology, Hartl (2019) obtains an average leakage rate of 4.3%, where strong leakage is limited to the metal, machinery, and transport sectors.

Finally, Ben-David et al. (2021) study the impact of climate policies on multinational firms (using a data set of 1,970 large public firms, headquartered in 48 countries, and their CO_2 emissions in 218 countries over the period 2008–2015). Their measure of policy stringency and enforcement is a score provided by the World Economic Forum (WEF), using business surveys. They find evidence of a strong relocation effect.

4.3. Ex Ante Evaluation

Ex post empirical evidence on carbon leakage is mixed. Moreover, the (near) absence of border adjustments in operation does not allow for an ex post assessment of the extent to which such compensation has actually reduced leakage.[8] We therefore turn to ex ante assessments. They can be based on partial equilibrium or general equilibrium models.

[8]However, when an ambitious and long-lasting policy of carbon pricing can be clearly identified, ex post econometric studies and ex ante general equilibrium models provide consistent results, as shown by

4.3.1. Partial versus general equilibrium approaches. CGE models accounting for the adjustment of the international market for fossil fuels will capture both direct and indirect leakages. In contrast, partial equilibrium models address only the competitiveness channel, which is mitigated by their ability to incorporate granular information about industries. In the cement industry, the leakage rate induced by the pricing of carbon in the EU-ETS market could reach 50% (Demailly & Quirion 2006) or even 70% when additional layers of complexity, such as regional markets, multiplant firms, and production capacity constraints, are introduced (Ponssard & Walker 2008). The leakage rate in the steel industry reached 53% in Annex B countries of the Kyoto Protocol (Mathiesen & Mæstad 2004). In the USA, a $25 carbon tax would result in a median leakage of 46% across industries (Fowlie & Reguant 2022).

4.3.2. Rio, Kyoto, and Paris with general equilibrium approaches. In simulations with a CGE, leakages are quantified by putting a cap on GHG emissions in a region of the model, by deriving the corresponding carbon price (or, alternatively, by imposing an exogenous price on carbon), and by computing the change in emissions between the scenario and the baseline in this region and in the rest of the world.

The first series of studies is highly stylized. Using a dynamic general equilibrium model, Felder & Rutherford (1993) introduce a unilateral cap on OECD countries' emissions (reduced by 1–4% per annum). In their model, the leakage rate will reach 40% by 2035 with the most ambitious cuts. In an alternative scenario, OECD countries' EITE exports are maintained at their baseline level, despite carbon taxation, to show the prevalence of the indirect leakage channel. Such a conception of the exercise may seem peculiar in the current debate, but recall that it was envisaged by the European Commission during the preparation of the Rio Summit (and is also known as the Ripa di Meana proposal, named after the Commissioner for the Environment). Böhringer et al. (2018) use a general equilibrium model featuring a more detailed database and obtain, depending on the parameterization, a 9–23% leakage rate induced by a 20% reduction in carbon emissions relative to 2011 emission levels across the OECD.

Another series of ex ante general equilibrium studies assesses the leakage rate associated with the Kyoto Protocol, obtaining leakage rates of at most 25% (Elliott et al. 2013, Paltsev 2001, Weyant 1999). A comparative modeling exercise surveyed by Böhringer et al. (2012a) documents leakage rates associated with post-Kyoto emissions reduction pledges, following the 2009 Copenhagen Conference. Based on common modeling assumptions, 12 models obtain leakage rates ranging from 5% to 19%, with a mean of 12%. A bird's-eye view of the CGE literature from the 2000s suggests limited leakages, despite the specificities of the models used. GEM-E3, used to simulate the leakage rate associated with the Energy–Climate Directive of the European Union (which frames a decarbonization path to 2020), shows negligible leakage rates (Bernard & Vielle 2009). The GREEN model of the OECD (Burniaux & Oliveira Martins 2012) and G-Cubed (McKibbin et al. 1999) are also in the lower bound. In contrast, higher leakage rates are obtained with GTAP-E (Kuik & Gerlagh 2003), WorldScan (Boeters & Bollen 2012), and especially the Emissions Prediction and Policy Analysis (EPPA) model from the Massachusetts Institute of Technology (Babiker 2005). These differences partly mirror different assumptions or parameterization choices, as we discuss below.

The last series of studies simulating carbon leakages with CGE models builds on the pledges of the Paris Agreement. Wu et al. (2022) associate the NDCs of the Paris Agreement with an overall

Carbone & Rivers (2017) using the British Columbia carbon tax introduced in 2008 as an experiment (sectoral employment is the outcome).

13% leakage rate. A carbon price set exogenously at US$50 within the EU-ETS would lead to a 22% leakage rate (Mörsdorf 2022). Such orders of magnitude are in line with a meta-analysis by Branger & Quirion (2014) of 310 estimates of carbon leakage ratios from 25 studies (20 studies used CGE models, and the remaining 5 relied on partial equilibrium models) conducted between 2004 and 2012. Estimates range from 5% to 25%, with a mean of 14%.

Beyond the modeling choices, a key component of the simulated scenarios is the assumption made about the ability of countries to achieve the decarbonization contributions they have committed to provide. Adopting the extreme assumption that only countries with unconditional NDCs and a national carbon market comply with their NDCs with endogenous carbon pricing (leading to a much higher allowance price in the EU-ETS market), and using a dynamic general equilibrium model featuring imperfect competition and value chains, Bellora & Fontagné (2023) obtain a leakage rate of 54% in 2040 for the European Commission's Fit for 55 package with free allowances in the EU-ETS, without a BCA.

In light of the wide range of differences between ex ante–simulated leakage rates, it is now worth considering what is involved in the construction of scenarios, the parameterization of general equilibrium models, and the representation of modeled economic policies.[9]

4.3.3. Under the hood of the models. As illustrated by the extreme assumption of Bellora & Fontagné (2023), leakage rates increase with the ambition of reduction pledges and decrease with countries' participation in mitigation efforts (Böhringer et al. 2014a). While Böhringer et al. (2018) find that a 10% reduction in European emissions leads to a 15% leakage rate, the leakage rate is 21% with a 30% reduction pledge. But, if we keep the latter pledge and have a common cap-and-trade market among participants, the leakage rate drops to 6% if Annex 1 countries (minus Russia and China) join the effort. Similarly, Babiker (2005) finds that, with the USA out of the Kyoto Protocol, the leakage rate is 50% higher (reaching 30%). Given the lack of ambition in terms of emissions mitigation, the massive use of free allowances of quotas to industries exposed to international competition, and ultimately the low price of carbon in cap-and-trade markets, it is no surprise that most studies have obtained such low leakage rates.

An insight into the structure of the trade models used also reveals that leakage rates are highly sensitive to the modeling assumptions.[10] Three sources of differences in the response of models to international differences in prices of carbon-intensive goods are at play (Babiker 2005, Balistreri et al. 2018). First, imperfect competition and increasing returns to scale in sectors exposed to leakages magnify the leakage rate (Babiker 2005). Second, the higher the substitutability between domestic goods and foreign goods, the higher the leakages will be. CGE models typically have a nesting of demand with an Armington elasticity (Armington 1969) and then a substitution between sources of imports. The chosen Armington elasticity is a key parameter because a low elasticity leads to limited displacement of production toward nonparticipating countries and thus low leakages (Balistreri et al. 2018). Böhringer et al. (2018) find that, while the central leakage rate is 14%, halving the elasticity leads to a 9% leakage rate, and doubling the elasticity leads to a rate of 22%. Babiker (2005) shows that discarding the Armington assumption and considering perfectly homogeneous products, instead of a national or regional differentiation, amplify

[9] A less populated strand of research relies on the structural gravity model extended to account for emissions. Here, again, the leakage rate (competitiveness channel) for the pledges made at the Copenhagen Conference is 13% (Larch & Wanner 2017).

[10] Carbone & Rivers (2017) perform a meta-analysis of empirical estimates of the impact of unilateral climate change policies in the ex ante literature using CGE models, not on leakage but on competitiveness.

leakage dramatically. Third, the lower the supply elasticity of fossil fuels is, the higher the indirect leakage channeling through the impact of the reduced demand for those fuels will be in countries mitigating their emissions.

Combining the latter two determinants of the leakage rate explains 42% of the variance in this rate across CGE simulations in the meta-analysis by Gerlagh & Kuik (2014). Accounting with fixed effects for the specificities of the models other than the parameters of interest, only the supply elasticity of fossil fuels remains significant. Simulations using CGE models suggest that this fossil fuel supply elasticity plays a more important role in the final outcome than the Armington elasticity (Boeters & Bollen 2012, Burniaux & Oliveira Martins 2012). The simple thought experiment of a zero supply elasticity helps us understand the mechanisms at play: In response to a unilateral carbon tax policy in one region of the world, the world price of fossil fuels should fall such that demand remains constant. In other words, all the fuel saved in the region in question should be burned in the rest of the world. The prevalence of this mechanism would then be reinforced by the ambition and size of the region in question.[11] Ultimately, with significant indirect leakage, the effectiveness of a BCA decreases, as the adjustment affects only direct leakage. This mechanism, confirmed by the meta-analysis by Branger & Quirion (2014), suggests that the effectiveness of a BCA, which tackles the competitiveness channel, will decrease in the ambition of emissions mitigation policies.

5. CARBON ADJUSTMENT IN PRACTICE

5.1. Rationale

Confronted by leakage, a regulated zone may differentiate carbon prices between trade-exposed and other sectors if tariffs cannot be optimally chosen, for example, because of tariff binding and the antisubsidy rules of the WTO (Hoel 1996). Otherwise, the carbon content of imported goods has to be compensated for at the border (Droege 2011). In this section, we examine which instruments can be used and show why a BCA may be preferred.

5.1.1. De facto subsidy. Not pricing carbon is a de facto subsidy to domestic production that should ring the bell of trade defense instruments, namely of countervailing measures: Subsidies are not allowed at the WTO, and an import tax should be levied to offset the subsidy (Stiglitz 2006). Although this argument is provocative, it does not fit the legal framework of the Agreement on Subsidies and Countervailing Measures (WTO 1994a). The subsidy must be actionable in order to be offset, and three criteria have to be fulfilled: a financial contribution, by a government or a public body, which confers a benefit. Because the first criterion is not fulfilled, not taxing carbon is not a subsidy in WTO parlance.

The multilateral framework, however, leaves the door wide open for action. The preamble to the Marrakesh Agreement Establishing the World Trade Organization emphasizes that environmental objectives come first. It reads: "[r]ecognizing that their relations in the field of trade and economic endeavor should be conducted with a view to raising standards of living, . . . while allowing for the optimal use of the world's resources in accordance with the objective of sustainable development, seeking both to protect and preserve the environment" (WTO 1994c, p. 13).

[11] More specifically, the usual approach is to model the supply of fossil fuel as a constant elasticity of substitution (CES) function, where a natural resource (fixed) is combined with other primary factors. As the price of fuels is driven down by climate policy, the distributive share of the natural resource increases and the supply elasticity of fuel decreases at a given CES elasticity larger than one, which magnifies the leakage rate (Boeters & Bollen 2012).

This statement has been confirmed by the jurisprudence of the appellate body in the US gasoline dispute (WTO 1996).[12] Similarly, Article XX of the General Agreement on Tariff and Trade 1994 (GATT 1994), about environmental exceptions with regard to exhaustible natural resources (WTO 1994b), was interpreted broadly in the report of the appellate body in the US shrimp dispute (WTO 1998).[13]

But action must adopt a different approach than countervailing measures. Different policy instruments can curb leakages and restore the competitiveness of high-emission industries that have to face carbon pricing or intensity standards (Holland et al. 2009).

5.1.2. Output-based rebate or full exemption. Output-based rebates or full exemption may be considered as a first solution. In a simple two-country model where only one of the two implements a climate policy, combining a tax on carbon (or a carbon-intensity standard leading to the equivalent implicit price of carbon) with an output-based rebate (equal to the average emissions of the sector times the tax) preserves the price signal and largely wipes out the competitiveness effects on the domestic and exporting market.[14] Full exemption is indeed preferable from the competitiveness point of view, as opposed to the environmental perspective (Böhringer et al. 2017). The free allocation of emissions allowances—which can be likened to a total exemption—partially or fully corrects the two sources of direct leakage but compromises the effectiveness of the mitigation policy.

5.1.3. Carbon tariff *cum* export subsidy. Alternatively, one can combine a carbon tariff (based on the actual carbon content of imports) with an export subsidy. Such a combination of a BCA and a rebate to exporter is usually referred to as a complete or full BCA. It is equivalent to a consumption tax (Böhringer et al. 2018, Elliott et al. 2010) and is a substitute for an output-based rebate, which means that free allowances must be phased out. Without free allowances, however, exporters in the taxing country are penalized in foreign markets with less ambitious climate policies—hence the justification for the refund of allowances to exporters, characterizing the full BCA. Unfortunately, the latter solution is not compatible with the WTO, as it would be interpreted as an export subsidy.

A tax on carbon embedded in imports is a safer substitute for a tariff when the carbon in domestic products is effectively subjected to a similar tax. When the importing country uses a cap-and-trade market to contain its emissions, the tariff can be replaced by allowances purchased by importers. Where the importing country relies solely on regulatory instruments such as intensity standards, setting an implicit price for these standards is a prerequisite for carbon compensation at the border.

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[12] "[I]n the preamble to the WTO Agreement and in the Decision on Trade and Environment, there is specific acknowledgment to be found about the importance of coordinating policies on trade and the environment. WTO Members have a large measure of autonomy to determine their own policies on the environment (including its relationship with trade), their environmental objectives and the environmental legislation they enact and implement. So far as concerns the WTO, that autonomy is circumscribed only by the need to respect the requirements of the General Agreement and the other covered agreements" (WTO 1996, p. 30).

[13] "The words of Article XX(g), 'exhaustible natural resources', were actually crafted more than 50 years ago. They must be read by a treaty interpreter in the light of contemporary concerns of the community of nations about the protection and conservation of the environment. While Article XX was not modified in the Uruguay Round, the preamble attached to the WTO Agreement shows that the signatories to that Agreement were, in 1994, fully aware of the importance and legitimacy of environmental protection as a goal of national and international policy" (WTO 1998, para. 129–131).

[14] This is the spirit of the so-called fee-and-rebate programs, in which carbon is actually priced but the revenue is rebated to the industry on a per-unit-of-output basis. In this way, the incentive to abate emissions is preserved, as the more efficient (below-average) plants will receive more than they pay.

5.1.4. What makes a border carbon adjustment attractive. Absent WTO compatibility concerns, a BCA would essentially be a carbon tariff combined with an export subsidy, amounting to a tax on consumption. The political acceptability of BCA makes it attractive: It avoids the introduction of a carbon tax on consumption,[15] while the carbon tax on producers is made acceptable by a rebate to exporters and the protection provided by the tariff on their domestic market.

Beyond political acceptability, the first justification of a BCA is the level-playing-field argument: The carbon embedded in imports ought to be taxed like the carbon emitted by domestic industries. Of course, the problem of competitiveness in export markets cannot be addressed by carbon compensation at the border—a problem that diminishes with the size of the coalition taxing carbon in a comparable manner. Exporters are therefore entitled to apply for continued free allocations or to receive export refunds. This is the full BCA approach.

The next line of argument involves the incentivization of nonparticipating countries. Compensating for carbon at the coalition border reduces the market opportunities for exporting countries that do not tax carbon, which should encourage those countries to also tax carbon to avoid this compensation. The validity of this argument increases with the size of the coalition's market. The strategic dimension of the BCA, loosely interpreted as a tariff, goes in the same direction: The threat of a carbon tariff induces unregulated regions that are tightly connected to regulated ones to adopt carbon pricing (Böhringer et al. 2016). Another incentive to tax carbon in the exporting country is to repatriate foregone taxes paid in the importing country (Keen et al. 2021).

A BCA is not a panacea, however. First, it does not solve the problem of competitiveness (in the domestic and export markets) of industries using carbon-intensive products as intermediate inputs. In contrast, by aligning the price of imported carbon with the price of domestically emitted carbon in their intermediate consumption, the BCA worsens their competitive situation. This problem is particularly important if importers of carbon-intensive products compete with domestic producers in the market for emissions allowances. Establishing a different market for emissions allowances for importers only partially alleviates this problem, as domestic producers, protected by the BCA, will demand more allowances in a supply-capped situation (Bellora & Fontagné 2023). Second, a BCA fails to address global emissions, insofar as countries that are not part of the coalition can redirect their exports to other markets rather than engage in emissions reductions.

5.1.5. Global value chains and border carbon adjustment. Input–output analysis allows for the assessment of embedded carbon in traded products due to the development of global value chains (GVCs), in which a given good crosses borders several times before reaching the final consumer. GVCs displace the country of origin of emissions and add to those emissions, at least through the transport of intermediate products. The carbon content of intermediate imports, which arises from the production of exported products, nearly tripled between 1995 and 2016, a phenomenon that is particularly prevalent in the chemical, machinery and equipment, automotive, and electronics sectors (Hertwich 2020).

Klotz & Sharma (2023) provide an illuminating quantification of how GVC and trade barriers on intermediate goods interact, which complements the results of Cristea et al. (2013) and Shapiro (2016) cited above. Klotz & Sharma (2023) identify two channels. First, the reduction of trade barriers increases gross trade flows relative to value added, which can be interpreted as a lengthening of value chains: There are more production steps, which mechanically increase transport-related emissions. The second mechanism is more subtle and refers to the one identified by Feenstra & Hanson (1999): Trade cost reductions decrease the relative price of intermediate

[15]The yellow vest protests in France, inspired by an increase in the carbon tax on gasoline, illustrate the unacceptability of carbon taxes to consumers (Douenne & Fabre 2022).

consumption compared with wages, inducing a substitution of imported intermediate goods for labor and, consequently, an increase in emissions per unit of value added. The more the tariff reduction is biased toward goods upstream of the value chain, the larger these impacts will be. Klotz & Sharma (2023) quantify these channels using a new quantitative trade model in which transportation costs are determined by fuel prices. The effects identified are not trivial: Eliminating tariffs would increase global GDP by 0.5% and global emissions by 1.8%, implying that the increase in emissions goes beyond the scale effect. Reversing these arguments, an increase in trade costs targeting intermediate goods is expected to reduce transport emissions and induce a substitution of labor for intermediate products, ultimately leading to lower emissions per unit of value added. These are exactly the mechanisms expected from a BCA.

5.1.6. A simple exposition and some extensions. To illustrate these arguments, let us introduce a textbook two-country (Home and Foreign) model. Home puts in place a unilateral carbon price, whereas Foreign does not. The unit production costs in the two countries are, respectively, $C(\bar{e} - e) + \tau e$ at Home and $C_f(\bar{e}_f - e_f)$ in Foreign, where e and e_f are emissions per unit of output, $\bar{e}$ and $\bar{e}_f$ are emissions per unit of output absent climate policy, and τ is the carbon price at Home. Abatements are $\bar{e} - e$ and $\bar{e}_f - e_f$, respectively. If Home and Foreign behave optimally, then the efficient levels of emissions are e^* and e^*_f, given by $C'(\bar{e} - e^*) = \tau$ and $C'(\bar{e}_f - e^*_f) = 0$; that is, $e^*(\tau) = \bar{e} - C'^{-1}(\tau)$ and $e^*_f(0) = \bar{e}_f$. Unit production costs are then $C(\bar{e} - e^*(\tau)) + pe^*(\tau)$ and $C_f(0)$.

A full border adjustment designed to solve the loss of competitiveness of Home producers consists of two parts: making Foreign exporters pay the carbon price τ on the goods they sell at Home and rebating their carbon payment $pe^*(\tau)$ to Home exporters. Foreign producers will then be incited to emit $e^*_f(\tau) = \bar{e} - C'^{-1}_f(\tau)$[16] and will now have to pay the abatement cost $C_f(\bar{e}_f - e^*_f(\tau))$ and the carbon payment $\tau e^*_f(p)$. However, as far as climate is concerned, a full BCA is not necessary. The rebate to Home exporters is justified only for cost competitiveness. Therefore, if the BCA is framed as a climate policy and not as a competitiveness policy (as it should be for WTO compatibility), it must be asymmetric: carbon payment on imports, no rebate to exports.

If climate policy at Home takes the form of a cap-and-trade system with free allowances of α% of emissions per unit of output, which are not removed when the BCA is put in place, the price signal to be sent to Foreign producers is still τ, and from a cost-competitiveness point of view the emissions subject to the border adjustment should be $(1 - \alpha)e^*(\tau)$. Free allowances and a BCA can coexist, but only if the BCA is reduced accordingly.

Suppose now that Foreign puts in place a command-and-control climate policy and that Home and Foreign have the same technology and the same unit production cost $C(\cdot)$. The Foreign regulation produces an abatement $\bar{e} - e^r$ and Foreign producers pay the abatement cost $C(\bar{e} - e^r)$, whereas Home producers pay the abatement cost $C(\bar{e} - e^*(\tau))$ plus the carbon payment $\tau e^*(\tau)$. If $e^r < e^*(\tau)$, meaning that the implicit carbon price embodied in Foreign regulation is higher than the Home carbon price τ, the competitiveness motive and the climate motive for a BCA are not aligned. From a climate point of view, there is no need for a BCA. From a cost-competitiveness point of view, it is legitimate to impose on Foreign producers a BCA τe^r. If $e^r > e^*(\tau)$—that is, if Foreign climate policy is more lenient than Home policy—then the BCA imposed on Foreign producers should be $\tau(e^r - e^*(\tau))$ from a climate perspective and $\tau e^*(\tau)$ from a competitiveness perspective.

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[16]This incentive is weak, since carbon pricing does not apply to all Foreign producers but only to Foreign exporters and, moreover, Foreign exporters may turn to third countries to sell their products.

This first model, of course, is unable to encompass all the relevant effects of border adjustments. To go further, it is necessary to introduce trade explicitly, as done by Fischer & Fox (2012). These authors use a simple two-country partial equilibrium model to compare the properties of four types of BCA: an import border adjustment, an export rebate, a full border adjustment, and an output-based rebate. They compute the change in global emissions induced by an increase in the Home carbon price, as a measure of the environmental effect of the policy, and the change in Home output and in Home net exports as possible measures of the competitiveness effect. They show that the impacts of the four carbon adjustment schemes on competitiveness and global emissions differ, and that it is not possible to rank the options because the effect of each policy is contingent on the relative emission rates and the elasticities.

This model has several limits. Emissions are exogenous; in particular, the border adjustment does not incentivize Foreign producers to reduce their emissions. The Foreign price is exogenous. The Home and Foreign production processes are not modeled; in particular, substitution possibilities between inputs (clean and dirty) are not taken into account, limiting the mechanisms through which leakage can materialize. The model is static, making it impossible to represent how substitution possibilities change over time thanks to (clean or dirty) innovation. Finally, the consequences of the different policy options are not evaluated through the lens of social welfare. Indeed, as Kortum & Weisbach (2017, p. 423) forcefully point out, the choice to impose a border adjustment should be based on its effect on welfare, not on leakage or competitiveness, and "welfare is at best tenuously related to reduced leakage." From a welfare perspective, the optimal border adjustment rate is not necessarily identical to the Home carbon price, and free allowances or output-based rebates may be superior to border adjustment.

Building on Meunier et al. (2014), Fowlie & Reguant (2022) present a model in which the unilateral carbon policy is compensated for at Home by an endogenous output-based subsidy. The emission coefficients at Home and in Foreign are exogenous, but the outputs are endogenous and can be expressed only as a function of the subsidy rate, for a given level of the Home carbon price. The authors compute the rate of output subsidy that maximizes social welfare, defined as Home consumer surplus (consumption in Foreign is exogenous) minus Home and Foreign costs minus damage proportional to global emissions. The optimal subsidy rate is lower than the Home carbon price. It is the product of the Home carbon price, the Foreign emission coefficient, the Foreign output price elasticity, and a trade ratio. The exercise could be replicated for a border adjustment, and the optimal adjustment rate would differ from the Home carbon price, contrary to the implicit common belief in most of the BCA literature.

Large countries with market power imposing carbon compensation at the border benefit from an improvement in their terms of trade, in line with the optimal tariff argument. Böhringer et al. (2014b) underscore the importance of neutralizing this strategic component of the tariff in order to isolate its environmental effect. The equivalence of the Pigouvian pricing of domestic and imported carbon emissions is actually misleading: Balistreri et al. (2019) extend the Markusen (1975) model by adding the constraint that the border adjustment does not deteriorate Foreign welfare, which translates into a border adjustment to be set below the Home carbon price.

Finally, a small literature investigates the strategic effect of a border adjustment. Indeed, the ultimate objective is to make as many countries as possible adopt a climate agreement, despite the many obstacles (see Section 2.2). Could a border adjustment increase countries' willingness to join such an agreement?[17] Using a two-country strategic trade model, Al Khourdajie & Finus (2020) show that a border adjustment makes it less attractive to be outside the agreement (the

[17] A border adjustment could, in contrast, provoke retaliation (Böhringer et al. 2016, Fouré et al. 2016).

punishment effect) and more attractive to join, because the gains of cooperation increase with the size of the agreement as leakage decreases.

5.2. Design

The design of a BCA is necessarily a compromise between environmental effectiveness in preventing leakage, economic effectiveness in preserving competitiveness and ensuring acceptability, technical feasibility of the implementation, and WTO compatibility (Bellora & Fontagné 2020, Keen et al. 2021). Most importantly, the chosen design must also pave the way toward international cooperation through climate clubs and may accommodate sectoral initiatives.

5.2.1. Imports only or also export rebate? WTO compatibility requires that the BCA be justified as an environmental policy, not as a competitiveness policy. It must therefore apply to imports and not provide export rebates that would be challenged as export subsidies.

5.2.2. Which proxy for the carbon content of imported goods? The choice of reference emissions used as a basis for taxing the carbon content of imports has three dimensions: environmental, economic, and legal. From an environmental point of view, it is desirable to take into account the real emissions, that is, those of the exporter—not of the exporting country, but of the production unit from which the exported products originate. It theoretically provides the greatest incentive to reduce emissions to avoid border compensation. In practice, however, the exporting country can then circumvent the BCA by specializing its lower-emitting plants for export to BCA countries, and the remaining plants are used to produce for the domestic market or export to non-BCA countries. The alternative of using the average emission intensity of the exporting country as a benchmark does not incentivize the least efficient exporting firms to reduce their emissions. Most importantly, the least efficient importers have no incentive to disclose their emissions. In this case, the importing country will have to use the average emissions of the country concerned or the average of the world emissions as a reference. Finally, the national treatment principle might suggest the use of the same reference emissions for imported products as for domestic products, which would take away much of the effectiveness of the BCA.

5.2.3. Scope of emissions. Identifying the carbon emissions attributed to a given good requires deciding how far to go down the production process of the good. To do so, three scopes of emissions have been defined:

- Scope 1 emissions are direct emissions from the production process of the good.
- Scope 2 emissions are indirect emissions from purchased electricity, steam, heating, or cooling consumed during the production of the good; they depend on the national energy mix.
- Scope 3 emissions are all other indirect emissions that occur in the value chain, including in the transportation of purchased products and the use of sold goods.

Of course, the scope of emissions covered by the BCA must not be greater than the scope of emissions covered by the domestic climate policy. Within this limit, the trade-off is between the administrative complexity of collecting reliable information on direct and indirect emissions and the gain from the point of view of leakage.

5.2.4. Geographic scope. While the most natural solution would be to apply the BCA to all trade partners of the regulated zone, two other options are available. The first involves exempting the least developed countries, in line with the principle of common but differentiated responsibility. These countries should be eligible for special and differential treatment—a provision adopted in most WTO regulations—or they may benefit from a parallel program whereby BCA revenues are at least partly redirected to decarbonization in these countries. The second solution has an environmental motive. It consists of exempting the countries able to demonstrate that they have adopted an equivalent implicit carbon price through standards and regulations.

5.2.5. Reference carbon price. A simple approach would be to price the carbon content of imports at the domestic carbon price, just like domestic production. However, theory suggests otherwise (see Section 5.1.6), and two additional elements of complexity must be taken into account. The first is the explicit price that the exporter ultimately pays for carbon, which is easily deducted from the price of carbon in the importing country, despite a combination of fiscal instruments (e.g., a national carbon tax on fossil fuel uses not subject to the EU-ETS). The second and thorny issue is the implicit price of the regulations faced by the exporter in the origin country, as discussed above.

5.2.6. World Trade Organization compatibility. There are good studies on the complex issues of WTO compatibility of carbon compensation at the border (Englisch & Falcao 2021, Fischer et al. 2002, Parry et al. 2021b, Pauwelyn 2020). The first line of reasoning is to determine what should be compensated for. The WTO allows the offsetting of an indirect tax. Regulations, in contrast, can hardly be offset, but a regulation establishing a cap-and-trade market is a gray area. As emphasized by Fischer et al. (2002), while it may be difficult to compensate for carbon permits at the border because the GATT contains no such provision, it may be easier because this approach is not explicitly prohibited by the GATT. Combining this gray area with the general environmental and health exceptions of Article XX (WTO 1994b) and the preamble (WTO 1994d) to GATT 1994, mentioned above, may ensure that offsetting is legally compatible. To exploit the flexibility offered by the WTO legal framework, a BCA must indeed respect the usual principles of the most-favored-nation requirement, tariff binding (GATT 1947), national treatment, and prohibition of quantitative import restrictions. In the specific case of EU-ETS compensation, the feasibility of a BCA under EU law is an additional layer of complexity. The inclusion of importers of like products in the EU-ETS appears to be a feasible option (Pauwelyn 2020).

5.2.7. Sectoral initiatives on reporting. Granularity is a typical pattern in international trade. Only a fraction of firms export; these firms are larger and more competitive and account for the lion's share of a country's total exports (Freund & Pierola 2015, Gaubert & Itskhoki 2021), which has macroeconomic implications (Di Giovanni et al. 2017). This pattern is even more prevalent in highly concentrated industries, enabling the leveraging of sectoral initiatives. The typical example is the steel industry: Iron and steel production accounts for 8% of annual CO_2 emissions, and a quarter of global steel production is exported. A range of initiatives and organizations (e.g., Responsible Steel, World Steel Association, Greenhouse Gas Protocol, Sustainable Steel Principles) are developing measurement standards, definitions, and performance thresholds (WTO 2022). While the Sustainable Steel Principles are primarily the backbone of banks' efforts to report on the alignment of their portfolios with decarbonization goals (incentivized by the Climate Bond Initiative), these private standards could also be used to facilitate reporting by exporters (or importers, in the case of the European BCA on the carbon content of traded products). The problem with the proliferation of measurement initiatives and approaches, however, is the lack of globally accepted definitions; for example, European and Chinese car manufacturers use different standards to report emissions embodied in steel products.

5.2.8. The European proposal. CBAM, the proposed regulation for a European BCA, is following the ordinary legislative procedure. The European BCA is neither a tax nor a carbon tariff but rather takes the form of a regulation (actually a reform of the EU-ETS market). Unanimity between member states is not required, but the European Parliament, Council, and Commission have to agree on a common draft. The European Parliament voted on the principle of a BCA in March 2021. The European Commission presented a draft regulation in July 2021. The European Council reached an agreement on the broad lines of the regulation in March 2022, without fixing the issues of the calendar of phasing out free allowances and the compensation of exporters. In June 2022, the Parliament adopted a revised regulation in first reading, which launched the process of final negotiations on a common text between the three parties. In December 2022, the Council and Parliament reached a final deal, pending the formal endorsement of the corresponding legislative texts (Eur. Council 2023).

The initial proposal of taking into account five carbon-intensive sectors at risk of leakage (i.e., iron and steel, aluminum, cement, fertilizers, electricity generation) has been extended to include hydrogen and a limited number of downstream products (e.g., screws and bolts). Importers from these sectors must buy emissions allowances at the weekly EU-ETS price on a separate market. There is no export rebate.

The scope of compensated emissions is scope 1 in the transitional period, with a possible extension to indirect emissions associated with electricity consumed in the production process (scope 2) after this period. Before the end of the transitional period, the Commission will assess the need to further extend the CBAM to additional products, with the aim of covering all industry sectors by 2030. The carbon content of goods used as a basis for compensation is that of the exporter. No BCA payment will be required in the transition phase (2024–2025); the only obligation will be to report embedded emissions of CO_2, N_2O, and perfluorinated compounds. After this transition period, importers will need to obtain authorization from a dedicated authority and will purchase carbon certificates at a price directly linked to the weekly EU-ETS price. Importers may claim a reduction of up to 100% of the certificates in order to account for the explicit carbon price paid in the exporting country. In the absence of such reporting, a default value will be applied. A margin of flexibility is preserved: Importers may obtain exemptions for products from jurisdictions that implement carbon pricing equivalent to the EU-ETS according to the treatment of equivalent climate policy. No exemptions are granted to the least developed countries.

A thorny issue is that of free allowances. The original proposal called for a 10-year phase-out; until the phase-out was achieved, compensation would be applied only to the proportion of emissions that do not receive free allowances under the EU-ETS. The adopted version foresees a gradual introduction of the BCA starting in 2026, in parallel with a (nonlinear) reduction of free allowances, which will be entirely phased out by 2034.

The use of BCA revenues for decarbonization purposes is a sensitive issue at the WTO. Because, according to the principle of universality governing the EU budget, revenues should be allocated to the EU budget, the European Parliament proposed that BCA revenues should translate into at least equivalent financial support for decarbonization efforts by the least developed countries.[18] This was not the solution that was finally agreed upon: Support for decarbonization in developing countries is only one possible use of the collected revenues. Measures to avoid deforestation and support the protection of marine ecosystems in developing countries that have ratified the Paris Agreement, as well as measures to transfer technology and facilitate adaptation to the adverse effects of climate change in these countries, are also eligible.

[18]The auctioning of previously free allowances will partly contribute to member states' decarbonization efforts.

5.3. Impacts

While BCAs may differ in their coverage and detail design, they all share common features and face similar limitations. The EU CBAM is no exception.

5.3.1. Generic impacts of a border carbon adjustment. The simulated economic and environmental impacts of a BCA depend on its design, its ambition in terms of emissions reductions in the baseline scenario, and the modeling assumptions. What is common to all simulation exercises, however, is that a BCA cannot reduce indirect leakage.[19] Therefore, partial equilibrium models that focus on the competitiveness channel find that carbon compensation at the border is more effective than CGE models, which take both channels into account.

Even if we neglect the choice of whether to rebate the carbon tax to exporters, the BCA design combines embodied carbon coverage (direct emissions, indirect emissions due to energy consumption, or all indirect emissions as informed by an input–output approach), sector coverage (EITE sectors or all sectors), tariff rate (differentiated by product origin, based on either the mean emissions of the coalition or the domestic emissions of the coalition), and the perimeter of the coalition of countries abating their emissions. Multiple combinations of choices exist in terms of tariffs, for each possible perimeter of the coalition (Böhringer et al. 2012b). Let us impose a 20% emission cut on Kyoto Annex B countries by means of a carbon price. The most efficient BCA design would take foreign emissions as a benchmark and would include indirect emissions from electricity consumption, but not the total indirect carbon content (which would be difficult to calculate in practice anyway) due to the risk of double-counting emissions (exported carbon that is reimported after the product is processed abroad). Such a BCA would reduce leakages by 35% in the case of a coalition restricted to the European Union (Böhringer et al. 2012b).[20] The same conclusion pertains to an exercise where OECD countries introduce carbon pricing consistent with a 20% reduction in CO_2 emissions relative to 2011 (the pledge made at the Copenhagen Conference). A tariff on the direct content of imports reduces leakage by 23%, and by as much as 37% when indirect emissions from electricity use are added (Böhringer et al. 2018) (this simulation uses the model of Böhringer & Rutherford 2002).

With a rebate to exporters, a full BCA increases the effectiveness of the instrument in terms of reduction of leakage. The increase in emissions in developing countries would offset more than 20% of the reductions achieved by Annex B countries if the latter were to impose a carbon tax of US\$29/t CO_2 without border adjustment (Elliott et al. 2013). A full BCA would reduce this leakage and significantly redirect trade flows with the USA, for example, reducing carbon imports from non–Annex B countries by 44%.[21]

The changing nature of carbon trade in past decades should also be taken into account in the design of BCAs and may even call into question the opportunity for such a carbon offset. The carbon content of non-OECD countries' export value to OECD countries was halved in

[19]Indirect leakage refers to leakage through energy markets. The only way to deal with this form of leakage is to simultaneously withdraw fossil fuels supply at home (Harstad 2012) or tax the extraction of fossil fuels (Weisbach et al. 2022), which prevents international energy prices from falling.

[20]In this exercise, performed using the Statistics Norway world model, global emissions are assumed constant in all scenarios for a given coalition size, implying that the burden of reducing emissions is passed on to non–Annex B countries with the BCA: The price of carbon decreases (e.g., it drops 18% within the European Union). As the coalition expands, the carbon price reduction within the coalition dissipates. This result for carbon price is reversed when the assumption is relaxed, making global emissions endogenous (Bellora & Fontagné 2023).

[21]Elliott et al. (2013) use the CIM-EARTH CGE model to quantify the impact of scenarios of taxes that compensated for carbon at the borders of Annex B countries before the USA opted out.

carbon-intensive industries between 2000 and 2014; non-OECD countries are increasingly trading carbon with one another; and, finally, non-OECD countries' carbon emissions are increasingly linked to electricity generation (Böhringer et al. 2021). A BCA should therefore target scope 2 emissions. But BCA-affected countries could easily redirect their exports to non-BCA countries, while the increasing contribution of electricity generation to emissions reinforces the importance of fossil fuel supply elasticity and the indirect leakage channel, which cannot be addressed with BCAs.

5.3.2. Impacts of the European initiative. Similar approaches focusing more specifically on the European perspective have been employed. Initial approaches considered an exogenous price of carbon and required importers to acquire equivalent quota allowances at this price, either on the basis of the average EU carbon content or on the basis of the carbon content of the country of origin of these products. At a price of €20, using the EU reference, leakage would be reduced by 18% in the steel sector, whereas using the exporter's carbon content would virtually eliminate leakage (Kuik & Hofkes 2010) (this simulation was performed with the static GTAP-E model). At a price of US$50, and with emissions related to the production process (in addition to those related to the combustion of fuels) taken into account, the leakage rate would be reduced by one-third with a BCA targeting scope 1 emissions, by one-half if scope 2 emissions were targeted, and by two-thirds in the case of a complete BCA (Mörsdorf 2022). Alternatively, Fouré et al. (2016) cap, with an endogenous tax, EU emissions to the announced targets separately for EU-ETS sectors and the rest of the European economy, and they introduce a single endogenous tax on emissions of other countries to respect their Copenhagen pledges.[22]

At first glance, the effectiveness of different types of leakage compensation mechanisms should be closely related to their ability to level the playing field: Less leakage means that domestic producers are less exposed to export competition from countries that are less ambitious in terms of emissions mitigation. The output loss of carbon-intensive industries induced by carbon pricing would be halved with a BCA system targeting scope 1 emissions (and using the exporter's baseline emissions) and would be almost wiped out by a full BCA system under a simple model assuming an exogenous carbon price (Mörsdorf 2022). With a richer modeling framework that endogenizes the price of emissions allowances in the EU-ETS market and introduces a second market for importers' certificates (mimicking the price of the first market), which takes GVCs into account, the effectiveness of the BCA in leveling the playing field is more questionable (Bellora & Fontagné 2023). With a cap on emissions, the price of allowances increases as a result of the protection a BCA offers to European producers of EU-ETS products. This increase reduces the benefits of protection in the domestic market for EU-ETS products and leads to a loss of competitiveness in third markets in the absence of an exporter rebate. A final consideration in terms of the effect on competitiveness is the need to remove free allocations of allowances to industries exposed to foreign competition as border compensation is implemented. This substitution causes one instrument to be substituted for the other in practice, making a BCA less advantageous for exporters, who lose the free allocations without the protection of the BCA (Bellora & Fontagné 2023).

An undesirable feature of any BCA is that it gives market power to the importer of carbon-intensive goods, more so when the coalition of countries mitigating their emissions is large. This terms-of-trade effect shifts the burden of emissions mitigation onto non-OECD countries (Antimiani et al. 2013, Böhringer & Rutherford 2002, Böhringer et al. 2018), while the BCA encourages the consumption of carbon-intensive goods in countries not engaged in emissions

[22]The carbon price paid in the exporter country is not deducted, and importers compete with domestic producers in the market for allowances, thereby influencing their price.

mitigation. These are two arguments for setting the tax rate below a strict compensation for the difference in carbon prices between the jurisdictions if a pure environmental objective is assigned to the instrument. A Pigouvian-based BCA aiming to correct the environmental externality is therefore suboptimal (Balistreri et al. 2019, Böhringer et al. 2014b).

6. CONCLUSION

There has been a recent explosion in the literature on BCAs, triggered by negotiations on the European Union's CBAM design and alternative proposals, as well as by evidence that isolated ambition will be undermined by inaction in other jurisdictions. The literature seems to have reached a balance point, where a majority of scholars agree on the desirable features of an efficient and simple design focusing on a limited number of highly emitting products while excluding free allocation of emissions allowances and export rebates. However, there remain some gray areas in which further research is needed. Instead of including contentious scope 2 emissions, which are subject to green subsidies in most countries, imported carbon in agriculture, forestry, and competitiveness issues for downstream industries should be further investigated. More evidence of the microeconomic impacts of a BCA in the presence of heterogeneous firms is needed. Theory could inform how exporting countries may circumvent a BCA by reorienting exports or specializing production units by destination, thus providing guidance for the administration of the carbon compensation. Finally, the principle of common but differentiated responsibility should be seriously taken into account, as the least developed countries will be severely affected by climate change without having the technological and financial resources to reduce their emissions. Therefore, further consideration of the use of BCA revenues for decarbonization in low-income countries would ease the international tensions surrounding this measure. More generally, economic analysis should now focus on how to articulate a BCA—even a WTO-compatible one—with the broad participation of countries at different levels of development and with different abatement policies.

A. APPENDIX: DATABASES CITED IN THE TEXT

In this appendix, we briefly describe the databases cited in the text, in order of appearance.

A1. Nationally Determined Contributions

NDCs are the central element of the Paris Agreement in that they provide the long-term decarbonization targets to which the parties are committed under the Paris Agreement (2015, art. 4, para. 2). NDCs are submitted to the UNFCCC Secretariat every 5 years, but they can be adjusted at any time to increase the level of ambition. In accordance with the Paris Agreement (2015, art. 4, para. 12), submitted NDCs are recorded in a public registry maintained by the Secretariat. The registry can be accessed at **https://unfccc.int/NDCREG**.

A2. World Input–Output Database

The November 2016 version of the WIOD (Timmer et al. 2016) is maintained by the Groningen Growth and Development Centre. It consists of a series of databases covering 28 EU countries and 15 other major economies over the period 2000–2014. The European Commission's Joint Research Centre (Román et al. 2019) has published data on energy consumption and CO_2 emissions by industry and country consistent with this version, based on EDGAR (Emissions Database for Global Atmospheric Research). The data can be accessed at **https://www.rug.nl/ggdc/valuechain/wiod**. EDGAR can be accessed at **https://edgar.jrc.ec.europa.eu/emissions_data_and_maps**.

A3. FIGARO

EU intercountry supply, use, and input–output tables (EU-IC-SUIOTs) are produced by the FIGARO (Full International and Global Accounts for Research in Input–Output Analysis) project—a cooperative project between Eurostat and the Joint Research Centre of the European Commission. Annual time series are provided from 2010 to 2019 for the EU27, the United Kingdom, the USA, and the 17 main EU partners. EU-IC-SUIOTs were first published in 2021 by Eurostat using NACE Rev. 2 (Statistical Classification of Economic Activities, Revision 2) (64 × 64 activities/products). Estimates of air emissions, which use a Leontief approach, are the environmental extension of the FIGARO model. Since private household carbon footprints are not covered by EU-IC-SUIOTs, they are not included in the model computations but rather are added separately to the final results. The dedicated project page of the project is available at **https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/figaro**, and estimates using the FIGARO model are available at **https://ec.europa.eu/eurostat/documents/4187653/14185648/CO2_footprints_overview_2022-05-11.xlsx/af2f0f90-1143-8777-35b8-3843e211e6e4?t=1652880014532**. A methodological note on CO_2 estimates is available at **https://ec.europa.eu/eurostat/documents/1798247/6191529/Methodological+note+onyFIGARO+−+CO2+estimates.pdf/50055337-634b-464c-7eba-7f3a30d3980d?t=1652798511599**.

A4. EXIOBASE

EXIOBASE (Stadler et al. 2018) is a multiregional and environmentally extended supply and use table and a MRIO table for 44 countries and 5 world regions. It uses a classification of 163 industries and 200 products. EXIOBASE was developed by a consortium of research institutes in the framework of projects funded by the European Research Framework Programmes.

A5. Global Trade Analysis Project

GTAP is an international network of researchers and policy makers who conduct quantitative analyses of international policy issues. At the heart of the project is a global database describing bilateral trade patterns, production, consumption, and intermediate use of goods and services, with an environmental dimension. The tenth version of the database (Aguiar et al. 2019) covers the years 2004, 2007, 2011, and 2014 and breaks down the world economy into 65 sectors and 141 countries/regions, accounting for 98% of world GDP and 92% of world population. The GTAP-E satellite database provides CO_2 emission data disaggregated by fuel and user for each of the 10 GTAP countries/regions. The data are based on the extended energy balances compiled by the International Energy Agency. Emissions are reported for three types of non-CO_2, methane, nitrous oxide, and fluorinated gases, in a second satellite database (Chepeliev 2020) that uses FAOSTAT data for agricultural non-CO_2 emissions and EDGAR data (see Section A3, above) for nonagricultural emissions.

A6. Carbon Disclosure Project

The CDP is a nonprofit organization that oversees the global disclosure systems of more than 13,000 companies and 90 countries to manage their environmental impacts. CDP has the world's largest self-reported environmental database. Information and data are available at **https://www.cdp.net/en/data**.

A7. World Economic Forum

As part of its 2013 Travel and Tourism Competitiveness Report (Blanke & Chiesa 2013), the WEF provided an indicator of environmental stringency and enforcement based on two questions:

1. Stringency of environmental regulation. How would you assess the stringency of your country's environmental regulations?
2. Enforcement of environmental regulation. How would you assess the enforcement of environmental regulations in your country?

The 2013 report was subsequently replaced by a Travel and Tourism Development Index, featuring an environmental sustainability component comprising 15 indicators. The index is available at **https://www.weforum.org/reports/travel-and-tourism-development-index-2021/in-full**.

A8. European Union Transaction Log

The EUTL is the transaction log required by Article 20(1) of the EU-ETS Directive for the purpose of registration, issuance, transfer, and cancellation of allowances (Eur. Council 2023). Through the EUTL, the European Commission provides public information on the compliance of regulated entities, active participants in the system, and transactions between these participants. Transactions can be recovered at **https://ec.europa.eu/clima/ets/transaction.do**. However, accessing the data is not convenient, and a relational database connecting the different elements of the EUTL has been made public (Abrell 2022). The corresponding data set is available at **https://euets.info/static/download/Description_EUTL_database.pdf**.

SUMMARY POINTS

1. Unilateral climate policies induce carbon leakages that jeopardize the action of countries abating their emissions.
2. Direct leakage can be corrected by putting a price on the carbon embedded in imported products with a border carbon adjustment (BCA).
3. The design of a BCA is a compromise between environmental effectiveness in preventing leakage, economic effectiveness in preserving competitiveness and ensuring acceptability, technical feasibility of the implementation, and World Trade Organization compatibility.
4. The design must also pave the way toward international cooperation through climate clubs.
5. An import-limited BCA is more effective than free emissions allowances in reducing leakage, but it does not preserve the export competitiveness of the country imposing it.

FUTURE ISSUES

1. Instead of including contentious scope 2 emissions, which are subject to green subsidies in most countries, imported carbon in agriculture and forestry as well as leakages in downstream industries should be further studied.
2. More evidence of the impact of a BCA in the presence of heterogeneous firms is needed.

3. Theory could inform how exporting countries may circumvent a BCA by reorienting exports or specializing production units by destination.
4. Further study of the use of BCA revenues for decarbonization in low-income countries would ease international tensions surrounding this measure.

DISCLOSURE STATEMENT

L.F. is an advisor to the International Economy and Cooperation Directorate of the Bank of France. K.S. is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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