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ANNUAL REVIEWS

Annual Review of Environment and Resources

Carbon Leakage, Consumption, and Trade

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Keywords

carbon leakage, climate policy, embodied emissions, industrial decarbonization, international trade, consumption, equity, climate clubs

Abstract

We review the state of knowledge concerning international CO_2 emission transfers associated particularly with trade in energy-intensive goods and concerns about carbon leakage arising from climate policies. The historical increase in aggregate emission transfers from developing to developed countries peaked around 2006 and declined since. Studies find no evidence that climate policies lead to carbon leakage, but this is partly due to shielding of key industrial sectors, which is incompatible with deep decarbonization. Alternative or complementary consumption-based approaches are

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needed. Private sector initiatives to trace and address carbon emissions throughout supply chains have grown substantially but cannot compensate for inadequate policy. Three main price-based approaches to tackling carbon leakage are potentially compatible with international trade rules: border adjustments on imports, carbon consumption charges, and climate excise contributions combined with emissions trading. We also consider standards and public procurement options to tackle embodied emissions. Finally, we discuss proposals for carbon clubs involving cooperation among a limited set of countries.

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Contents

1. INTRODUCTION

Ever since climate change became part of the political agenda, governments and civil society have mostly conceived the problem, and potential solutions, in terms of territorial emissions, presuming this best reflects principles of state sovereignty over the regulation of carbon-emitting or -sequestrating processes on their respective territories. Since then, however, globalization—an important driver of economic development—has led to a surge in international trade and extended supply chains. The share of greenhouse gas (GHG) emissions associated with the production of internationally traded products has grown to 25% of all emissions (1). This creates a divergence between territorial emissions and carbon footprints, which comprise both upstream and direct emissions of products consumed in a country, also called consumption-based emissions (*CBE*) accounts.

Critics consequently point to offshoring of emissions-intensive, trade-exposed (EITE) production—sectors like metals, cement, and basic chemicals—as potentially undermining the effectiveness and legitimacy of claimed national emissions reductions (2). In addition, the fear of policy-driven carbon leakage—companies moving emissions-intensive operations abroad to escape regulation—impedes many, perhaps most, mitigation policy options for EITE production, given the perceived risk of these shifting to jurisdictions with weaker climate policies.

At the same time, companies and consumers are concerned about the emissions throughout the supply chains that are implicated in the final product, with little reference to territorial issues. Aiming for net zero emissions at the national level through bigger cuts to domestic emissions may not only increase the relative importance of emissions from traded goods but also inescapably require policies that decarbonize EITE industries rather than cause carbon leakage. Corporate claims to aspire toward net zero corporate footprints will ring hollow if they narrowly limit themselves to their direct operations and fail to address their supply chains.

The challenge is pervasive. Energy is a basic need. For two centuries, fossil fuels have powered industrial production, transport, agriculture, and electricity generation, enabling a fundamental transformation of our societies from an agrarian, place-based patchwork of communities to an integrated, global economy. The production of many basic commodities and of the most commonly used materials in industrialized societies, such as steel, plastic, and cement, is highly carbon intensive (3). Territorial emissions thus depend partly on the position of countries in the global division of labor. Emissions from countries that specialize in basic industries and manufacturing (and meat production or forestry products) tend to emit more than one would expect from their consumption levels, and vice versa for countries that specialize in services or less emissions-intensive activities.

Ever since the first climate mitigation policies emerged in the early 1990s, governments have effectively ignored consumption-based responsibility. Countries outsourcing manufacturing could credit themselves for improving efficiency and giving consumers cheaper products (while claiming credit for emission reductions); however, the political limits of this have been tested by backlashes against globalization, especially since the financial crisis.

Regulating production-based emissions (*PBE*) in a globalized world inevitably entails the risk of policy-driven carbon leakage. This risk has thus far been largely circumvented by exempting EITE sectors from any strong incentives, such as carbon pricing or production standard-setting, most notably through free allocation in emissions trading. Such exemptions are incompatible with the ambition to stabilize global temperatures. Industrial production overall accounts for approximately 40% of global fossil-fuel-and-industry emissions.[1] Net zero emissions cannot possibly be

Greenhouse gases (GHGs): atmospheric gases responsible for causing global warming and climate change, such as carbon dioxide, methane, and nitrous oxide

Emissions-intensive, trade-exposed (EITE): carbon emissions-intensive, trade-exposed industrial sectors

Policy-driven carbon leakage: the phenomenon of companies moving emissions-intensive operations abroad to escape regulation, displacing rather than reducing emissions

[1]In 2019, direct industrial production and process emissions accounted for 10.3 $GtCO_2$, with other gases adding approximately 3.8 $GtCO_2$eq; indirect (electricity-related) emissions were 5.91 $GtCO_2$. These compare to global inventory estimates of 59 $GtCO_2$eq for all gases. Thus, direct emissions from industrial production account for approximately one-quarter of global GHG emissions, or one-third including the indirect emissions from industrial electricity consumption; agricultural and land use emissions account for approximately 22%. Omitting the latter, which have much larger uncertainties, industrial production accounts for approximately 25% (direct) and 40% (indirect) of global fossil-fuel and industry emissions. For specifics on the data, see Reference 4, figures TS.2 and 11.4.

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Carbon Border Adjustment Mechanism (CBAM): policy instrument to level the carbon price paid between goods produced domestically and abroad [see also the discussion on border carbon adjustments (BCAs)]

achieved while exempting the biggest emitting sectors, namely emissions-intensive industry. The Intergovernmental Panel on Climate Change (IPCC) highlights that while macroeconomic costs may be modest, abatement costs in some sectors—including key industrial sectors—could exceed €100/tCO_2 (5). We can no longer ignore the impact of trade, and issues of potentially shared responsibilities for emissions associated with producing goods in some countries fueled by consumption in others, particularly given the United Nations Framework Convention on Climate Change (UNFCCC) principle of common but differentiated responsibilities and respective capabilities, and the bottom-up philosophy of the Paris Agreement with its implication of diverse national approaches.

Fortunately, over the past 10–15 years, a burgeoning literature has developed to shed light on the issues involved. Initially, and still predominantly, this was focused on leakage concerns in relation to the use of carbon pricing. More recently, carbon pricing, emission standards, and subsidies have been recognized together as potentially important policy instruments for incentivizing the development and uptake of low- or zero-carbon technologies or practices. In addition, more direct demand-pull instruments, including public procurement, can also help as part of a more comprehensive policy mix (6). This may complicate the picture further, but also introduces new options. This review works systematically from the general global trends and sectoral structures, through the nature of supply chains and private sector initiatives, to examine the policy responses and options particularly in relation to policy-induced carbon leakage.

Section 2 focuses on the empirical foundations, presenting the latest knowledge on the scale of emissions transferred through international trade, in terms of the divergence between production and consumption emission accounts, highlighting the sectoral structure and outlining the mechanisms and potential scales of carbon leakage. This establishes that while production of tradeable goods accounts for one-quarter of global emissions, the aggregate emission transfers between developing and developed regions peaked around 2005 and have declined significantly since. We also indicate how the scale of transfers depends on accounting approaches to exports.

Section 3 then examines the extensive growth of private sector responses, often taking an inherently more international, supply chain–oriented view. This includes information conveyed through Product Carbon Footprints (PCFs) and Environmental Product Declarations (EPDs), which combine with growing corporate environmental norms to generate significant pressures through supply chains.

Section 4 then explores the main public policy options that have been proposed to address leakage concerns. To date, the main debate has contrasted free allowances and exemptions against proposals for border carbon adjustments (BCAs), an old debate now reinvigorated by the specific European Union (EU) proposal for a Carbon Border Adjustment Mechanism (CBAM). We also identify two other approaches to pricing, as well as regulatory approaches.

In Section 5, this is then juxtaposed by explicitly considering equity and distributional implications of various measures aimed at addressing carbon leakage—an enduring flashpoint, as revealed by the EU's CBAM proposal. This points to the deep complexity of the challenge, ethically and politically.

This leads naturally to a conclusion that solutions will have to be inherently evolutionary, testing options and "feeling the stones" across a complex minefield of conflicting perspectives and domestic and international interests. We briefly explore these themes in Section 6, including diverse proposals for so-called carbon clubs involving a limited set of countries, before finally drawing broad conclusions.

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2. NATIONAL ACCOUNTING AND CONCERNS: TRENDS IN PRODUCTION VERSUS CONSUMPTION AND CARBON LEAKAGE

2.1. Production Versus Consumption Accounting: The Wedge Between Territorial Emissions and National Carbon Footprints

In principle, national emissions can be counted either in terms of emissions generated in a territory (by industrial production, and locally emitting consumption such as driving and heating homes) or in terms of emissions associated with all consumption, including of traded goods (7). The UNFCCC system, including the Paris Agreement and emission pledges under it, is based on territorial emission accounting, often termed production accounting.[2] In principle a country can claim credit for reducing its territorial emissions while maintaining its consumption pattern and lifestyle, by outsourcing the production of certain (emission-intensive) goods consumed domestically. The growth of international trade, especially with rapid globalization since the early 1990s, begs the question of whether emission reductions increasingly observed in industrialized countries (9) primarily reflect a real mitigation effort or the offshoring of emissions (10, 11). A related question is how much of the rapid increase in emissions from some developing countries has been due to rising consumption in industrialized countries. Consequently, a consumption-based accounting framework has been suggested as a fairer depiction of responsibility for current emissions (12).

Implicit in these debates are questions of how to account, measure, and attribute responsibility for emissions associated with internationally traded products. Since the early 2000s, a growing body of literature has employed consumption-based accounting, using several global multiregional input-output (MRIO) datasets, to quantify the emissions attributable to finished goods and services through the global value chain and the national carbon footprints. Formally, the carbon footprint of a territory, whether it is a city or a country, comprises emissions generated directly and indirectly along the global supply chains to satisfy the final consumption in the territory (13, 14). Mathematically, consumption-based emissions (*CBE*) accounts or carbon footprints are *PBE* accounts, minus the carbon footprint of products exported (*CFX*) plus the carbon footprint of products imported (*CFI*) (15):

$$CBE = PBE - CFX + CFI.$$

Despite commonly expressed doubts about the reliability of MRIO datasets given the various sector classifications, attribution of emissions from infrastructure and investments, trade assumptions, and other economic issues, differences in the CO_2 emissions data (rather than trade) are the main cause of differences in their *CBE* estimates (16). The *CBE* and *PBE* estimates derived from different MRIO datasets differ by less than 10% for most countries (16, 17).

For any region/country, the difference between *CBE* and *PBE*, or equivalently, between *CFI* and *CFX*, measures its net emission transfers (NT) with the rest of the world by international trade. The economically advanced countries of the Organisation for Economic Co-operation and Development (OECD) as a whole have higher emissions associated with imports than with exports, while the reverse is true for emerging economies as a whole, as indicated by the bands in

[2] *PBE* accounts are often equated with territorial emissions in the literature. The UNFCCC process utilizes terrestrial emissions, with separate accounting of international transport. *PBE* accounts reflect a classification, consistent with economic accounting, covering all emissions including international territories, aviation, shipping, and nonresident activities, which are not strictly territorial (8). In *PBE*, aviation and shipping are allocated according to the residence of the airlines and freight companies owning the ships.

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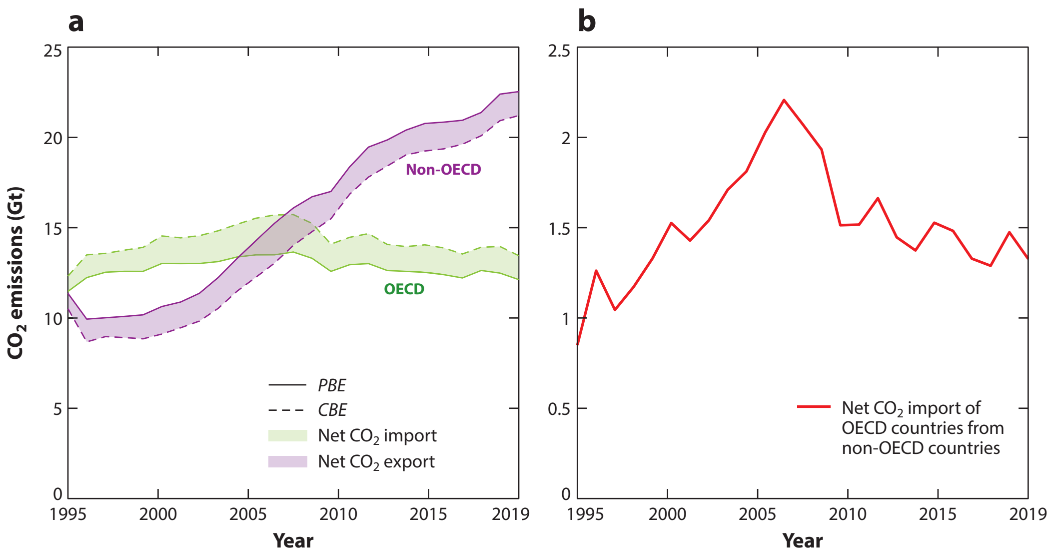

Figure 1

(*a*) Trends in production-based (*solid line*) and consumption-based (*dashed line*) CO_2 emissions and (*b*) net CO_2 import of OECD countries from non-OECD countries (1995–2019). The figure is an updated version of Wood et al. (18, figure 4) (CC BY 4.0). Abbreviations: *CBE*, consumption-based emissions; OECD, Organisation for Economic Co-operation and Development; *PBE*, production-based emissions.

Figure 1*a*. Crucially, the net transfers from OECD to non-OECD countries peaked in 2006 and decreased to a pre-2000 level by 2019, which is different from an increasing trend that many had assumed (**Figure 1*b***). This is mainly due to a declining emissions intensity of traded goods, especially from developing countries, which has outpaced the effects of increasing trade volume since 2006 (18).

Additional and national-level insights in **Figure 2*a*** show the evolution of *PBE* and *CBE* in terms of development pathways for different countries as their economies have grown (the x-axis, per capita GDP). The net transfers are influenced by the trade balance, the energy mix in a region compared to its trade partners, and the position of the region in the global division of labor. Trade deficits (US), a low-carbon energy mix (EU-15), and a specialization in services and light industries (EU-15) tend to lead to net imports, whereas a trade surplus (China), a dirty energy mix (China), and a specialization in resources and heavy industry (Russia) drive net exports. In much of the developed world, the trends up until the financial crisis (2008–2009) did involve divergence, with territorial emission reductions alongside a rising carbon footprint, but *CBE* have since declined as much as or even more than *PBE*. The meteoric rise of China did include significant emissions from exports, and China now is at a level of both per capita income and carbon intensity similar to that of western Europe around 1970; however, its carbon intensity is approximately twice that of Brazil or Mexico at the same stage of per capita income, due more to its abnormally high rate of investment and widespread use of coal than of its export industries. The peak and subsequent decreasing net transfers are also visible in most of the country/region pathways.

A positive net transfer has been commonly equated with emissions outsourcing, but recent literature highlights a problem if this is understood as shifting energy-intensive activities abroad. If two countries trade the same product and amounts between each other, yet one has a cleaner energy mix than the other, it results in a net transfer: Countries with more carbon-efficient technologies than their trading partners have a higher national carbon footprint even if such trade

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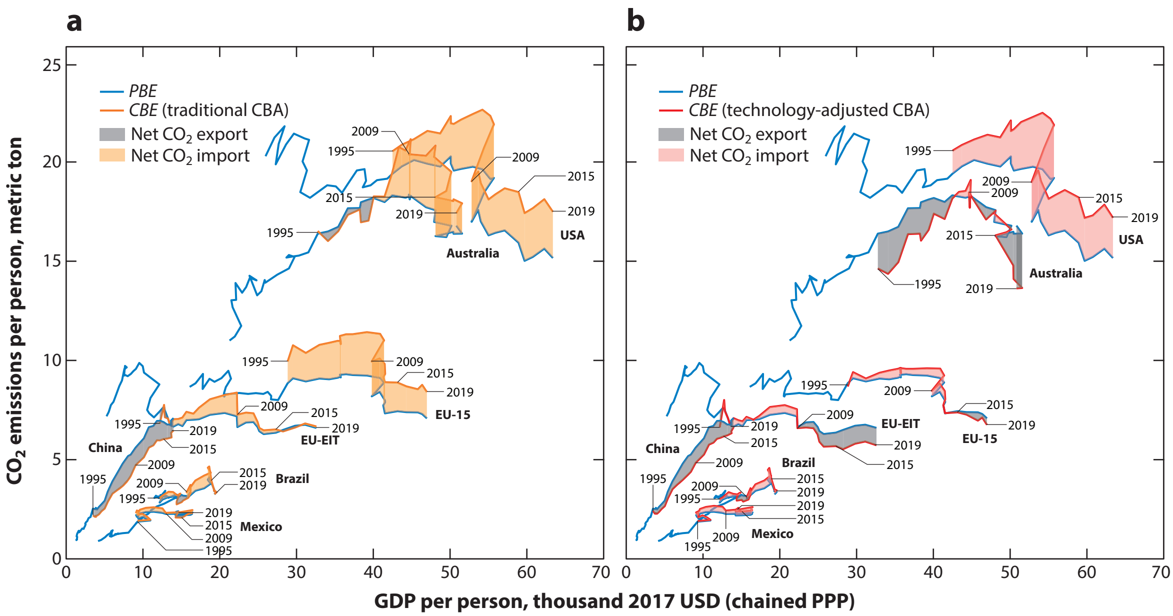

Figure 2

Evolution of production (since 1975) with consumption-based (since 1995) CO_2 emissions per capita of selected countries as a function of GDP per capita, (*a*) based on the CBA method and (*b*) with TCBA. Conception of panel *a* as per Grubb et al. (19) and updated by the authors (specifically, R. Wang). TCBA is with exports counted at global average emissions intensity. EU-15 refers to the 15 members of the European Union as of 1995, primarily Western and Scandinavian countries, before enlargement to include the Eastern European Economies in Transition (EU-EIT). The GDP was adjusted for PPP, i.e., the relative domestic purchasing power of different currencies. Additional abbreviations: CBA, consumption-based accounting; *CBE*, consumption-based emissions; GDP, gross domestic product; *PBE*, production-based emissions; PPP, purchasing power parity; TCBA, technology-adjusted consumption-based accounting.

reduces global emissions by displacing dirtier foreign production (13). An alternate, technology-adjusted consumption-based accounting (TCBA) method adjusts the emissions intensity of exporting sectors based on the global average emissions intensity, which credits efficiency improvements in exported goods. This acknowledges countries' contributions to global emissions reduction (13) (compare EU between **Figure 2*a*** and ***b***) and also yields a more positive evaluation of purported leakage under the Kyoto Protocol (20). TCBA accounting indicates that the EU-15 and Australian emissions trade balances switched around 2015. The technology adjustments have little impact on the United States, indicating the overall carbon intensity of the relevant US (exporting) sectors is close to the global average.[3] Some other TCBA adaptations have been proposed, notably around investment, but the additional benefits are somewhat unclear (21).

[3]TCBA accounting correspondingly reduces the attributed developing–developed country transfers, being approximately 1 $GtCO_2$/year lower than indicated in **Figure 1*b*** (13). However, TCBA itself suffers from limitations regarding the measurement and comparison of carbon intensity and sectoral aggregation effects. Intensity measured as $kgCO_2$ emissions per traded value neglects the price differences of production among countries. The TCBA methods based on MRIO tables also suffer from the sectoral aggregation issue. The composition of a sector's products in one country may differ substantially from the global average, which makes the comparison implicit in the correction problematic. Therefore, TCBA's technology adjustment based on carbon intensities at the sector level improves the conventional NT accounting but leaves some critical issues unsolved.

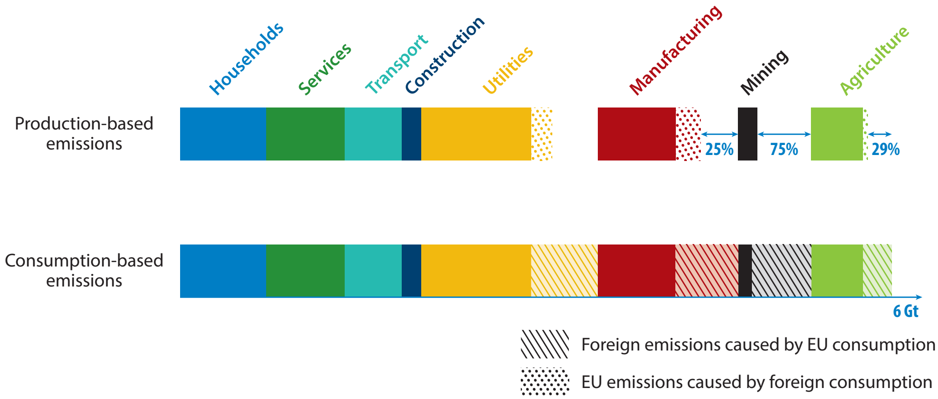

Figure 3

Production-based versus consumption-based emissions by sector: internal and external attribution. Figure adapted with permission from Wood et al. (22, figure 6) (CC BY 4.0). Abbreviation: EU, European Union.

2.2. Sectoral and Distributional Structure of the Issues

Differences between *PBE* and *CBE* can be traced back to a few relatively concentrated economic activities. **Figure 3** illustrates that for the EU (and generally), there is little or no difference for households, services, transport, and construction, which are not traded. The additions associated with international carbon footprints arise mostly from utilities (such as upstream emissions for gas imports), manufacturing, mining, and agriculture. For Europe, many of these activities unavoidably occur elsewhere for simple reasons of natural resource endowment. Among major economic regions, Europe is unusual in the extent of the overall imbalance between production and consumption, especially given its relatively limited (remaining) mining and agricultural potentials.

Most policy discourse about competitiveness and carbon leakage concerns emissions associated with industrial products. In gross terms, 50% of product-related emissions arise from products manufactured outside of the EU, but the net effect is only 25%, due to EU exports (which indeed would offset far more with the TCBA approach). The imbalance is more pronounced in agriculture with 29% net imports and very high in mining with net imports of 79% of embodied GHG emissions. Like Japan and South Korea, the European economy depends on imports of resources, and it is this—including mining and agriculture—that drives the wedge between the EU's *PBE* and *CBE* (21). Globally, emissions from manufacturing form a larger share of GHG emissions than for the EU, and rising ambition on climate mitigation makes decarbonizing the manufacturing industry an ever-more pressing concern. In turn, the past decade has increasingly highlighted that emission-intensive activities are highly concentrated: Two-thirds of industrial emissions, or one-quarter of global GHG emissions (including electricity-related), arise from the production of basic materials like steel, cement, plastics, fertilizers, aluminum, glass, and pulp and paper (23).

While the majority of trade-related emissions transfers are attributable to non-energy-intensive sectors that are traded in much greater volumes (1), concerns about carbon leakage primarily focus on EITE sectors, in which energy and carbon costs represent a high share of overall costs. This is illustrated in **Figure 4**, which shows for the EU the potential impact of carbon costs relative to value added by sector—which the literature (24) concludes is the most appropriate indicator—in the EU economy. This underlines the extent to which industrial CO_2 emissions are heavily concentrated in sectors that are also expected to grow globally and that face strong international competition.

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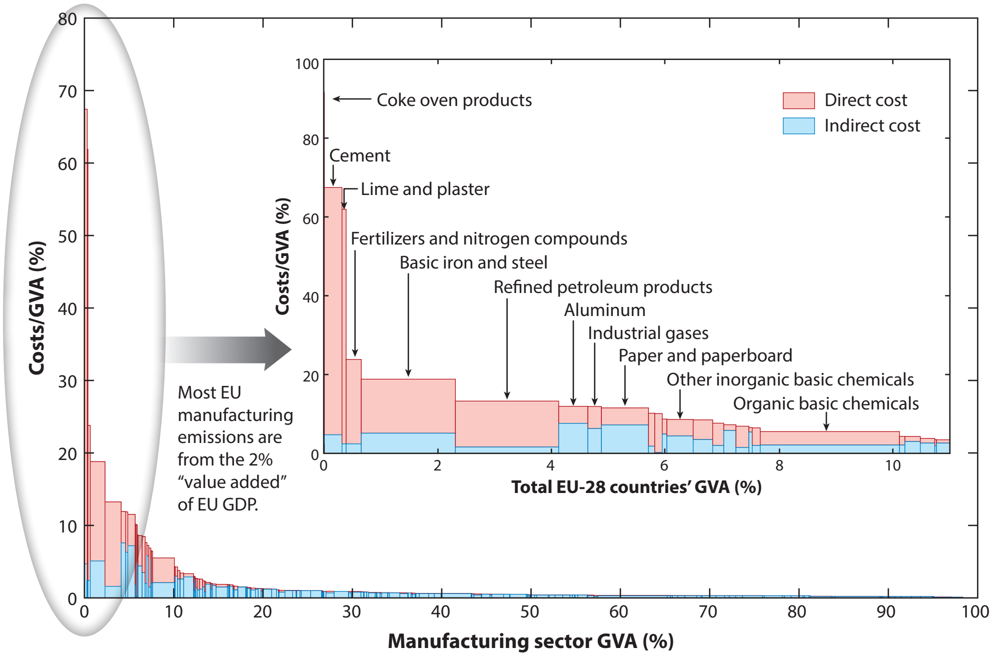

Figure 4

Potential impact of €30/tCO_2 carbon cost (if no free allocation) on manufacturing sectors in Europe (EU-28), and their share of total manufacturing GVA (2018). Data from the authors' calculations, on the basis of Eurostat and the EU ETS EUTL, updating Reference 27, figure 8.4. GVA for manufacturing sectors from NACE Rev. 2, B-E (**https://ec.europa.eu/eurostat/databrowser/view/sbs_na_ind_r2/default/table?lang=en**), with all level-4 NACE manufacturing sector (C) codes, for 2018 as the last year that includes the United Kingdom within the EU (EU-28 countries). Manufacturing does not include extraction/utility industries. Direct emissions from the EUTL database (**https://euets.info/**), with verified emissions by installation obtained from the "compliance" subdataset and allocated to each corresponding NACE 4 sector for consistency with GVA data, multiplied by CO_2 price of €30/tCO_2, the same as used for the 2015–2019 carbon leakage assessment. The same indirect (electricity-related) emissions costs to GVA ratios as those reported for the 2015–2019 carbon leakage assessment were assumed (**https://ec.europa.eu/clima/system/files/2016-11/carbon_leakage_detailed_info_en.pdf**). Abbreviations: EU ETS, European Union Emissions Trading System; EUTL, European Union Transaction Log; GVA, gross value added; NACE, Nomenclature statistique des activités économiques dans la Communauté européenne.

A consumption perspective also has distributional implications. Rich households have higher carbon footprints than poor households; the consumption of the wealthiest 10% of the world's population is estimated to account for 36–45% of all GHG emissions and an even higher share of energy and industrial CO_2 emissions (25–27). The "super-rich" have carbon footprints estimated at well over 100 tCO_2 per capita (28). Approximately half of this comes from air travel—much of it international, often outside national accounting systems—with much of the rest associated with other forms of conspicuous consumption, often through long international supply chains.

Embodied emissions: the greenhouse gas emissions that have accumulated to extract the resources required, produce and distribute a product

2.3. Carbon Leakage and Supply Chain Leverage: Mechanisms and Scale

The specter of carbon leakage stifles the regulation of production-based industrial emissions. Climate-policy-induced carbon leakage (abbreviated to carbon leakage in this article) represents a subset of all embodied emissions in trade that is specifically driven by international differences in climate policies. Carbon leakage is a displacement rather than a reduction of emissions as a

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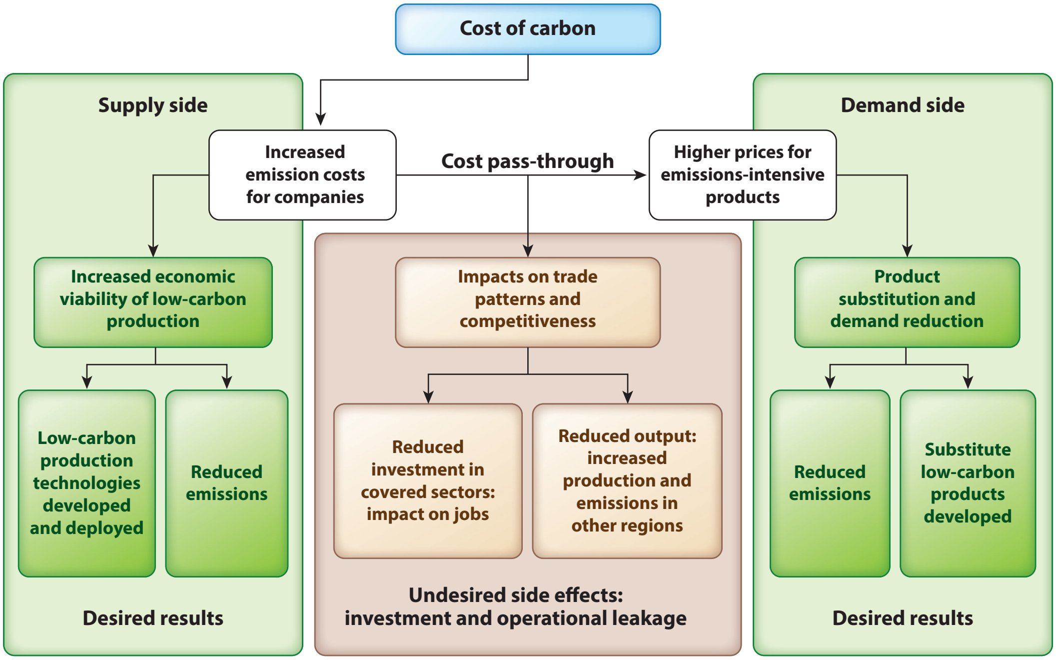

Figure 5

Desirable and problematic dimensions of mitigation in energy-intensive industries. Adapted with permission from Reference 86, chart 2b.

direct consequence of climate policy choices. Leakage can also occur through other indirect climate policy impacts, for instance by reducing international fossil fuel prices or changing domestic and foreign demand, but here we focus on leakage through trade and capital flows.

Climate policies such as carbon pricing and emission standards, in principle, encourage mitigation throughout the value chain by producers, consumers, and all the intermediate stages (e.g., assembly, construction). On the supply side (left-hand side of **Figure 5**), emissions pricing incentivizes low-carbon innovation and emission reductions in the primary emitting industries. On the demand side, the additional costs are passed on to intermediate and final consumers (right-hand side of **Figure 5**), encouraging them to reduce consumption of carbon-intensive goods and switch to low-carbon alternatives, given so-called full carbon cost internalization.

Where trade enables the spatial separation of production from use, competition from lesser-regulated foreign producers (in domestic or export markets) may limit the pass-through of carbon costs and generate undesired side effects, including leakage. **Figure 5** illustrates this dilemma. On the one hand, full carbon cost pass-through is necessary to recover costs and create incentives on the demand side for consumers to use lower-carbon products and services and for companies to create products to meet this demand. However, if companies do pass through carbon costs to their product prices, they may lose ground to imports and/or lose exports. If companies do not fully pass through their costs, profitability declines and investment is driven away in the absence of supplementary measures (middle of **Figure 5**). Both may risk carbon leakage (operational or investment) (29, 30).

In practice, the idea of companies literally relocating factories is simplistic. High fixed plant costs and immobile physical capital of energy-intensive sectors can make a direct physical move infeasible. However, higher domestic costs tend to deter new investment, thus shifting new investment abroad, a process that is slower and harder to detect (31–33). Overall, the literature provides

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little to suggest that the effectiveness of existing climate policy has been substantially affected by leakage. While model-based studies find moderate trade-related leakage rates in the 3–15% range (34), empirical studies testing for evidence of leakage from existing policies such as the EU Emissions Trading System (ETS) do not find strong support; however, this is hardly surprising given the generous free allocations granted with the express aim of preventing leakage (35, 36) (Section 4). The evidence does not rule out the possibility of higher leakage at higher carbon prices, in the absence of free allocation, and suggests leakage rates would be higher in smaller jurisdictions (34).

The extent to which companies can pass through costs to prices is usually linked to the sensitivity of demand and supply to price and the degree of competition, which in turn depends on multiple factors including trade barriers and global excess capacity; the likely extent of pass-through can be very hard to estimate (37–39).

In electricity, only tradeable through wires, the risk of leakage through import substitution is generally low except in jurisdictions with significant cross-border interconnection capacity and trade such as California (28, 40). Full carbon cost pass-through is observed in liberalized electricity markets (41, 42) but negligible in highly regulated markets such as South Korea (43). The policies that have proven most effective in promoting renewables largely circumvent leakage concerns, taking the form of contracts for clean energy, and recovering the costs through charges on domestic electricity consumption.

Analysis shows that leakage risk varies considerably both across and within sectors, being ultimately limited to a number of narrow, specific cases (37, 44) that are linked mainly to carbon intensity of production (**Figure 4**) and the inability to fully pass forward CO_2 costs to product prices given major trade exposure (24, 45). While leakage risk is low overall and concentrated in a few key material sectors, politically, it cannot be ignored. Companies will almost always fight efforts by government to extract revenue from their sector, and at a local level, politicians can rarely ignore a company threatening to cut jobs and relocate demanding exemptions from, or compensations for, climate policy (46).

To circumvent the problems arising from differences in production-based climate policy across jurisdictions, consumption-based instruments are being considered as complementary or alternative measures. However, information on the carbon emissions incurred along transnational supply chains before the act of consumption can be hard to get by. The next section outlines initiatives providing such information, often in response to consumer concerns, before turning to public policy instruments countering carbon leakage in Section 4.

3. CONSUMERS, COMPANIES, AND INFORMATION: PRODUCT AND CORPORATE CARBON FOOTPRINTING

3.1. Consumption Perspectives

Most government mitigation policy to date has focused on GHG-emitting or energy-using installations or devices but has otherwise neglected the carbon emissions that are generated throughout supply chains before a product gets consumed. A purely consumption-oriented approach has a theoretical advantage of avoiding any carbon leakage: Whether consumers avoid an emitting activity or purchase, shift to cleaner alternatives, or preferentially purchase improved (e.g., lower GHG-emitting) versions of the same products is in principle blind to the country of origin (43, chapter 5 and supplementary material). Moreover, the importance of demand as a source of technological change, and particularly as a source of innovation in energy, is well documented in the literature (47), suggesting the potential for consumption-based policies to develop markets for low-carbon alternatives driving down carbon footprints globally.

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Most GHG-intensive production activities are classic second-domain decisions, driven mainly by economic criteria in which relative prices are a crucial factor. By contrast, many consumption choices related to energy and final goods are first domain in character, based on habits, behavioral norms, and biases and potentially much influenced by noneconomic factors (29, 48). From a consumption angle, therefore, a much wider range of motivations and instruments can be considered. One review (6) identified more than 30 different consumption-based instruments with potential impacts through the supply chain, divided into four main categories: informational instruments supporting private initiatives, regulatory/administrative, economic, and infrastructural. The recent IPCC mitigation report (48) examines in more depth consumption-oriented measures along with the emerging evidence around their effectiveness.

A full review is beyond the scope of this article, but a key point of connection concerns information. Whether influencing consumption choices or implementing policy and governance, measures that seek to directly target the carbon embodied in products require information about their carbon footprints. This section looks at emerging private and relevant public policy efforts, including motivations for carbon disclosure and how product carbon footprinting links to sectoral and firm-level carbon reporting.

3.2. Product Carbon Footprinting

GHG emissions can be added along the supply chain to calculate the carbon footprint or embodied emissions of a product (1, 49). Policies targeting the carbon footprints of specific products require considerable technological, administrative, and coordinative capacities. Methodologies have been increasingly refined and standardized to improve the comparability of results between different methodologies and data sources. Improvements make it easier to develop high-quality environmental labels (50). Internationally agreed standards for PCFs [International Organization for Standardization (ISO) 14067:2018] (51–54) and EPDs (ISO 14025:2005) (51–53, 55, 56) already provide common, albeit imperfect, bases for the certification of embodied emissions. EPDs communicate the results of life cycle assessments (LCAs) of the overall environmental impacts associated with the production of a product, whereas PCFs focus on GHG emissions.

For policy instruments to successfully build on product carbon footprinting, rigorous standards must ensure robust embodied emission assessments (57). Product Category Rules (PCRs) specify key parameters for the LCAs underlying PCFs or EPDs. However, PCRs vary considerably in terms of data sources, modeling assumptions, and subsequent assessment outcomes, even in the relatively simple and short supply chains of construction products (58). The lack of coordination between PCR creators limits the comparability of PCFs and EPDs. Various actors engage in the creation of PCRs, ranging from material-specific trade associations to dedicated institutes for EPD creation and standardization agencies to public authorities (59). Carbon labels have received more attention in the social science literature than EPDs (56, 60). Bibliometric studies suggest that labels purely focusing on carbon have proliferated mainly in the food retail sector, where consumer visibility is high (61, 62). By contrast, EPDs have been adopted in particular by the basic materials sectors (63, 64) such as steel and cement, and are therefore very relevant, e.g., in construction, including city/public procurement and some manufacturing (e.g., vehicles).

The construction sector has seen the most significant institutional use of such information. Private sector activity has been an important driver for the diffusion of EPDs and PCFs, for instance in the form of private sustainable building certification schemes, which often provide incentives for procuring products that come with EPDs (55, 63).

While EPDs and PCFs are ostensibly private measures, public policy has significantly contributed to their emergence and diffusion. In terms of informational push, in Europe a range of policies have created incentives for industry associations to engage in the collection and sharing of data on environmental performance (64). In terms of informational pull, in some instances governments have incentivized the adoption of private sustainable building certifications or have closely collaborated with private certification schemes to develop their own schemes (for example BNB in Germany and Code for Sustainable Homes in the United Kingdom). The State of California has started to draw on EPDs for its public procurement decisions (see Section 4.2). Asian countries have also come out with PCFs, EPDs, and PCRs, notably Japan, South Korea, and Taiwan (65).

3.3. Links Between Corporate and Product Carbon Footprinting

Data generated by firm-level environmental reporting may help to inform product-level environmental footprinting (50). While there are clear limitations to the direct rescoping of data from the firm to the product level, there is a significant functional overlap in terms of skills and infrastructure, such as environmental reporting systems, indicating how greater firm-level reporting can help with environmental footprinting of products.

The GHG Protocol (66), an industry standard, helps in measuring and managing the carbon footprint of a company from its operation and across the value chain by facilitating GHG emission calculation. The carbon footprint is calculated from emissions directly controlled by a company (Scope 1), from the indirect emissions associated with its use of energy carriers (mainly, electricity) (Scope 2), and the carbon footprint attributed to other inputs in the value chain, such as energy-intensive materials (Scope 3). Scope 3 can also include downstream emissions, e.g., from the transport, use, or disposal of products (67).

While calculating Scope 1 and 2 emissions is relatively easy, a plethora of challenges crop up in estimating Scope 3 emissions that are embodied in the supply chain. Some of these hurdles include lack of transparency in the supply chain, absence of direct links with suppliers, complex accounting principles due to multiplicity of intermediate production steps (68) and ambiguity in industry standards (69), and variation in interpretation of Scope 3 categories and boundaries among players (70) leading to reporting inconsistencies.

In view of these challenges and complexities, corporations tend to focus their efforts on measuring, reporting, and reducing Scope 1 and 2 emissions (68). Yet a major rationale of corporate carbon footprinting is to assess the carbon exposure of a corporation for which it is critical to ensure that all three scopes are accurately calculated (71). Supply chain emissions disclosure remains voluntary, and results are often unverified (70).

Nevertheless, the increasing adoption of Scope 3 emissions reporting leads to a stronger alignment between firm- and product-level reporting, as both draw on the same set of databases for default values (64). PCFs typically comprise a combination of specifically measured and generic values, whereas Scope 3 reporting mostly uses generic values. The GHG Protocol website suggests that the same third-party databases may allow users to collect data for both product life cycle and corporate value chain GHG inventories (72), with corresponding business value in developing both inventories in parallel (73). While EPDs and PCFs are currently rather static documents, in the future improved real-time communication along supply chains could help dynamically update them (74), bringing Scope 3 emissions accounting and carbon labeling even closer together.

The pull factors that drive calculations of the corporate carbon footprint for more proactive companies include the sustainability imperative (75) and the potential to gain competitive advantage through product and business model innovation (76). The following push factors (77) nudge corporations to measure and control their carbon footprint:

- pressure from stakeholders and shareholders,
- anticipated regulatory and liability risk,

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- concerns for reputation and brand image, and
- concerns for rising energy prices and energy security.

All these factors, if left unattended, can potentially hamper the value creation process of a corporation and have serious financial implications. Therefore, carbon footprinting also provides a metric of the transition risk that companies are facing in the supply chains (69). In this context, in 2015 the Financial Stability Board created the Task Force on Climate-Related Financial Disclosures (TCFD) to develop consistent climate-related financial risk disclosures for use by companies, banks, and investors. The Task Force's recommendations cover four key thematic areas, namely governance, strategy, risk management, and deciding on metrics and targets (78). Many of the TCFD recommendations were included in a 2022 regulation proposed by the U.S. Securities and Exchange Commission (79).

More than 800 companies have taken up commitments to reduce carbon emissions following the Science Based Targets initiative (68). The pursuit of science-based targets relies on credible measurements of corporate emissions, ideally across all scopes. Such corporate measurements are likely to improve the conditions for product-level footprinting in terms of available skills, institutions, and infrastructures. More widespread and credible product carbon footprinting allows for a greater repertoire of public policy instruments for tackling embodied emissions and carbon leakage, to which the following sections turn.

4. INCORPORATING CONSUMPTION AND LEAKAGE CONCERNS INTO PRICING AND REGULATORY INSTRUMENTS

Carbon pricing, emission standards, and subsidies are the key elements of public policy approaches to drive emission reductions across sectors (6). Traditionally, carbon leakage is discussed primarily in the context of carbon pricing. Exemptions and free allocations to shield industry from carbon pricing deter leakage but weaken incentives for the development and uptake of low-carbon technologies or practices. Transforming these sectors to carbon neutrality requires a more joined-up perspective combining multiple instruments while addressing potential leakage, without losing relevant incentives at different stages of the value chain from production to final consumption.

Key constraints for climate policies targeting heavily traded products arise from potential international repercussions, especially from incompatibilities with international trade law. The details rapidly get complex (80), but there are two relatively simple founding principles. First, such measures should not discriminate between imported and domestically produced products (i.e., national treatment): If they are considered like products, they should be treated as such. Second, a measure should not discriminate between trading partners (i.e., most-favored nation treatment). This means that like products are treated alike, irrespective of their origins.

Measures that violate these core rules of international trade law, such as overt decisions about who to trade with, may still be upheld if they are taken for legitimate public policy objectives and if they are applied in a way that does not lead to arbitrary or unjustified discrimination, or constitute a disguised restriction on trade. Correspondingly, measures for decarbonizing industries can be divided into two broad categories: those that at least attempt to respect these broad principles and those that do not (like some of the proposals for carbon pricing clubs with sanctions against nonmembers, indicated in Section 6). This section discusses approaches that seek to tackle carbon leakage within these broad principles of international trade law. We first discuss approaches to countering carbon leakage in carbon pricing systems, then consider other approaches, namely embodied carbon product standards, green public procurement (GPP), and low-carbon-technology subsidies, and conclude with a look at complementary uses of these various policy instruments and sequencing issues.

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4.1. Carbon Pricing Approaches

Carbon pricing matters especially for basic materials and commodities where their high energy cost share (**Figure 4**) and a huge diversity of final products and processes complicate the use of standards, making price an ideal broad-based incentive. Here we show that there are more approaches to price carbon while tackling leakage than generally appreciated; however, all have important complications.

4.1.1. Exemptions and free allowances.

The dominant measure to avoid carbon leakage is simple in conception: For the exposed sectors, carbon costs can be reduced by exemptions (from carbon taxation), free allocation of emission allowances (in cap-and-trade systems), or compensation (for indirect carbon costs in electricity). These approaches enhance the political feasibility of carbon pricing because they avoid confronting highly mobilized producer groups who highlight the risk of carbon leakage as well as economic losses (81). However, they have many drawbacks.

In the case of free allocation, there is an inherent trade-off around how allowances are given out, with battles over multiple options.[4] In practice, systems have tended to move to output-based allocation—a benchmark value (e.g., tCO_2 per tonne of steel produced) times the output. Output-based free allocation works precisely because it takes most of the carbon price out of the product: The carbon cost of producing more is offset by the value of the additional free allowances obtained. Thus, the cost pass-through from upstream (supply) to downstream (product) is avoided.

This approach largely prevents leakage, by shielding producers from the full carbon cost and by avoiding carbon cost pass-through to export prices or a charge on the emissions from imports (**Figure 6**). Modeling studies show that output-based free allocation protects against leakage (83), a conclusion reinforced by the absence of observed carbon leakage (84) (Section 2.3).

The major downside of this approach is that it severely weakens incentives for efficient domestic production. As illustrated in **Figure 6**, although producers have incentives to make incremental carbon efficiency improvements to meet the benchmark, without carbon costs reflected in material prices, output-based allocation negates any economic incentive for efficient material use (85) and thus raises the overall cost for any given goal.[5] The IPCC (48) identifies efficient materials use, and substitution of high- by low-carbon materials, as potentially major and low-cost ways to cut industrial emissions. Free allocation forgoes auction revenues that could be used, for example, to cover investments in climate-neutral production processes and their incremental operational costs or offset distributional impacts. Moreover, it involves complex issues and trade-offs around the number and level of benchmarks (84).

Another downside is that by offering value in an uncertain world, free allowances create huge incentives for industry to lobby in favor of generous allocations on the basis of optimistic projections of output and exaggerated difficulty of cutting emissions, which has in practice frequently

[4]Grandfathering allowances on the basis of recent emissions creates a perverse incentive: the more a source emits, the more allowances it may receive. Giving fixed amounts based on a benchmark (intensity, per unit output) performance is much better, but may not forestall leakage; companies could replace their output by imports and cash in surplus allowances. Some earlier phases of the EU ETS attempted to forestall this by only offering allowances if plants' output exceeded a certain threshold. In the cement sector, this resulted in the remarkable feat of reversed leakage, with domestic production being maintained, even for export, to secure the allowances at the threshold (82).

[5]Modeling for the Carbon Trust estimated that moving to output-based free allocation in cement, steel, and aluminum would increase the carbon price by approximately 30%, compared to full auctioning, whereas using border adjustments (border carbon-cost leveling) to tackle leakage would increase the carbon price by less than 10% (86).

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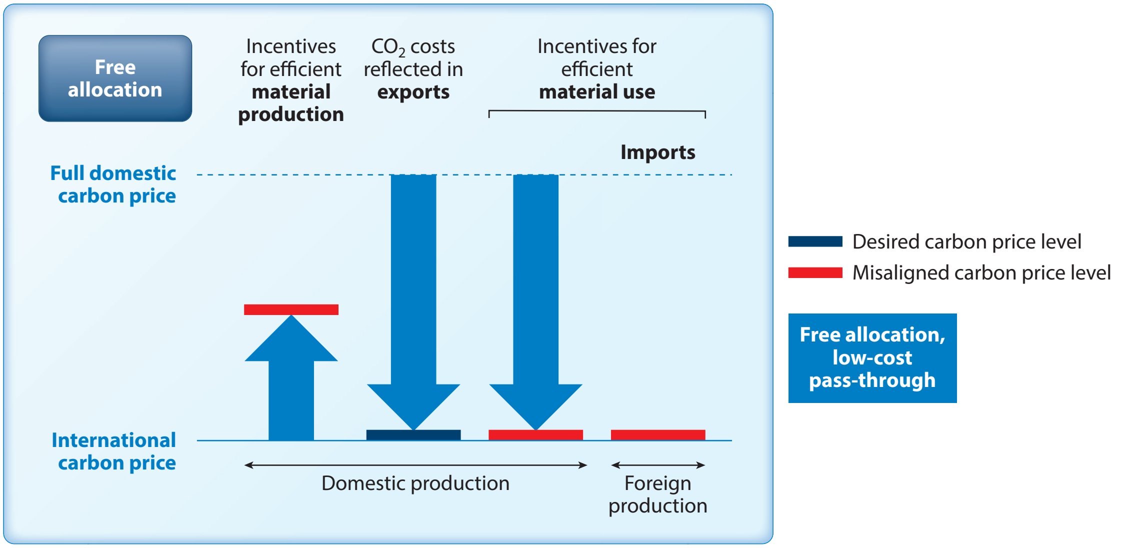

Figure 6

Free allocation/exemptions: incentives and misalignments (compared to from full carbon cost internalization). Carbon pricing with benchmarked thresholds (e.g., free allowance allocation or similar exemptions below a threshold) creates some incentives to improve existing production processes (within a given benchmarked category) and can largely avoid leakage, but gives little incentive (or revenues) for deeper innovation and mutes any downstream incentives for efficient material use and recycling.

resulted in large windfall profits (87), potentially even deterring abatement (88). Internationally, questions have been raised about whether free allocation is an actionable subsidy under World Trade Organization (WTO) law (89, 90); however, no complaints have been brought before the WTO.

Thus, free allocation is neither simple—as demonstrated by the tortuous evolution and endless negotiations of allocation approaches in the EU ETS (46) and other systems—nor free. It is actually very costly and makes it much harder or even impossible to achieve the objective of deep decarbonization.

These drawbacks have underpinned the search for alternative and complementary measures. The rest of this section outlines three broad options beyond exemptions and free allocation: BCAs, carbon footprint charges, and climate excise duties, to contribute downstream incentives (and revenues). All of these could, in principle, create incentives for efficient material choice, use, and recycling and also generate revenue for low-carbon innovation and infrastructure (91, 92). They do, however, face varied challenges in implementation and differ in the relative balance between production and consumption-based incentives, international implications, and the degree to which they are relatively blunt but easy to administer or more precise and data-intensive.

The following subsections organize the options in terms of where they focus the price incentive: (*a*) at the point of production or import (BCAs), to flow downstream; (*b*) at the point of final consumption (consumption charge), aiming to leverage upstream decisions; or (*c*) separation of the incentives between point of production and a direct charge on the use of carbon-intensive materials.

4.1.2. Border carbon adjustments. BCAs seek to level the carbon price paid between goods produced domestically and abroad. Imported goods from other countries are subject to a carbon price at the same level as domestically produced goods (assuming no carbon price is already paid)

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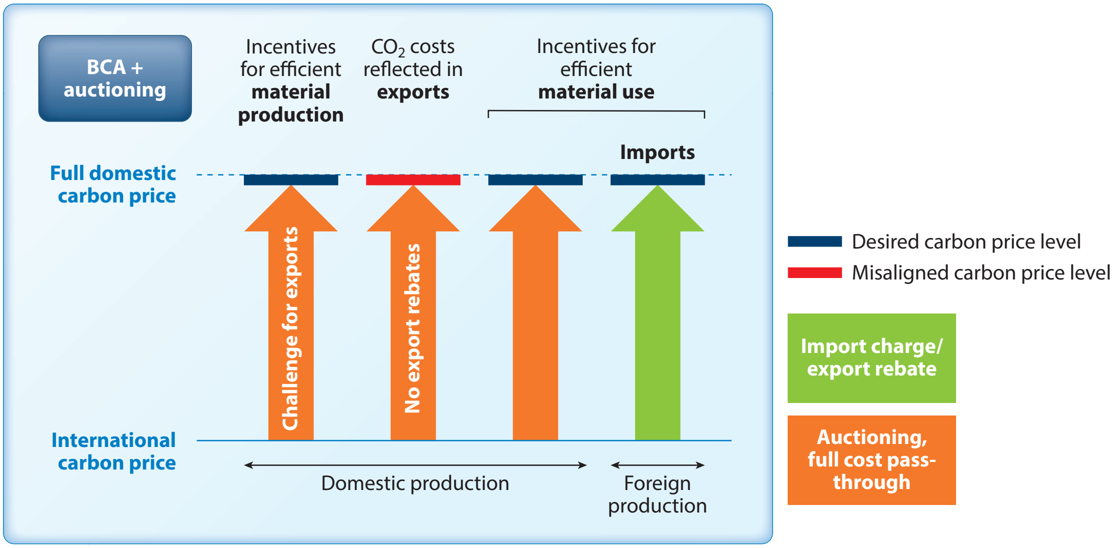

Figure 7

Full carbon pricing with border adjustments: incentives and misalignments. Full carbon pricing, e.g., with auctioned allowances, or no thresholds for taxation, in a closed economy creates full incentives for improving existing production and would encourage innovation. Applying similar carbon charges to imported materials also facilitates cost pass-through, with incentives for efficient use of materials. However, WTO constraints largely preclude export rebates, so applying full carbon costs would harm exports (export carbon leakage). Abbreviations: BCA, border carbon adjustment; WTO, World Trade Organization.

(**Figure 7**). BCAs could take on the form of a tax, a tariff, or an obligation to procure emissions permits (80). Theoretically, a BCA would tackle carbon leakage insofar as it symmetrically charges importers and rebates exporters, thereby ensuring that carbon prices paid in domestic production would not be undercut by producers elsewhere avoiding these costs. This would render obsolete the rationale for free allocation of emissions permits to products that are sold to the domestic market, enabling full auctioning, and this full carbon price would be passed through, offering incentives for all mitigation options. Variations include treatments of imports versus exports, use of benchmarks versus full-chain accounting, use of domestic emission intensities applied to imports (93), and treatment of electricity (as also modeled in 86, which recommended sector-specific variations in design).

Analyses of the WTO compatibility of BCAs (80, 94–99) suggest that it can in principle be designed and implemented in accordance with international trade law, but the details would matter and differ from the elegant theoretical solution with full symmetry. To be unequivocally compatible with international trade law, BCAs would need to have a clear environmental rationale (i.e., reduce carbon leakage), exclude export rebates, account for the mitigation efforts and costs by other countries, and provide for fairness and due process in the design and implementation. Studies show considerable loss in effectiveness and efficiency with large deviations from a theoretically sound to a WTO-compatible BCA design (100).

A key problem arises in relation to exports. Exempting exporters from carbon pricing through rebates could constitute a prohibited subsidy under the WTO Agreement on Subsidies and Countervailing Measures (ASCM), and undermine the environmental defense of a measure (80). Without rebates, however, they would be disadvantaged in export markets (**Figure 7**) and lose market share, leading to leakage (83). A meta-analysis (101) finds that without such export rebates, even at a carbon price of €30/t, approximately 10% of EU exports would face significant cost increases and leakage risk (80, 91). This would make it politically challenging to move to full auctioning. If some exemptions or free allocation continue to address this, incentives for efficient material production will be compromised. Even if export rebates were allowed, it would create an incentive to reshuffle within a product or material category; i.e., businesses would sell products made with low-carbon footprints—diverting, in jurisdictions with such incentives, high-carbon outputs to countries that do not assess and price the carbon content of imports (98, 102, 103). The extent to which this is a problem would vary according to the flexibility of specific markets and supply chain relationships, and also whether one views such policies purely statically or as part of an evolving system in which such consumption-based incentives are expected to spread. These issues are of limited relevance for countries without significant exports (100, 104).

Choices on benchmarked versus actual embodied emissions to calculate the adjustment matter (see Section 4.3) and bring complex implications and diverse views about the impact on compatibility with WTO principles (80). An underlying conceptual issue concerns whether varying emissions in producing a product mean that it can no longer be treated as a like product under WTO rules and, if so, how the rules or benchmarks applied to domestic producers can be replicated or mimicked for imports.

Another challenge for BCAs is whether any carbon costs have already been paid along the value chain before the product entered the country applying the BCA: If export rebates are not possible, any carbon price already paid in countries of origin would need to be taken into account to avoid a situation akin to double taxation. An additional complication arises from the cost impact of nonpricing policies, and whether—and, if so, how—to credit them.

In July 2021, the European Commission proposed gradually phasing in a Carbon Border Adjustment Mechanism (CBAM) while phasing out free allocation by 2035, focused on electricity, cement, certain fertilizers, basic iron, steel, and aluminum products. The CBAM would oblige importers to buy carbon import certificates at the same cost as EU ETS allowances, based on actual verified emissions of the imported goods in question. Evidence of carbon prices already paid abroad would result in a corresponding reduction in the number of required certificates. No export rebates are envisaged in the original proposal, although the European Parliament has signaled its preference to include them. The proposal is limited to direct (Scope 1) emissions but already requires disclosure of indirect (mainly electricity-related, Scope 2) emissions, in anticipation of potentially including them (105).

In June 2022, a bill (S.4355) was introduced into the U.S. Senate that would establish declining emission benchmarks for carbon-intensive products along with a rising carbon fee for emissions above the benchmark, applied to both domestic- and foreign-produced products [similar to what Kopp et al. (106) propose]. Domestically, in addition to products, there are also proposals addressing carbon leakage in the electricity sector, with a subnational BCA already established in the state of California (107).

Although it remains to be seen whether BCAs or other measures targeting embodied emissions to tackle carbon leakage will be challenged under WTO law, other measures targeting the emissions from production processes taking place outside of the regulating country have been challenged, as exemplified by Indonesia and Malaysia's challenges of the EU's biofuel sustainability criteria (108).

4.1.3. Carbon footprint consumption charge (and personal carbon allowances). The risk that rebating carbon costs on exported goods may violate WTO law—notwithstanding that EU exports in aggregate are cleaner than the goods they displace (see Section 2.1)—presents a substantial domestic political problem for the EU's CBAM proposal. This and some other international challenges arise from pricing emissions at source of production. Aside from free allocation and

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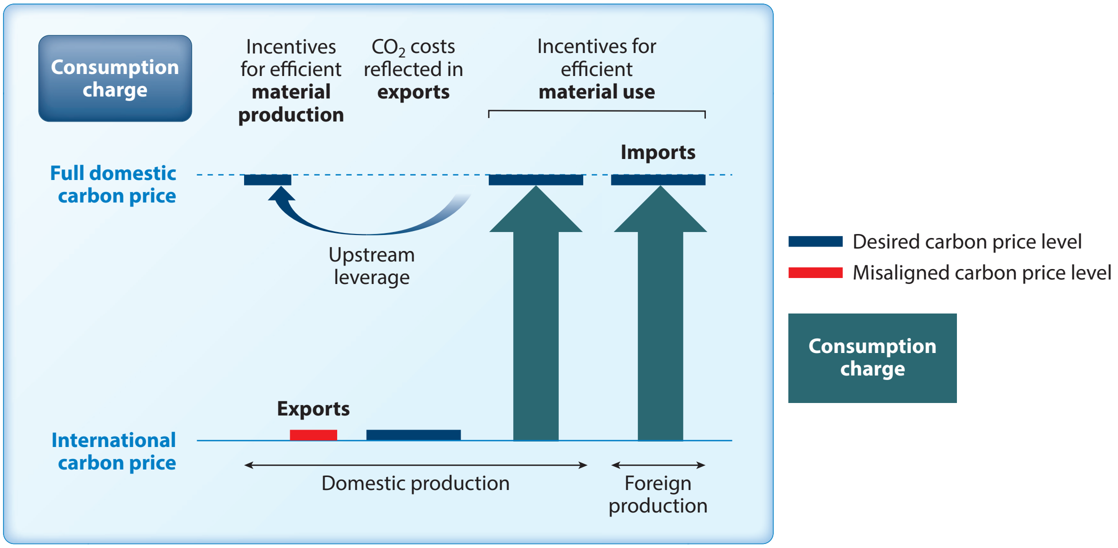

Figure 8

Consumption charge/personal allowances: incentives and misalignments: Applying a carbon embodied charge to final consumer goods, requiring verified full supply chain accounting through to consumer products, in principle creates incentives for producers (including of imported goods) to improve carbon efficiency or shift to cleaner alternatives for the domestic market, but not for exported materials or products (*red bar*).

BCAs, other options emerge if the focus moves away from purely production measures with state boundaries, to consider options at different stages of the overall supply chains.

In principle, a radical alternative could place a charge at the opposite end of supply chains, charging the consumption of emissions based on carbon footprints. Proposals for a consumption charge involve tracing emissions along the value chain, and then placing a charge at each point of consumption of the goods in question (109). Domestically and internationally produced materials and products are treated equally; hence, carbon leakage concerns are avoided (**Figure 8**).

A consumption charge based on actual emissions would have the biggest effect, transmitting the price signal through the value chain, providing incentives for efficient production in upstream and intermediate segments, and incentivizing exporting jurisdictions to shift toward low-carbon products and pathways (110). However, tracing the actual embodied emissions along global value chains for innumerable final products requires enormous administrative efforts and coordination to ensure a high level of quality while minimizing the risk of fraud (98, 103) (see Section 3). The same problems—and more—would apply to earlier proposals for personal tradeable carbon allowances, though it has been recently argued that AI may substantially ease such problems (111). Ultimately, however, challenges relating to monitoring and verification along value chains in third countries for domestic fiscal use remain. Shortcuts based on default values for different product categories might be feasible to calculate consumption charges (105, 112), but would need to be applied to imports and domestically made goods equally, to align with international trade law—so this would not resolve border-related complexities.

A consumption charge in theory seems close to an economic ideal and could generate considerable resources, but the practical and political obstacles appear formidable (6). In addition to the high administrative complexity is the observation that most final consumer decisions involve first-domain decision-making, determined by many factors other than price alone, while that carbon price would itself be highly diluted at the point of final consumption (Section 2.2). However,

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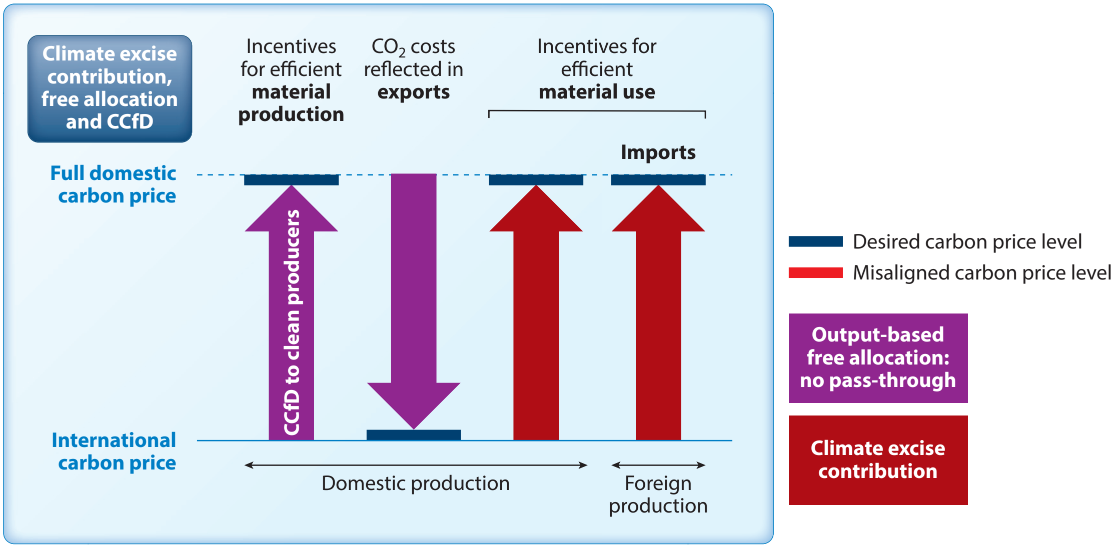

Figure 9

Climate excise contribution: incentives and misalignments. The climate excise contribution, like other excise charges, would be levied symmetrically on domestic production and imports (but not due for exported materials), creating incentives for efficient use of carbon-intensive materials and products. Combined with an ETS with free allocation (**Figure 6**), it would retain those incentives for improved production, while generating finance that could be used to support emerging low-carbon investment or other climate-related measures. Abbreviations: CCfDs, carbon contracts for difference; ETS, Emissions Trading System.

consumption charges (and, to a lesser extent, BCAs) which involve full carbon footprints also create upstream incentives on producers to minimize both carbon costs and reported embodied emissions (110).

4.1.4. A climate excise contribution complementing point-of-emissions carbon pricing. A recent proposal in Europe would apply a climate excise contribution to carbon-intensive products, most notably to materials. This would apply to both the production and import of basic materials (also as part of products) in proportion to the weight of the material (e.g., steel) multiplied by a domestic carbon price and a default emissions factor. This being applied irrespective of production process or location avoids discriminating between domestic and foreign products based on their carbon intensity and hence addresses carbon leakage while avoiding WTO concerns (113, 114) (**Figure 9**). The climate excise contribution restores the carbon price throughout the value chain and provides incentive for efficient material use, substitution, and recycling in manufacturing and construction activities as well as final consumption.

In essence, this would make it legally analogous to existing excise duties already imposed in many countries, for example on gasoline, alcohol, and tobacco—none of which, of course, exempt imported goods from paying the charges (112). Being anchored in the established legal and customs basis of other excise duties, it could piggyback on existing legal and administrative infrastructure. Using a default emission factor irrespective of the production process simplifies implementation. Cleaner producers nonetheless benefit from revenues being recycled back to fund the incremental costs of climate-neutral production domestically.[6]

[6]The general principles of excise duties would imply applying the charge equally to clean or dirty products in the same materials category (115). The use of revenues would thus be important to support novel production

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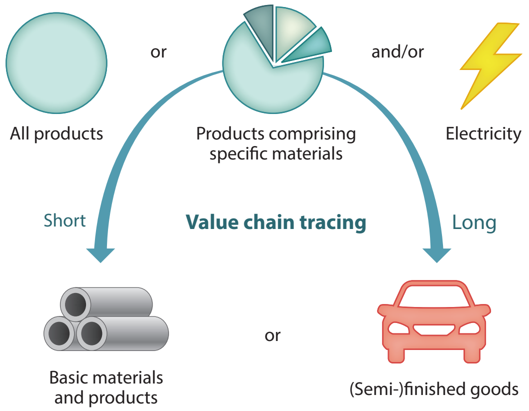

Figure 10

Variations in the scope of measures targeting carbon leakage.

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While a climate excise contribution could be levied as standalone, it would be most effective as a measure to restore the carbon price downstream in combination with carbon pricing upstream (83, 116). Specifically, implementing the contribution jointly with a benchmarked output-based allocation in an ETS ensures incentives for cleaner production, (83, 116) while avoiding export leakage (**Figure 9**). The free allocation in this setting avoids double charging from the upstream pricing and climate excise contribution, and thus provides an economic and WTO-consistent basis for the free allocation. The revenues from the climate excise contribution can be earmarked for upstream support of decarbonization, for example with CCfDs for clean production (117). While this combination simultaneously provides effective incentives for a domestic transition to climate neutrality and avoids carbon leakage risks, it does not directly influence production or policy decisions beyond the border like the traditional BCA approach: It neither penalizes dirty nor rewards clean production abroad. Moreover, it would not incentivize third countries to implement carbon pricing. The climate excise contribution approach thus lends itself to cooperative approaches to international climate governance, offering a policy example but not requiring early coordination on carbon pricing levels to address carbon leakage risks. Thus, cooperation can focus on other instruments (sustainable finance, labeling, product standards, cooperative innovation). Some of the revenue could be used to support an inclusive transition to carbon neutrality in developing countries (Section 5).

4.1.5. Overview of three carbon-pricing options. These three broad approaches to tackle carbon leakage via pricing mechanisms vary in potential scope (**Figure 10**), and the key components and points of incidence in supply chains (**Figure 11**). They also involve different trade-offs in terms of administrative complexity, possible ambiguities in relation to international trade law, equity aspects, and overall environmental effectiveness, all of which also can affect political feasibility. **Table 1** indicates some of the relevant characteristics that affect impact and political feasibility.

Finally, one key question, which in part spans all approaches but also differentiates them, concerns the extent to which they can rely on default benchmark values or require data on actual carbon footprints of individual goods, in order to be effective or comply with international law

methods. In the EU, individual Member States (e.g., France, Germany, and the Netherlands) as well as the European Commission are planning to fund incremental costs of climate-neutral production processes with so-called carbon contracts for difference (CCfDs) (see next section).

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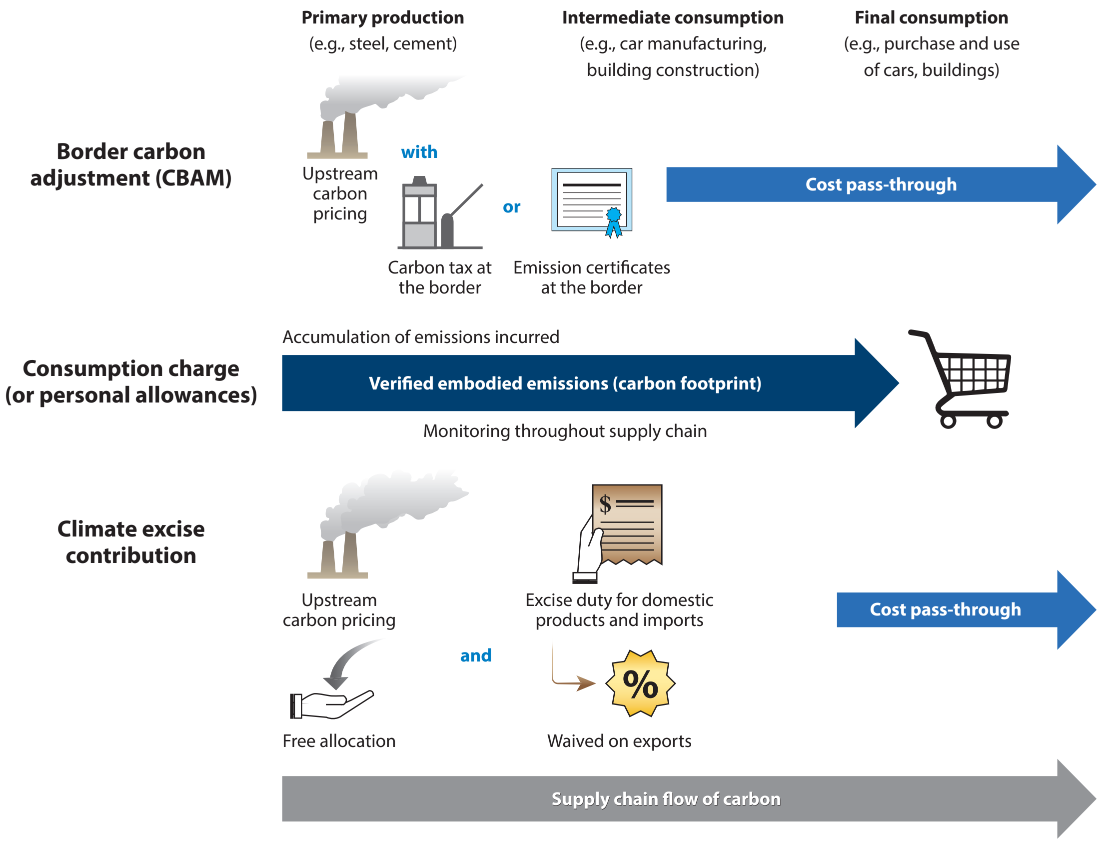

Figure 11

Key components and points of incidence in the supply chain of three prominent proposals for addressing carbon leakage via pricing mechanisms. Abbreviation: CBAM, Carbon Border Adjustment Mechanism.

or to be considered equitable, acceptable, and feasible. We return to this question in Section 4.3 after discussing nonprice instruments, for which some similar questions arise.

4.2. Complementary Policies for Industrial Transition

Embodied carbon standards, green public procurement, and green subsidies can ideally complement carbon pricing instruments, but can also be adopted in lieu of them, in order to drive the net zero industrial transition. In the following, we discuss each of these complementary policies.

4.2.1. Embodied carbon standards. A modest but growing literature examines instruments beyond market-based carbon prices, which can contribute to low-carbon solutions and innovation, particularly from materials production and consumption, while addressing concerns about carbon leakage.

Product standards on intermediate or final goods can focus on a variety of objectives including the carbon efficiency of materials, the life cycle emissions of final products, and the recyclability of products. First, standards on the embodied emissions in basic materials can take the shape of minimum performance standards for materials sourced from production processes, excluding those exceeding a certain carbon intensity threshold (118). Such standards could help accelerate the phasing out of the most inefficient, polluting plants such as, for example, inefficient wet kilns

Table 1 Key characteristics of three different pricing approaches addressing carbon consumption and leakage concerns

	Border carbon adjustment	Carbon consumption charge	Climate excise contribution
Point of application	Direct emissions and point of import	Final consumption	Production and import
Relation to upstream carbon pricing	Complement (to a carbon tax, or ETS with auctioning)	Alternative	Complement (e.g., to carbon tax or ETS with free allocation)
Requires phasing out of free allocation	Yes	Yes	No
Carbon leakage risks	Remains if coverage of value chain limited, and export leakage not covered	No	No
Incentives for exporters to mitigate carbon emissions	Yes, if export rebate not possible	No	Yes, if complementary to an upstream cleaner production incentive (e.g., ETS with free allocation)
Resource shuffling concerns	Yes, as use of default values would be limited	Yes, as long as not entirely reliant on default values (which would not seem desirable)	Not as long as limited to the use of default values

Abbreviation: ETS, Emissions Trading System.

for cement clinker production. In sectors with less clear technology differentiation, it will be more difficult to define, apply, and monitor suitable standards.

Second, governments can set standards mandating outright maximum limits for embodied or overall life cycle emissions of final products, such as buildings or cars. Finland, France, the Netherlands, and Sweden have all adopted or announced such policies for buildings; the Dutch policy goes beyond carbon and comprises an environmental LCA for 11 impact categories, including embodied carbon.[7] In their footsteps, the European Commission is seeking to revise the EU's Energy Performance of Buildings Directive to begin introducing mandatory calculation and disclosure of full life cycle carbon emissions for all new buildings in the EU by 2027 (130).

Carbon-intensity standards for different kinds of intermediate or final industrial products can provide incentives for the adoption of carbon labels in the form of PCFs and EPDs, which would help to prepare industry to have the data ready to comply with BCAs (74); they may also offer an alternative to BCAs, applied at the point of putting a product on the market, rather than at the border. Carbon intensity standards for intermediate products are likely to partially duplicate the

[7] In 2018, the Dutch government introduced such a policy for all new homes and offices over 100 m^2 (119–121). France and Finland have announced similar policies, starting in 2022 and 2025, respectively, with mandatory life cycle calculations preparing the way for the eventual introduction of emissions reduction targets (122–125). As of January 1, 2022, Sweden requires developers to measure and declare embodied emissions; limit values for the climate impact may be introduced later (8). In 2021, Denmark introduced targets for whole life carbon in buildings 1,000 m^2 to limit emissions to 12 kg CO_2e/m^2/year, with a tightening of limit values every other year until 2029 (4, 126). The Dutch policy on environmental LCA requires impact assessment for 11 impact categories, including embodied carbon, with each impact category converted into a currency value. The cap for overall environmental life cycle impacts is set at €1/m^2/year (75 years for residential, 50 for offices), with embodied carbon weighted at €50/tCO_2e (127–129).

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incentives under emissions trading systems, but in lieu of BCAs, they could partially address carbon leakage concerns. Such standards could also help to induce more robust carbon certification and verification regimes, and where there is no carbon pricing scheme, such as at the federal level in the United States, embodied carbon standards could be a standalone measure for mitigation without carbon leakage. Finally, carbon intensity standards could complement BCAs by setting stronger incentives than a carbon price in selected sectors or product categories. Targeted subsidies and standards have a track record of creating lead product markets by supporting innovation and the emergence of new industries (47).

Rather than setting maximum carbon intensity standards, one could use embodied or whole life cycle emissions to define thresholds as a basis for specifying different taxation classes, analogous to the way many countries already use operational CO_2 emissions intensity to determine vehicle tax rates (131–134). In this instance, standard-setting and pricing instruments overlap. In all these instances, such product standards would not only steer domestic construction and manufacturing industry toward low-carbon or climate-neutral products and processes but also create incentives for emissions reductions in industries abroad that wish to sell into this market.

Standards within a product class primarily induce substitution between different products within that class. It can also foster more transformative, interproduct substitution—a feature usually more associated with a carbon price. For example, if only green steel was permitted but it was highly expensive, demand for reinforced-timber construction would rise.

Intermediate and final product standards could be combined to eliminate the most polluting products within a category from the market and, at the same time, incentivize the innovative substitution between intermediate products at the level of final products, such as buildings or vehicles (135)—a combination that could induce more radical innovation.

Product standards also share the advantageous property with excise levies that they can be adopted at smaller governmental levels "behind the border," without necessarily needing coordination with higher governmental levels. By contrast, the introduction of BCAs would need to be aligned at the level at which trade policy is decided.

4.2.2. Green public procurement. GPP uses state purchasing power to boost market demand for products with low embodied or whole life cycle emissions. As government procurement is responsible for large shares of infrastructure investment, buildings, and industrial goods, it can be used to deliver the objectives of typical demand-side policies. This can create early niches with the potential to develop into lead markets (136) and early signals for broader policy agendas. It can also help to prepare regulatory or fiscal action by already discerning among more or less carbon intensive products, thus helping to create demand for information on embodied or whole life cycle emissions.

GPP may focus on intermediate or downstream products. The Buy Clean California Act approved in October 2017 is an example. Partly to help ameliorate concerns about carbon leakage from the Californian ETS, it requires that the state only procures building materials below specified global warming potential (GWP) levels, verified by means of EPDs (60) (Section 3), an example subsequently followed by the State of Colorado.[8] As of 2022, the Biden administration is exploring the adoption of the approach at the US federal level (141).

[8]Throughout 2021, the maximum acceptable GWP limits in California were established and the awarding authorities started to refer to EPDs to gauge the GWP compliance of relevant materials (137). The State of Colorado (138) adopted its own Buy Clean legislation, House Bill 21–1303, *Concerning Measures to Limit the Global Warming Potential for Certain Materials Used in Public Projects, and*, *in Connection Therewith*, *Making an Appropriation* (139, 140).

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GPP can also focus on final downstream products, such as buildings. For example, in Germany and Switzerland governments use sustainable building rating systems or carbon performance targets to incorporate LCAs into their procurement criteria (119, 136).

4.2.3. Subsidies. Unlike in electricity, zero-carbon technologies for materials and many basic chemical processes are not yet commercially viable. Due to the enormous costs involved in the development and upscaling of carbon-neutral material alternatives, such as green hydrogen steel, incrementally rising but relatively low carbon prices by themselves do not provide sufficient incentives, or confidence, for their development. Standards banning carbon-intensive products or those that are not carbon neutral are ideally introduced once a sufficient volume of preferred products is on the marketplace.

Therefore, subsidies—for both production and lead markets—play a crucial role in the development of niche and early lead markets, akin to the development of solar and wind energy industries. Such subsidies can also have important links with pricing instruments. Examples include the set-aside provisions in the EU ETS, a prime source of funding for low-carbon industrial innovation, and growing attention to CCfDs, which guarantee a value for the carbon savings from low-carbon industrial projects, relative to an assumed carbon price on incumbent, high-carbon producers (142). To ensure compatibility with the WTO ASCM, payments should be limited to incremental costs—the additional cost associated with the low-carbon technology (114).

4.3. Conclusions: Implementation Options and Interactions in Open Economies

As indicated in Section 2.3, policies need to not only target the carbon intensity of production (including through recycling) but also stimulate demand shifts toward cleaner primary commodities, and/or final consumption. As shown, both price and nonprice policies can address both these dimensions. Nonprice instruments such as carbon intensity product standards can serve several functions in relation to pricing instruments in open economies: As shown, they could be adopted in preparation for the eventual phasing in of BCAs, in lieu of BCAs, or as a complement to BCAs. In concluding, we consider two cross-cutting dimensions.

First, complementarities. The complexity of carbon pricing in relation to trade and leakage concerns is one reason for policy mixes including regulatory instruments. But an underlying challenge is that the intellectual foundations of both carbon pricing and trade law rest in classical, second-domain theories of economics and comparative advantage, whereas deep decarbonization inevitably involves third-domain processes of innovation and transition, which are dynamic and necessarily involve public investment and technology direction, often supporting niches for emerging clean technologies. The latest IPCC report underlined not only the general need for policy packages (48) but, more specifically, the complementary roles of different instruments in the course of transitions, often with the upfront need for significant strategic investment, and appropriate standards, to support the emergence of new technologies at scale (48) in order to combine technology push and demand pull.

Specifically, subsidies to novel cleaner production can be complemented by early lead markets through GPP, standards, and also private consumer choices. The latter can be informed by product labeling and carbon footprint tracing as explored in Section 3, which details how business associations and individual companies have already developed information systems on product and corporate footprints, before any government policies have required those (60, 64). The availability of such product information offers an established blueprint for government policies to draw on and thereby increase the technical feasibility of measures targeted at the emissions embodied in products.

Indeed, there are important public-private interactions that may foster both financial incentives and strategic guidance for cleaner products, building and infrastructure design. As new technology options are built up, various forms of carbon-related standards on materials and products could start to bring these to scale and displace existing high-carbon technologies from the market. The need to combine price and nonprice measures, and the unambiguous reality that different jurisdictions differ enormously in their approach (or political capacity) to implement carbon pricing, underlines the value of considering the three different broad approaches to carbon pricing in the international context, as well as their potential interactions with nonprice measures.

Second, several aspects of choices around benchmarks versus full chain carbon footprinting can—theoretically at least—apply across a range of price and complementary policy options. Three options can be considered:

1. Fixed benchmarks, with economic incentive or regulation applied to the assumed average emissions intensity of given materials or other product categories.
2. Full chain carbon footprint accounting, applied instead to the actual measured and reported emissions incurred in making specific materials/products.
3. Default benchmarks with derogations for verified embodied emissions, in which a benchmark is assumed as default, but with the economic incentive or regulation adapted to reflect actual embodied emissions if the supplying companies can demonstrate these were lower than the benchmark.

A BCA that is exclusively based on fixed benchmark values (option 1, above), and does not allow importers to challenge the default by demonstrating superior carbon efficiency (option 3), would probably violate WTO principles by treating some imported products less favorably than domestically produced products (143). This is unlikely to be an issue for consumption charges, which requires option 2, or a climate excise contribution if using fixed values (option 1) for all like products, e.g., steel. The latter sacrifices incentives for improved production within a product or material category, unless complemented by an upstream incentive system (e.g., ETS) or equivalent standards (**Table 2**).

Table 2 Summary issues on use of benchmark emission intensities versus actual embodied emission values

	Fixed benchmark values (e.g., assumed GHG per tonne of steel)	Actual footprint values (i.e., verified embodied emissions for all products)	Default benchmark values with derogations if verified embodied emissions presented
Incentives to shift production of specific materials toward low-carbon or climate-neutral processes	No	Yes, all production	Yes, to improve market access for production that is cleaner than the default
Incentives for shuffling high- and low-carbon sets within classes of materials	No	Yes	Yes, cleaner production targeted at specific markets
Administrative effort for tracing	Low	High	Restricted to cleaner production applying for derogations
WTO compatibility	Low, if coupled with a carbon tax or ETS	High, if coupled with an equivalent carbon tax or ETS	High, especially if benchmark reflects high ambition

Abbreviations: ETS, European Union Emissions Trading System; GHG, greenhouse gas; WTO, World Trade Organization.

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Conversely, the use of actual embodied emission values would have the biggest effect but is an enormous administrative challenge. It would most plausibly build on existing efforts to standardize product carbon footprinting (e.g., PCFs and EPDs as discussed in Section 3), but the quality of the procedures of the relevant certification agencies would need to significantly improve if they were to become a solid foundation for transnational carbon pricing. Using actual embodied emissions could prompt resource shuffling (Section 4.1.2).

Finally, and consistent with technical findings a decade earlier (86), important political economy arguments have recently emerged for taking a sector-by-sector approach rather than trying to treat all of industry in the same way (144), which risks a lowest-common-denominator outcome. Until there are clear and significant green technology options commercially available at sufficient scale in material sectors, a blunt instrument like an excise charge would be most convenient. Once zero-carbon products become available at scale, such as green hydrogen steel, public procurement could start to exclusively procure such products, eventually leading up to embodied carbon standards that phase out all nonclean products in a specific category.

5. DISTRIBUTIONAL AND EQUITY IMPLICATIONS AND OPTIONS

The challenge of tackling embodied emissions in trade is confronted with various temporal and spatial inequities (see Section 2.3) (14, 25, 145–150). Among the range of climate-related policies, BCAs and others relating to trade have turned out to be one of the most controversial, owing among other things to their international equity and distributional implications.

5.1. Equity Concerns Related to Border Carbon Adjustments

Calls for BCAs are not new. The first such calls in industrialized countries can be traced back to concerns about the lack of comparable climate commitments in developing countries and US withdrawal from the Kyoto Protocol (151). The US Waxman-Markey bill, which sought to introduce federal carbon pricing, included clauses that would have allowed the United States, after a grace period, to take trade measures against other countries if they were evaluated as not having taken "comparable action." In other words, it left the question of which countries have assumed their fair share up to US decision-makers, which is highly problematic in relation to basic WTO principles (80), as well as in light of the UNFCCC principles on common but differentiated responsibilities and respective capabilities (80). The sentiment that rich countries might decide on what constituted comparable action fed fears for years after that BCAs could or would be used as discriminatory instruments of leverage and blurred the discourse even on nondiscriminatory measures.

Since then, BCAs have been periodically discussed and deliberated in both policy and academic circles (152). In terms of the focus of this article, and the three carbon-price-related options considered in Section 4, the equity concerns arise in three main forms.

The first is contextual, reflecting particularly issues around historical responsibility and intergenerational equity. The argument is that BCAs and related measures are agnostic of the historical disadvantages and vulnerabilities that developing countries—and in particular least developed countries—face from adverse climate impacts. These impacts are largely triggered by the growth in stock of cumulative GHG emissions due to the process of industrialization and fossil fuel–driven growth in developed countries. It is hard to envisage what practical measures could apply directly to past emissions, but the undercurrent of historical inequity is a major factor in some countries' fundamental opposition to BCAs, almost irrespective of WTO compatibility or detailed design.

Second are the practical impacts (consequential). If designed and implemented appropriately, BCAs could strengthen the environmental effectiveness of domestic measures (153), but as

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a consequence they would reduce consumption (and corresponding emissions) of imported energy-intensive products (154, 155) and potentially extend incentives to give preference to lower-carbon imports. Many studies indicate that such BCAs would shift the economic consequences of emission reduction from abating industrialized countries to nonabating countries (93, 156–160). However, it is not easy to disentangle how much of this is due to the inevitable impact of reducing carbon-intensive activities, as opposed to the impact of BCAs on specific trade flows, and it does depend on where the revenues go.

In general, the modeling literature using computable general equilibrium models predicts that BCAs reduce trade-related income to energy-intensive exporting countries in particular and developing countries as a whole, alongside global emission reductions (51). To the extent that trade shifts from more to less carbon-intensive exports (and countries), assuming this also means from developing to developed countries, the trade terms of already disadvantaged countries would potentially worsen. Several studies pertaining to the EU's CBAM proposal (161–163) have found that energy-intensive exporters, especially Russia and China, are likely to be adversely impacted (159).[9]

Of course, the net economic effects of charges on embodied carbon flows also depend on who receives the revenues. The same models show that carbon-intensive exporters overall could gain if they implemented an export charge themselves, instead of it being levied by importing countries. However, exporting countries face an obvious coordination challenge: not wanting to risk losing export volumes to competing exporters. The literature has yet to consider whether and how the apparently declining gap between developed country production and consumption footprints noted in Section 2.1 may affect this, especially insofar as it reflects converging emission intensities.

Finally, a concern in the context of the potential distributional implications of BCAs is that of green protectionism (161, 164). This debate has revolved around allegations that industrialized countries have on occasion invoked environmental policy measures as a means of limiting imports from developing countries (51, 80).

5.2. Distributional Aspects of Alternative Options

Against the background of the numerous concerns about BCAs, as traditionally conceived, it is useful to consider the distributional aspects of the other carbon pricing approaches outlined in Section 4. To the extent that free allocation of emission allowances to domestic emitters has less trade impact than BCAs, the trade and livelihood impacts on exporting countries (e.g., developing and the least developed countries) would be less (80, 162). In that respect, free allocation could be regarded as more economically benign than BCAs, but it has severe downsides, as discussed in Section 4.1, such as undermining environmental incentives along the value chain, generating windfall profits, and forgoing auction revenue.

Direct consumption charges would be inherently nondiscriminatory since domestic products and imports are treated symmetrically. The equity and distributional implications would still depend on their impact on imports from developing and least developed countries. As with other measures, this would depend on the strength of application (price)—the more it reduces consumption of carbon-intensive products in the implementing jurisdiction, the greater the likely impact on trade partners as well (163), along with potential economic and livelihood implications.

The climate excise duty, as with other excise duties, would be nondiscriminatory between domestically produced goods vis-à-vis imports, as the same duty would apply on a particular material,

[9]UNCTAD identifies the top seven countries whose exports to the EU are likely to be affected by CBAM as Russia, China, Turkey, the United Kingdom, Ukraine, Korea, and India.

irrespective of origin or production process. The main potential difficulty would be if multiple jurisdictions were pricing carbon in different ways, and some imported materials had already paid a carbon price that was not faced by domestic producers. This, effectively double taxation, would be affecting the relative competitiveness of imports vis-à-vis domestically produced materials. However, this has more to do with the level of free allocation, compared to other jurisdictions, rather than the excise duty itself.

Key determinants of distributional impacts would concern the incidence of costs and distribution of revenues. Aside from the (difficult) possibility of exporters themselves implementing emissions charging (so collecting the revenues directly), in principle all three options involve importers raising revenues, but the institutional and political characteristics differ. A "standard" BCA would involve revenue collection at the border, the revenues from which could potentially be a point of negotiation. Consumption charges might raise the most revenue if all emissions consumption were charged, with the richest consumers (higher emitters) paying the most, but the revenues would presumably be paid directly into Treasuries as part of tax collection, complicating any redistributional discussion. A climate excise contribution by design includes use of the revenue for promoting climate-neutral production, which might more overtly raise the question of whether such revenue should be recycled not only to the implementing jurisdiction but extended internationally—to affected trade partners, or to the most needy and vulnerable.

5.3. Sovereignty, Procedural, and Capacity Dimensions

Finally, beyond purely economic concerns, other dimensions are raised particularly by critical design choices between full-chain carbon accounting, pure benchmarks based on average carbon intensity, and potential default values. As discussed in Section 4.3, measures to target embodied emissions clearly could be more environmentally effective (in reducing embodied as well as national emissions) if they reflect actual carbon emissions through the supply chain. The ethical underpinning would be that the consumers take responsibility for their full carbon footprint, and pay for it. Conversely, however, this takes little account of differing energy, environmental, and political circumstances that influence the mitigation capacity and capabilities (165). Mitigation efforts are largely fragmented and vary not only in terms of the coverage but also with wide disparity across nations (166). Charging for full supply chain emissions not only involves an administrative burden to track emissions through supply chains but also carries an extraterritorial dimension that could be construed as interfering with other countries' national sovereignty, over and above the commitments that countries make voluntarily under the Paris Agreement.

Conversely, the idea of pure benchmarks, as exemplified in the climate excise contribution, treats imported and domestic products symmetrically in terms of not only geography but also production process for a given product (e.g., steel)—not seeking to either charge or reward on the basis of the emissions associated with how a given product is made. As noted in Section 4.3, an intermediate stance could be to allow derogations for importers who demonstrate that the carbon footprint of their imported material or product is less than presumed default values. However, the burden of such demonstration ultimately falls on the exporters, which may be easier for organized and registered large business entities compared to small or medium-sized enterprises in a developing country (143).

When introducing measures addressing emissions embodied in trade, it is important to consider the different circumstances of countries, in particular developing countries. From the perspective of the international climate regime, this would be in line with the principle of common but differentiated responsibilities and respective capabilities. For WTO compatibility, moreover, any measure to address embodied emissions should be applied with sufficient flexibility to take into account the conditions prevailing in exporting jurisdictions (162).

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For instance, some developing countries may find it challenging to introduce mechanisms like an ETS or carbon tax because of political or institutional constraints. However, they may be well positioned to adopt other policies and programs that have clear climate and sustainability benefits and are also befitting for their local circumstances and political realities. Hence, allowing for policy flexibility to these countries may provide room to them for maneuvering within their unique constraints. Such flexibilities may also help in encouraging innovation, increase transparency and trust, and spur competition between jurisdictions so that the effectiveness and equity concerns could both be addressed (165).

Climate action in many developing countries, and particularly in the least developed countries, is constrained by availability of funds and appropriate technology at affordable prices. Existing multilateral efforts toward ensuring financial and technology support have been far from adequate (161). In this context, introducing BCAs will be perceived as unfair by developing countries. To help address such concerns, BCAs should go hand-in-hand with strengthened financial, technology transfer and capacity building support for such countries, based on an ethic of shared responsibility between producers and consumers for embodied emissions (167). Alternatively, the revenues could flow to the Green Climate Fund for further distribution. However, operationalization of any such revenue recycling system may be complex, and the political will may be lacking, as seen in the EU's CBAM which has proposed utilization of the revenue for domestic public finance purposes alone (110). The ultimate dilemma is that while the distributional consequences of BCAs and related measures are seen by many developing countries as inequitable, so too would be the consequence of continuing to largely exempt energy-intensive industries from effective mitigation measures.

6. CONCLUSIONS: MISSING PIECES IN A COMPLEX PUZZLE?

From its initial forays some 20 years ago, the literature on carbon consumption, leakage, and trade has mushroomed. Developments in MRIO models and comparative studies between the major databases indicate that at national level, trade data are not the major source of uncertainty in embodied emissions, but there are important definitional issues particularly around accounting exports and investment. Notwithstanding these, it is established that aggregate North–South outsourcing of emissions associated with globalization peaked around the mid-2000s and has declined substantially since then, largely reflecting some convergence in carbon intensity between regions (Section 2).

Along with globalization, private sector initiatives have become widespread, with well-developed if still sometimes contested presentation of carbon footprint data for consumer products and environmental performance declarations in supply chains (Section 3). Public policy, by contrast, has made little progress, with limited government interest in consumption-based accounting and carbon pricing almost universally still accompanied by exemptions or free allocations for exposed (EITE) sectors to forestall fear of carbon leakage, which leaves the empirical findings of minimal leakage ambiguous. This review has illustrated a very rich academic literature covering the technical data, modeling, economic and trade law dimensions of carbon consumption and carbon leakage, and associated policy dimensions, which point to numerous issues and options including relatively new proposals and variants (Section 4).

The contrast between all this analysis and the negligible progress in adopted policies is glaring, perhaps in part because of limited engagement with international equity concerns (Section 5). The extensive technical literatures also contrast with relatively sparse literatures in the arenas of politics, practical modes of international cooperation, and deeper examination of ethical underpinnings of policies and WTO principles, as they relate to the practical problems of tackling GHG emissions from internationally traded goods. There is also very little connection between the literatures on private measures (Section 3) and public policies (Section 4). We conclude by touching briefly on each of these areas in turn.

6.1. The Politics of Extraterritorial Incentives

Irrespective of whether measures respect WTO principles, actions that are deemed by other nations to be seriously inequitable and/or infringe on their sovereignty, for example by targeting the emissions from processes and production methods that take place in other countries, may lead to retaliation (168–170). Thus, there were strong reactions to the EU's attempt to extend its ETS to include emissions from international aviation to all flights in and out of the EU's airspace—which by implication had an extraterritorial dimension. Widespread opposition included the canceling of aircraft orders by China and prohibitions to fly over Russian airspace, ultimately forcing the EU to retreat (171). Likewise, the first reactions to the EU's CBAM proposals have included suggestions for (trade) retaliation (172).

In itself, adverse reactions do not negate the case for some such efforts: Indeed, although the EU aviation legislation itself caused diplomatic ructions and ultimately was suspended, the pressure it generated likely prompted governments to finally take action on international aviation emissions, resulting—some two decades after the Kyoto Protocol indicated a central role for the International Civil Aviation Organization (ICAO)—in the commitment to cap net aviation emissions, implemented through an emissions offsetting system, with 111 countries now participating (see **https://perma.cc/6FZQ-BTX2**).

A key challenge for industrial emissions is that unlike aviation, there are no appropriate international institutions that could play a role akin to ICAO for aviation. Nevertheless, one obvious implication is that when tackling emissions associated with energy-intensive, traded goods, major initiatives like the EU's CBAM should from the outset consider international diplomacy. Ultimately, there is a common challenge of how to decarbonize key sectors in ways consistent with the agreed goals and normative standards of the Paris Agreement, including international equity concerns (Section 5), and hence seeking to contribute to both domestic and global climate objectives, including technology and policy learning and potentially use of revenues.

6.2. On Clubs and Multijurisdictional Cooperation

Yet, what are the options should all the main approaches summarized in Section 4 still prove impossible to implement unilaterally, due to the combination of internal resistance and international reactions that overwhelm the initiatives of any single jurisdiction? A global agreement on common carbon pricing is evidently impossible, and even "dual track" approaches proposed for carbon pricing and convergence (173) seem "doomed to fail" (174). Amplified by enduring geopolitical realities (see, e.g., 175), even global regulatory standards for embodied carbon face huge obstacles, leading researchers to turn increasingly to ideas of smaller groups of countries collaborating to drive policy forward.

One approach reflects the dominant economic framing around the centrality of pricing and burden-sharing, emphasizing common carbon pricing among club members, with clear rules, and economic deterrence to free-riding by nonmembers (176–179). In game-theoretical terms, the associated trade measures would be sanctions, in the absence of which there is no hope of avoiding free-riding in global climate politics (52, 176). Retaliation would be likely (178); however, other analyses conclude that BCAs with open membership can lead to economically stable agreements and incentives ultimately to global participation (180–182).

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A carbon pricing club was the broad original conception behind Germany's efforts to promote such approaches in its G7 Presidency of 2022, building on the EU's CBAM proposals and hoping to extend the same principles with others. In the event, this potentially did more to show the limitations, not least stemming from the mismatch between geopolitics and climate policy: The idea of building a carbon pricing club from the G7, when two of its most powerful members (the United States and Japan) have consistently proved incapable of implementing any effective price domestically, was always fanciful. Attempts to meet the domestic needs of those countries in terms of some kind of equivalence measure only served to complicate further the notion of a prespecified club of countries committed to comparable, economy-wide action.

The other approach on cooperation emphasizes potential for positive gains from membership, not through external sanctions but from the benefits of internal cooperation, in more focused ways: for example, from harmonizing rules for linking emissions trading systems, or a focus on coordinated measures to accelerate beneficial innovations, and build profitable markets for them, among the participating countries. This approach naturally tends to a more evolutionary and "building blocks" process (183), perhaps with a range of "multijurisdictional cooperative arrangements" (184) on a sector-by-sector basis.

Overall, a patchwork of consumption-based policies would be in line with a polycentric approach to climate change (185). Policies targeting embodied emissions can support the transition away from high-carbon goods, even in a patchwork of dynamically developing polycentric initiatives rather than in a fixed club. Future research could extend theorizations on clubs to sets of diverse jurisdictions with unstable mutual recognitions of their mitigation efforts. One obvious initial route would include collaboration on at least informational and institutional measures enabling policies that target embodied emissions (175). In terms of regulatory measures that might be associated with extension from normative goals to so-called bargaining clubs, the absence and deprioritization of carbon pricing at the US federal level (186) provides a particularly strong rationale for focusing more on the potential of excise taxes and product standards for embodied carbon, perhaps at the state rather than federal level in some countries.

6.3. Ethical Underpinnings and World Trade Organization Constraints

To a large degree, the literature on policies to tackle embodied carbon seems to be divided between theoretical economic and modeling approaches which simply ignore the established principles of international trade law on the one hand, and the more legally oriented literatures which seek to interpret and apply WTO rules on the other. The latter still explore major distinctions between possibilities for climate change actions to gain legal exemptions under GATT Article XX, compared to the design of policies intended to be consistent with the two founding nondiscrimination principles of national treatment and most-favored nation treatment.

However, trade law was never developed with a problem like climate change in mind, most obviously with respect to the global nature of impacts from emissions anywhere, but also, concerning the need for government-led investment in low-carbon solutions, as partly a global public good. The three different approaches to carbon pricing for embodied emissions surveyed in Section 4 do illustrate some important resulting constraints. The two most obvious are that reimbursing for carbon costs incurred during production upon export raises WTO concerns, while the requirement for national treatment may constrain the choice between the use of fixed benchmarks and actual embodied emissions, whether in pricing or in standards. While full export rebates for embodied emissions would create a risk of reshuffling the dirtiest production for export, the TCBA accounting debate (Section 2) does highlight the reality that exported goods produced in ways cleaner than the global average do contribute to global emission reductions. Banning export

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rebates even for such goods is thus environmentally questionable, and especially so if it renders politically impossible any CBAM with full carbon costs that make EITE exports uncompetitive.

Similarly, efforts to tackle embodied emissions could face a catch-22 if a jurisdiction like the EU employs a system of domestic emissions control based on actual embodied emissions (i.e., the EU ETS), in the event that trade law suggests applying the same rigor to imported goods—which could then impose an unreasonable administrative burden on foreign producers exporting into Europe (Section 5). Simpler benchmarks, as fixed charges, e.g., per tonne of steel, could face challenges as a border measure and would be most familiar and uncontroversial as a form of excise duties applied to all similar products used domestically—which would lose direct incentive for clean production, unless implemented in concert with an upstream ETS.

Ultimately, therefore, aspects of trade law may need to be reviewed to cope with the new realities of climate change, especially if, in addition, getting anywhere close to net zero requires extensive government-led innovation and investment, which—as with the disputes over photovoltaics trade and tariffs—could easily be held to fall foul of the ASCM. The latest IPCC report (48) acknowledges debate on various options vis-à-vis WTO, proposed "to minimise conflicts, and strengthen the role of trade agreements in climate action . . .."[10]

6.4. Complementary Roles of Public and Private Actors

There seems little literature on the potential relationship between public and private actions on embodied carbon flows, despite experience gained from decades of corporate and consumer activity, for example in organic food, fair trade, and sustainable forestry, and the obvious complementarity of public and private action. Governments necessarily bring a nation-state perspective; many companies have a global perspective. Governments like to emphasize sovereignty; many companies press them to harmonize regulations, to reduce trade frictions. Perhaps most centrally, governments generally try to respect WTO laws to present the trade system descending into tit-for-tat anarchy; but consumers have a clear right to decide what they do and do not want to buy, and to demand the information with which to do so. Although governments worry and argue about the complexity and burden of providing full PCF information, the private sector is continuing to improve the basis for doing so (Section 3). And while for multiple reasons governments might have to use benchmark averages for charging or setting embodied emission standards on traded goods, consumers—including, indeed, government or city procurement—could demand full reporting of embodied emissions for the products they buy.

Finally, concerning the deep innovation required for global low-carbon transitions, the roles of government, industry, and consumers are deeply intertwined, and in general they share a common interest in opening up markets for emerging low-carbon products. Thus, the Breakthrough Agendas at COP26, endorsed by 36 states, comprised sector-specific collaborations in clean power, transport, steel, and hydrogen. Each of these spanned a diversity of key actors and international initiatives to establish goals, processes, and checkpoints for low-carbon transformation of these sectors, which for steel and hydrogen at least must necessarily include consideration of embodied

[10]The report notes options "including: (1) the amendment of WTO agreements to accommodate climate action; (2) the adoption of a 'climate waiver' that temporarily relieves WTO members from their obligations; (3) a 'peace clause' through which members commit to refraining from challenging each other's measures; (4) an 'authoritative interpretation' by WTO members of ambiguous WTO provisions; (5) improved transparency of the climate impacts of trade measures; (6) the inclusion of climate expertise in WTO disputes; and (7) intensified institutional coordination between the WTO and UNFCCC [. . .]. In addition, issue-specific suggestions have been put forward, such as reinstating an exception for environmentally motivated subsidies under the ASCM [. . .]" (48, chapter 14, p. 74, and references therein).

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emissions, and the international development of markets for materials and molecules (e.g., hydrogen, ammonia) made in low-carbon ways (see **https://perma.cc/UV49-JHJ6**). Many such issues are relatively new in the UN arena but may help to foster ways forward for a field in which the technical analysis has, to date, run so far ahead of implemented actions.

SUMMARY POINTS

1. Net zero emissions cannot possibly be achieved while exempting the biggest emitting sectors, namely emissions-intensive industry, but the fear of policy-driven carbon leakage—companies moving emissions-intensive operations abroad to escape regulation—impedes many, perhaps most, mitigation policy options for emissions-intensive, trade-exposed production, given the perceived risk of these shifting to jurisdictions with weaker climate policies.
2. Aggregate North–South outsourcing of emissions associated with globalization peaked around the mid-2000s and has declined substantially since then, largely reflecting some convergence in carbon intensity between regions.
3. While the distributional consequences of measures targeting emissions embodied in trade are seen by many developing countries as inequitable, so too would be the consequence of continuing to largely exempt energy-intensive industries from effective mitigation measures.
4. Approaches to tackling carbon leakage via pricing mechanisms involve different trade-offs in terms of administrative complexity, possible ambiguities in relation to international trade law, equity aspects, and overall environmental effectiveness, all of which also can affect political feasibility.
5. Embodied carbon standards, green public procurement, and green subsidies can ideally complement carbon pricing instruments, but can also be adopted in lieu of them, to drive the net zero industrial transition.
6. The sequencing and interplay of different policy measures should be tailored to each industrial sector's specific challenges rather than a one-size-fits-all approach.
7. Policies targeting embodied emissions can support the transition away from high-carbon goods, even in a patchwork of dynamically developing polycentric initiatives rather than in a fixed carbon club.
8. The absence and deprioritization of carbon pricing at the US federal level provide a particularly strong rationale for focusing more on the potential of excise taxes and product standards for embodied carbon rather than on border carbon adjustments, perhaps at the state rather than federal level in some countries.

FUTURE ISSUES

1. Future research should extend theorizations on carbon clubs to dynamically evolving and polycentric sets of diverse jurisdictions with unstable mutual recognitions of their mitigation efforts.

2. The relation between private measures and public policies targeting embodied carbon deserves more scholarly attention, in particular with respect to the informational dimension.
3. While the study of the legal implications and economics of potential pricing-based instruments for targeting emissions embodied in trade are relatively far advanced, nonprice instruments merit more attention.
4. The practical problems of tackling greenhouse gas emissions from internationally traded goods require a deeper examination of the ethical underpinnings of trade policies and World Trade Organization principles; and reform may be required to cope with the new realities of climate change.

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DISCLOSURE STATEMENT

The authors are 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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