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Supply-Side Crediting to Manage Climate Policy Spillover Effects

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Keywords Climate change; spillover effects; emissions leakage; supply-side approaches; technology; offset credits

JEL Classification H23, K33, O30, Q54

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Supply-Side Crediting to Manage Climate Policy Spillover Effects

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1. Introduction

As decarbonization efforts intensify in a world in which climate action proceeds at different speeds, two types of spillover effects will increasingly determine success in achieving emission reductions consistent with international commitments and the recommendations of climate science.

First, climate policies that seek to mitigate greenhouse gas emissions by mandating their reduction or increasing their cost can give rise to a negative spillover effect known as emissions leakage, which describes the relocation of emissive production and consumption activities from regions implementing such carbon constraints to regions with weaker climate policies. Left unchecked, emissions leakage not only threatens to limit or reverse the benefits of climate action, but it can also undermine political support for further decarbonization efforts and give rise to equity concerns. Existing safeguards against emissions leakage face serious shortcomings, calling for additional policy solutions to address this negative spillover.

Second, low-carbon technology research, development and deployment help lower the cost of these technologies and promote their global diffusion, a positive spillover effect. As low-carbon technologies reach cost parity with incumbent technologies, their adoption becomes less dependent on the stringency of domestic climate policies, which in turn limits emissions leakage caused by uneven climate policy efforts. Low-carbon technology diffusion depends on a dramatic increase in investment, however, at a time when persistent budget deficits, record levels of public debt, and rising interest rates threaten to widen the climate finance gap. Consequently, policy innovations are also called for to scale up low-carbon technology investment, especially from the private sector.

A policy innovation introduced in this article, supply-side crediting, can help mitigate emissions leakage while promoting low-carbon technology diffusion. It provides a revenue stream for the permanent decommissioning of economically viable fossil fuel reserves, thereby increasing global fossil fuel prices and unlocking investment in the development and deployment of low-carbon technologies. In other words, supply-side crediting leverages positive spillover effects while limiting negative spillover effects.

In the remainder of this article, the negative and positive spillover effects mentioned above are discussed in greater detail, along with the potential role of supply-side crediting in managing spillover effects. Section 2 defines emissions leakage and its accompanying challenges, and also describes the inherent weaknesses of leakage safeguards deployed to date. It continues by affirming the importance of supply-side approaches, and explores a possible design for a supply-side crediting mechanism. Section 4 proceeds to discuss the importance of low-carbon technology diffusion and its reliance on scaled investment. Highlighting the persistent climate finance gap, it describes the potential role of supply-side crediting in unlocking private sector investment in low-carbon technologies, such as carbon dioxide removals, to accelerate the technological learning curve and thereby promote their diffusion. Section 5 concludes.

2. Negative Spillovers and Climate Policy: The Challenge of Emissions Leakage

2.1 Carbon Constraints and the Risk of Emissions Leakage

In a world in which the Paris Agreement allows countries to move at heterogeneous speeds of decarbonization, and international trade allows capital, ideas, and goods and services to travel across jurisdictional borders, emissions leakage becomes an increasingly serious challenge as individual jurisdictions seek to leverage policies that mandate reductions in, or impose a cost on, greenhouse gas emissions. Collectively, these policies will be referred to as "carbon constraints" in the remaining article.

When subject to such constraints, emissions related to production and consumption tend to shift from countries with higher production and consumer costs to countries with lower production and consumer costs. Where this shift is induced by an asymmetry of carbon constraints, it reflects a process known as "emissions leakage."

Emissions leakage occurs when mitigation measures implemented in one country or region lead to increased emissions in other countries or regions (IPCC 2022). Formally, it can be defined as the "increase in … emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries" (IPCC 2007). Three channels of emissions leakage have been identified in the literature, of which two are related to trade in goods and the third is related to changes in global energy prices (Ward et al. 2015).

Leakage related to trade in goods occurs when climate policy results in production cost increases that undermine the comparative advantage of the implementing country in line with the "pollution haven" hypothesis (Pethig 1976; Siebert 1977). Sometimes referred to as "direct leakage", it manifests itself through two channels that differ in terms of their temporal dimension: an operational (or short-term competitiveness) channel that incurs relocation of production and lost market share, and an investment (or long-term competitiveness) channel resulting when investment in new production capacity and maintenance is redirected abroad in expectation of higher returns (Antweiler, Copeland, and Taylor 2001; Kuik and Gerlagh 2003).

Under the third emissions leakage channel, which is related to global energy markets and is therefore sometimes referred to as "indirect leakage", decreased demand for fossil fuels in regions with more stringent carbon constraints exerts downward pressure on global fossil fuel prices, stimulating uptake in regions with lower climate ambition (Bohm 1993; Felder and Rutherford 1993; Fischer and Fox 2012).

As such, emissions leakage represents a negative spillover effect that undermines the benefits of unilateral climate action taken at the domestic or regional level because emissions merely shift geographically rather than being actually reduced. In extreme cases, climate action may even lead to a net increase in global emissions when production and consumption relocate to regions with greater relative carbon intensity (Hoel 1991; 1994).

So far, however, evidence of leakage induced purely by decarbonization policies is scarce, owing in large part to the modest ambition of past climate action (Aldy and Pizer 2015; Dechezleprêtre and Sato 2017). Much of the empirical research has focused on the European Union Emissions Trading System (EU ETS), which imposes a carbon price on energy-intensive and trade-exposed sectors such as cement or ferrous and non-ferrous metals. There, too, low price levels and extensive measures to protect the competitiveness of industry have limited emissions leakage effects to date (Branger, Quirion, and Chevallier 2016; Dechezleprêtre, Nachtigall, and Venmans 2023; Verde 2020).

As climate policies become more stringent in line with committed decarbonization pathways, however, the impact of emissions leakage is expected to grow (Branger and Quirion 2014; Carbone and Rivers 2017). Some projections of future emissions relocation anticipate leakage rates well in excess of 100% (Babiker 2005). More importantly, the challenges associated with emissions leakage also arise when emissions are displaced for reasons other than asymmetrical climate policies, such as relatively more favorable factor endowments reflected in lower costs of labor, energy, and raw materials. A protectionist bias observed in the trade policy of most countries amplifies emission transfers through international trade, with higher import tariffs and non-tariff barriers applied to downstream industries relative to more carbon-intensive basic materials that serve as inputs for these industries (Shapiro 2021).

Negative spillover effects from emissions relocation, in other words, extend well beyond the channels of climate policy-induced emissions leakage described above, adding to the urgency of a solution. Already, an estimated 20-25% of global emissions are emissions released at different stages of the supply chain of goods traded across national borders, from the extraction and transportation of resources to refining, processing, and assembly of the finished product (Davis and Caldeira 2010; Hasanbeigi and Darwili 2022). As decarbonization accelerates in many parts of the world, the share of emissions embodied in traded goods is likely to increase as a percentage of declining overall emissions (Wood et al. 2020). Again, the resulting disparity between where production emissions occur and where the resulting goods are ultimately consumed may not be exclusively or even primarily caused by climate policies, yet it still has important policy implications, from the limited ability to regulate emissions beyond sovereign control to difficult questions about the attribution of emissions and responsibility for their mitigation.

When carbon-intensive production is outsourced to regions with no or lower climate policy standards, and the products – often more carbon-intensive than those originally produced domestically – are subsequently imported to meet demand in the outsourcing countries (Levinson 2010), accountability for the emissions associated with these products shifts under international emissions accounting rules. If goods are produced outside the country in which they are consumed, the embodied emissions are not counted towards the emission inventory of that country (IPCC 2006).

As a result of this accounting loophole, countries can claim progress towards their Nationally Determined Contributions (NDCs) despite having only shifted the geographic incidence of emissions. Countries such as Switzerland or Singapore, for instance, already import goods associated with greater emissions than they generate domestically, and most advanced economies import emissions corresponding to between one and two thirds of their territorial greenhouse gas emissions (Karstensen, Peters, and Andrew 2018).

Emissions displacement from such relocation effects also gives rise to another equity concern: historically, production has tended to shift from countries with higher production costs and more advanced environmental policies to countries with lower production costs and less stringent environmental policies. If this trend and related trade patterns persist, affluent countries will increasingly be able to meet decarbonization targets by outsourcing emissions-intensive activities to less affluent regions, not only burdening these with the formal responsibility for associated emissions, but also causing them to suffer greater local impacts such as natural resource depletion, air and water pollution, and the related health effects.

Climate policies that mandate a reduction in emissions or increase their cost thus threaten to repeat a pattern of "burden shifting" witnessed with air pollution policies in the 1970s, when increasingly stringent pollution controls in Europe and other advanced economies shifted both air pollution and the associated health impacts to developing countries while absolute pollution levels increased around the globe (Kanemoto et al. 2014). They also risk exacerbating a pattern of overconsumption by wealthy countries of the resources extracted in developing countries, where policy safeguards tend to be weaker and demand-side constraints could accelerate extraction (Chichilnisky 1994).

Finally, emissions spillovers are not only an environmental and moral problem: they also pose a significant political challenge, because the relocation of production and investment is accompanied by a loss of economic benefits, including investment and employment, along with a deteriorating trade balance and reduction in fiscal revenue. Concerns about emissions leakage and the underlying competitiveness impacts are therefore regularly cited as an obstacle to greater climate policy ambition (World Bank 2019). Conversely, the possibility of leakage can incentivize countries to defer or reverse climate action as a way to strengthen their competitive advantage (Beccherle and Tirole 2011). Political economy considerations are critical to the successful adoption of policies for deep decarbonization, and the policy innovation described later in this article can also improve support for climate action by altering the incentive structure facing key stakeholders in the energy economy. [Cross-Reference]

2.2 Addressing Emissions Leakage: Demand- and Supply-Side Options

Over 80% of global greenhouse gas emissions result from the production and use of fossil fuels (IPCC 2022), with displacement of fossil fuels and energy-intensive industrial production – as explained in the previous section – likewise representing the primary channels of emissions leakage. With regard to fossil fuels, climate policies can be broadly classified as demand-side approaches that directly target their consumption, and supply-side approaches that directly target their production (Prest 2022). As the following subsections will show, emissions leakage related to fossil fuels can be addressed both downstream at the level of fossil fuel consumption as well as upstream at the level of fossil fuel production, with important implications for the effectiveness of such efforts.

2.2.1 Demand-Side Options

Theoretically the optimal way to prevent emissions leakage from climate policy asymmetries, concerted action on carbon constraints – for instance through pursuit of a globally harmonized carbon price (Parry, Black, and Roaf 2021; Weitzman 2014) or sectoral decarbonization agreements (Meckling and Chung 2009; Rossetto 2023) – has proven politically elusive. Since its earliest origins, the architecture of international climate cooperation has charted an uneven trajectory to accommodate vastly different national circumstances and heterogeneous action, culminating in the decentralized Paris Agreement (Höhne et al. 2017; S. Rayner 2010).

Whenever jurisdictions have introduced carbon constraints, they have therefore typically been forced to blunt the effects of these policies with exemptions, rebates or other measures aimed at mitigating the economic burden imposed on sensitive sectors or vulnerable constituencies. Under most existing emissions trading systems, for instance, energy-intensive and trade-exposed (EITE) industries competing in global markets receive a majority of the allowances needed for compliance free of cost, a leakage safeguard known as "free allocation" (Antoci et al. 2022).

While such policy options have proven effective at counteracting emissions leakage, they have done so at the expense of muted abatement incentives and thus reduced climate benefits (Neuhoff et al. 2015), in some cases generating windfall profits (Sijm, Neuhoff, and Chen 2006) or incentivizing changes in production to increase benefits (Fischer and Fox 2007; Branger et al. 2015). More importantly, such exemptions and rebates, which defer or shift the burden of emissions abatement, are incompatible with deep decarbonization, in which all segments of the economy have to ultimately phase out or alternatively compensate their emissions. As a result, traditional safeguards against emissions leakage are increasingly seen as temporary solutions that will have to be abandoned in the near to medium term (Jakob 2021).

An alternative leakage safeguard that is finding increased discussion are border carbon adjustments (BCAs), which are trade-related policy instruments that can alleviate emissions leakage by extending a domestic carbon constraint to imported goods, sometimes in combination with relief for exported goods through an exemption from, or credit for, the same domestic carbon constraints (Condon and Ignaciuk 2013; Ismer and Neuhoff 2007; going back to Markusen 1975). While BCAs are most often thought of as a way to offset the leakage risk of carbon pricing, extending compliance obligations to the foreign production of imported goods – for instance technology and performance standards – follows the same logic of leveling the burden facing domestic and foreign producers.

As such, these approaches implement the destination principle which stipulates that fiscal or regulatory burdens on goods should be imposed by the jurisdiction in which they are ultimately consumed to safeguard trade neutrality (GATT 1970). Increasing unilateralism, more aggressive deployment of trade sanctions and accelerating stringency of climate policy commitments have contributed to a surge in the political discussion of BCAs (Mehling et al. 2018).

Among current efforts to introduce a BCA, the decision by the EU to introduce a CBAM on imports of six product categories – cement, iron and steel, aluminum, fertilizer, hydrogen and electricity – has received the most attention (European Union 2023). Other jurisdictions are likewise exploring the introduction of a BCA, including Canada (Canada 2021), the United Kingdom (United Kingdom 2022), and the United States, where several bills have been introduced in Congress to impose compliance obligations on imported goods even in the absence of a domestic carbon price (Coons and Peters 2021; Whitehouse 2022). At the subnational level, California has applied a BCA to electricity imports under its emissions trading system since 2013, requiring deliverers of electricity – regardless of geographic origin – to purchase and surrender allowances for the emissions released during its generation (California 2010; Pauer 2018).

Although conceptually appealing as a way to correct asymmetries in climate action and avert emissions leakage, BCAs introduce substantial uncertainties and costs in their practical implementation. Because they condition market access to the carbon intensity of goods, they risk violating the principle of non-discrimination enshrined in the General Agreement on Tariffs and Trade (GATT) as well as other treaties administered by the World Trade Organization (WTO).

A prudent approach to BCA design and implementation improves the prospects of compliance with free trade disciplines (Mehling et al. 2019), yet influential scholars have cautioned that a breach of treaty obligations – and thus a protracted and costly trade conflict – might nonetheless be difficult to avoid (Bacchus 2021; Quick 2020). Indeed, important trade partners of the EU, including China and India, have already raised questions about the CBAM before the WTO (Bermingham 2023; Law 2023).

BCAs are also politically controversial. Domestically, the cohesion and political determination of jurisdictions pursuing the introduction of BCAs will be tested by divergent stakeholder preferences regarding their purpose and design (Buylova et al. 2022). Political support may also erode due to concern about the inflationary impacts of BCAs on raw material inputs and consumer goods. Internationally, BCAs have been accused of serving as a pretext for economic protectionism by advanced economies to the detriment of their global trading partners (Holmes, Reilly, and Rollo 2011; Quick 2011).

For least developed countries (LDCs), BCAs could limit market access and potentially increase poverty levels by curtailing a source of income and employment, adding an equity dimension and prompting calls for geographic differentiation or country exemptions (Brandi 2013; Lowe 2021; UNCTAD 2021; Zimmer and Holzhausen 2020). Welfare estimations suggest that BCAs would thus exacerbate existing income inequalities by changing the terms of trade and further shifting the burden of emissions abatement from developed to developing countries (Böhringer, Carbone, and Rutherford 2018; Eicke et al. 2021; Perdana and Vielle 2022).

International surveys have unsurprisingly affirmed mostly negative views of proposed BCAs (Bergin et al. 2021), with ministers of major emerging economies expressing "grave concern regarding the proposal for introducing trade barriers, such as unilateral carbon border adjustment" (BASIC 2021). Political opposition from trade partners is not limited to developing countries, however, and may equally originate from more advanced economies (Overland and Sabyrbekov 2022).

At the diplomatic level, unilateral application of BCAs could thus undermine prospects for multilateral climate cooperation, including sensitive negotiations under the UNFCCC and Paris Agreement. Coordinated action on BCAs – for instance as part of a 'climate club' of like-minded countries (Nordhaus 2015) – may help avert some confrontations (Sawyer and Gignac 2022), yet faces its own political obstacles, as evidenced by the failure to include BCAs in a recent statement on climate clubs adopted by the Group of Seven (G7 2022), an option previously advanced by the German G7 Presidency (Germany 2021). Even between Europe and the U.S., agreement on efforts to introduce a joint BCA on imported steel and aluminum has proven elusive (Moens and Overly 2023).

Finally, and perhaps most importantly, BCAs pose daunting administrative and technical challenges (Böhringer et al. 2022). They require extensive data and a detailed understanding of production processes beyond the sovereign jurisdiction of implementing countries, incurring new administrative burdens and transaction costs (Felbermayr and Peterson 2020; Kortum and Weisbach 2017), and potentially straining the capacities of foreign producers to accurately quantify and report their emissions intensities. Resorting to benchmark or default values can alleviate some of these burdens (Persson 2010), but risks blunting the effectiveness of BCAs and compromising their alignment with international trade law (Mehling and Ritz 2023).

Altogether, BCAs are highly vulnerable to circumvention through adjusted trade flows in the form of resource shuffling or transshipment and strategic policy responses, such as export subsidies to restore the competitive advantage of affected producers. Displacement and substitution effects in third countries could entail production shifting from sectors subject to a BCA to those excluded from its scope (Golombek, Hagem, and Hoel 1995; Hoel 1996), producer reorganization to divest from polluting facilities, or product modification and processing to exceed covered value chain thresholds (Zachmann and McWilliams 2020).

While jurisdictions implementing BCAs can try to identify and counteract circumvention practices, the empirical record of economic and financial sanctions suggests that these require, at best, continuous adaptation to evasive action, and at worst backfire against those deploying them (Demarais 2022). Similarly, trade remedies aimed at correcting international trade distortions, such as countervailing and antidumping duties, are routinely circumvented by those to whom they apply (Forganni and Reed 2019). In the only example of a BCA operationalized to date, the Californian inclusion of imported electricity in its emissions trading system, research suggests widespread deployment of avoidance practices, essentially negating the environmental benefits from including electricity imports (Bushnell, Chen, and Zaragoza-Watkins 2014; Caron, Rausch, and Winchester 2015).

Overall, thus, demand-side solutions to emissions leakage that seek to level asymmetrical carbon constraints – either by offering relief to domestic emitters subject to compliance obligations, or by extending those obligations to foreign products and services - are either incompatible with global decarbonization or encumbered by legal, political, ethical, and technical complexities that jeopardize their successful implementation, calling for additional policy solutions to address this negative spillover.

3. Supply-Side Options

In view of the limitations facing demand-side solutions to emissions leakage, research early on affirmed the need for complementary supply-side policies (Markusen 1975). More recent literature has affirmed that any optimal solution to emissions leakage requires a combined deployment of demand- and supply-side elements (Green and Denniss 2018; Prest 2022; Weisbach et al. 2022).

In this strand of scholarship, supply-side interventions that target fossil fuel production offer a complementary approach to counteracting the emissions leakage risk of demand-side measures (Harstad 2012; Sinn 2012; going back to Bohm 1993). Constraining the global supply of fossil fuels through supply-side measures would effectively counteract emissions leakage by increasing the cost of fossil fuels across all jurisdictions, its proponents argue, thereby disincentivizing emissions everywhere and not just in the implementing jurisdiction.

As with demand-side interventions, the optimal approach would entail global coordination on fossil fuel supply restrictions (T. Rayner 2021). Such coordination could take the form of an agreement on the managed decline of fossil fuel production (Asheim et al. 2019), as exemplified by proposals for a fossil fuel non-proliferation treaty (Newell and Simms 2020), plurilateral 'club' approaches (van Asselt and Newell 2022), or extending fossil fuel producer responsibility with a mandated 'carbon takeback obligation' (Jenkins et al. 2021; 2023), but the political barriers are again significant (T. Rayner 2021). Failure to agree even on modest language on an aspirational phase out of fossil fuels at recent climate negotiations (Green and van Asselt 2022) suggests that any mandatory or coordinated approaches will remain elusive in the current political context.

A voluntary supply-side crediting mechanism based on the non-extraction of economically viable fossil fuel reserves, by contrast, would not depend on a political mandate or consensus between sovereign nations. Supply-side crediting generates a revenue stream to incentivize the permanent decommissioning of economically viable fossil fuel reserves so that these remain undeveloped, avoiding the greenhouse gas emissions that would have been released if these fuels were extracted, processed, distributed, and finally combusted (Welsby et al. 2021). By tightening fossil fuel supplies, supply-side crediting increases fossil fuel prices, exerting downward pressure on fossil fuel demand and thus on emissions.

Given supply elasticities, higher prices may stimulate increased fossil fuel production elsewhere, partly offsetting the emission reductions from forgoing extraction of a particular reserve (Dwyer 2022). Still, such leakage effects are limited by constraints on available infrastructure, differences in crude composition, and the timeline of new investments, with increasingly sophisticated economic analyses allowing calculation of expected leakage rates so that only net avoided emissions are credited (Schaufele 2021).

Avoided emissions can be quantified and credited using proven engineering methodologies to determine mine or well productivity and the size of fossil fuels reserves shut in with each decommissioned field (Jing et al. 2020; Masnadi et al. 2018). Because entire fields would be shut down, with existing wells plugged, capped, and abandoned, surface equipment removed, and land reclaimed, remaining reserves would typically lose economic viability.

Climate benefits from retired fossil fuel reserves are immediate, unlike alternative solutions such as biogenic carbon capture and sequestration, which take years to scale up and absorb carbon to achieve their full mitigation potential. That matters, because it helps prevent new investment in fossil fuel production assets and thereby reduces carbon lock-in effects (Seto et al. 2016). That, in turn, can help lower the risk – and economic cost – of future stranded assets (Semieniuk et al. 2022).

Supply-side crediting incentivizes and rewards avoided emissions, thereby offering greater transparency and permanence as well as greater climate benefits than removal credits due to the non-linear climate-carbon cycle (Zickfeld et al. 2021). By prioritizing the most emissive resources first, such as unconventional heavy oil (Masnadi et al. 2018), supply-side crediting also achieves greater cost-effectiveness than alternative policy options.

Its voluntary, project-based approach distinguishes it from large-scale and highly politicized efforts such as the failed Yasuní-ITT initiative, in which Ecuador would have been compensated for not exploiting the Ishpingo Tambococha Tiputini (ITT) oilfields in the Amazon Region (Sovacool and Scarpaci 2016), or top-down mandates such as the aforementioned 'carbon takeback obligation' that are unlikely to find sufficient support.

Like other forms of crediting, supply-side crediting needs to adhere to the procedural and material requirements of existing offset crediting standards, including independent third-party verification as well as a requirement that emission reductions be permanent and additional. Permanence can be ensured through legal commitments – such as conservation easements, land trusts or transfer of title – and physical interventions that guarantee the irreversibility of the resource retirement. Additionality would be secured through established methods to identify fossil fuel reserves that are economically viable under a wide range of fossil fuel and carbon price scenarios. Credits would only be issued as long as the decommissioned field is, and remains, profitable during the crediting period. With such a design, this approach would yield credits that help meet demand and provide liquidity in undersupplied carbon markets (Shell and BCG 2023).

Unlike support policies that target specific technologies, suffer from information asymmetries and create inframarginal incentives, supply-side crediting relies on market forces to identify the resources whose retirement offers the greatest marginal benefit to society. Should this mechanism be deployed at a scale that could have equity impacts on entire regions or countries, it might require some criteria to guide the distribution of projects (Sanchez and Linde 2023). It could be designed in a way that revenue is channeled into efforts to ensure a just transition, defraying worker relocation and retraining expenses, but also enabling some of the rents from decarbonization to accrue to developing countries that depend on energy resources for their economic advancement (Richter, Mendelevitch, and Jotzo 2018).

4. Positive Spillovers and Climate Policy: Investing in Low-Carbon Technology

4.1 Cost Parity of Low-Carbon Technologies to Prevent Leakage

Meaningful climate action requires overcoming daunting technological, economic and political challenges. Only once clean technology alternatives are available across all sectors and have reached cost parity while providing the same amenities as conventional technologies will decarbonization be driven by the market, and become independent from unpredictable political cycles.

While technological advances and growing maturity of supply chains have brought such cost parity within reach for decarbonization of electricity generation and, in the near- to medium term, for transportation, critical technologies in other sectors such as industry and land use, including carbon removal technologies such as direct air capture, are either not available at commercial scale or still in early stages of commercialization, in all cases with significantly higher cost than conventional alternatives.

Driving down the costs of these technologies will be critical for large-scale uptake. Innovation in low-carbon technologies and the provision of related network infrastructure are both costly, however, and create benefits to society that are not priced into their delivery. Known as a positive externality (Gillingham and Stock 2018; Jaffe, Newell, and Stavins 2005), this inability to capture private returns that reflect the full value of innovation and network infrastructure prevents optimal investment in research and deployment of low-carbon technologies (Gallagher, Holdren, and Sagar 2006; Margolis and Kammen 1999), as well as in infrastructure needed by some technologies to scale up and reach commercial maturity (Li et al. 2017).

Technology support policies such as fiscal subsidies, technology mandates or targeted public procurement can exert both a supply push and demand pull for low-carbon technologies, accelerating the technology learning curve to a point where learning by doing and economies of scale effects – reflected in deepening supply chains, growing competition, and managerial, regulatory and engineering optimization – bring down their cost (Kavlak, McNerney, and Trancik 2018; Nemet 2019; Ziegler, Song, and Trancik 2021).

They suffer from a number of limitations, however, such as targeting inframarginal activities and failing to equalize abatement costs, information and information asymmetries that lead to compensation of inferior solutions, and lowering the cost of energy resulting in rebound effects. Because they commit public resources and risk exacerbating inflationary pressures, they can also be politically vulnerable in a context of high levels of public debt, persistent structural budget deficits, rising interest rates and monetary tightening, as well as challenging demographic trends. Additional tools are therefore called for to generate revenue for low-carbon technology investment without competing for scarce public funds.

4.2 Catalyzing Low-Carbon Investment with Supply-Side Credits

Experience with the technology cost decline in renewable energy technologies has shown that the single most important factor in bringing down the cost of clean technologies is their deployment at scale (Nemet 2019), which requires activating multiple levers – such as incentives and lowered regulatory barriers – but ultimately depends on scaling up stable investment flows. Estimates of annual incremental investment required across sectors to ensure achievement of the temperature stabilization goal of the Paris Agreement and economy-wide net zero emissions in the second half of the century vary, but are all staggering in scale. According to a recent estimate, the economic transformation needed to achieve net-zero emissions by 2050 requires US$ 9.2 trillion in annual average spending on physical assets, an increase of US$ 3.5 trillion over current levels (Krishnan et al. 2022). Other estimates confirm the scale of incremental investment to achieve committed climate objectives (IEA 2021; IPCC 2018; 2022). Where assessments of clean technology finance unanimously concur is in their diagnosis of a significant investment gap (Naran et al. 2022).

With public budgets strained by debt-financed recovery and stimulus packages following the global COVID-19 pandemic, geopolitical tensions shifting public resources to competing priorities and directing resources to more rather than less hydrocarbon extraction, and inflationary pressures prompting rising interest rates and tighter monetary policies in the near to medium term, an important source of clean technology investment – public spending – already faces new constraints even in the industrialized world. Given the high perceived risk attributed to early-stage technologies, as well as political and regulatory risk in many parts of the world, however, financing sources other than debt and equity at market conditions will remain vital to accelerate private sector investment in clean technologies, a role normally played by public finance through grants, concessional loans, and credit guarantees.

Revenue from the sale of supply-side credits can unlock a new source of investment capital to help narrow the clean technology investment gap, lower risk for investors in early-stage clean technologies, and mobilize technical expertise, infrastructure and human capital relevant to clean technology commercialization. Adequate incentive structures and a robust governance framework would have to be established to ensure that these resources flow towards uses amplifying climate benefits.

5. Conclusions

As shown in this paper, supply-side crediting offers an innovative addition to the climate policy toolbox that can help address two spillover effects that will prove critical to rapid decarbonization of the global economy. Supply-side crediting can counteract emissions leakage caused by carbon constraints such as carbon pricing, a phenomenon that increasingly threatens to undermine climate policy efforts in a world of asymmetrical climate action. Additionally, it can catalyze investment in innovation and deployment of low-carbon technologies that are critical to decarbonization across all sectors of the economy, such as carbon removal technologies. Further research is warranted to better understand the political economy of this policy innovation, and to identify implementation options and relevant governance requirements to ensure supply-side credits leverage a positive spillover effect – the diffusion of low-carbon technologies – to counteract the negative spillover effect of greenhouse gas emissions leakage.

References

Aldy, Joseph E., and William A. Pizer. 2015. 'The Competitiveness Impacts of Climate Change Mitigation Policies'. Journal of the Association of Environmental and Resource Economists 2 (4): 565–95. https://doi.org/10.1086/683305.

Antoci, Angelo, Simone Borghesi, Gianluca Iannucci, and Mauro Sodini. 2022. 'Free Allocation of Emission Permits to Reduce Carbon Leakage: An Evolutionary Approach'. In Handbook on Trade Policy and Climate Change, edited by Michael Jakob, 76–93. Cheltenham: Edward Elgar Publishing. https://www.elgaronline.com/view/edcoll/9781839103230/9781839103230.00014.xml.

Antweiler, Werner, Brian R. Copeland, and M. Scott Taylor. 2001. 'Is Free Trade Good for the Environment?' American Economic Review 91 (4): 877–908. https://doi.org/10.1257/aer.91.4.877.

Asheim, G. B., T. Fæhn, K. Nyborg, M. Greaker, C. Hagem, B. Harstad, M. O. Hoel, D. Lund, and K. E. Rosendahl. 2019. 'The Case for a Supply-Side Climate Treaty'. Science 365 (6451): 325. https://doi.org/10.1126/science.aax5011.

Asselt, Harro van, and Peter Newell. 2022. 'Pathways to an International Agreement to Leave Fossil Fuels in the Ground'. Global Environmental Politics 22 (4): 28–47. https://doi.org/10.1162/glep_a_00674.

Babiker, Mustafa H. 2005. 'Climate Change Policy, Market Structure, and Carbon Leakage'. Journal of International Economics 65 (2): 421–45. https://doi.org/10.1016/j.jinteco.2004.01.003.

Bacchus, James. 2021. 'Legal Issues with the European Carbon Border Adjustment Mechanism'. Cato Briefing Paper 125. Washington, DC: Cato Institute. https://www.cato.org/sites/cato.org/files/2021-08/briefing-paper-125.pdf.

BASIC. 2021. 'Joint Statement Issued at the Conclusion of the 30th BASIC Ministerial Meeting on Climate Change Hosted by India on 8th April 2021'. https://www.gov.za/speeches/joint-statement-issued-conclusion-30th-basic-ministerial-meeting-climate-change-hosted.

Beccherle, Julien, and Jean Tirole. 2011. 'Regional Initiatives and the Cost of Delaying Binding Climate Change Agreements'. Special Issue: International Seminar for Public Economics on Normative Tax Theory 95 (11): 1339–48. https://doi.org/10.1016/j.jpubeco.2011.04.007.

Bergin, Daniel, Timothy Cheng, Victoria Gilbert, and Wander Meijer. 2021. 'Perception of the Planned EU Carbon Border Adjustment Mechanism in Asia Pacific: An Expert Survey'. Hong Kong: Konrad Adenauer Stiftung e.V. https://www.kas.de/documents/265079/265128/EU+Carbon+Border+Adjustment+Mechanism.pdf/fed1d5a4-4424-c450-a1b9-b7dbd3616179?version=1.1&t=1615356593906.

Bermingham, Finbarr. 2023. 'China Asks EU to Justify Upcoming Carbon Tax at World Trade Organization'. South China Morning Post, 16 March 2023, sec. News. https://www.scmp.com/news/china/article/3213676/china-asks-eu-justify-upcoming-carbon-tax-world-trade-organization.

Bohm, Peter. 1993. 'Incomplete International Cooperation to Reduce CO2 Emissions: Alternative Policies'. Journal of Environmental Economics and Management 24 (3): 258–71. https://doi.org/10.1006/jeem.1993.1017.

Böhringer, Christoph, Jared C. Carbone, and Thomas F. Rutherford. 2018. 'Embodied Carbon Tariffs'. The Scandinavian Journal of Economics 120 (1): 183–210. https://doi.org/10.1111/sjoe.12211.

Böhringer, Christoph, Carolyn Fischer, Knut Einar Rosendahl, and Thomas Fox Rutherford. 2022. 'Potential Impacts and Challenges of Border Carbon Adjustments'. Nature Climate Change 12 (1): 22–29. https://doi.org/10.1038/s41558-021-01250-z.

Brandi, Clara. 2013. 'Trade and Climate Change: Environmental, Economic and Ethical Perspectives on Border Carbon Adjustments'. Ethics, Policy & Environment 16 (1): 79–93. https://doi.org/10.1080/21550085.2013.768395.

Branger, Frédéric, Jean-Pierre Ponssard, Oliver Sartor, and Misato Sato. 2015. 'EU ETS, Free Allocations, and Activity Level Thresholds: The Devil Lies in the Details'. Journal of the Association of Environmental and Resource Economists 2 (3): 401–37. https://doi.org/10.1086/682343.

Branger, Frédéric, and Philippe Quirion. 2014. 'Would Border Carbon Adjustments Prevent Carbon Leakage and Heavy Industry Competitiveness Losses? Insights from a Meta-Analysis of Recent Economic Studies'. Ecological Economics 99 (March): 29–39. https://doi.org/10.1016/j.ecolecon.2013.12.010.

Branger, Frédéric, Philippe Quirion, and Julien Chevallier. 2016. 'Carbon Leakage and Competitiveness of Cement and Steel Industries Under the EU ETS: Much Ado About Nothing'. The Energy Journal 37 (3): 109–35.

Bushnell, James, Yihsu Chen, and Matthew Zaragoza-Watkins. 2014. 'Downstream Regulation of CO2 Emissions in California's Electricity Sector'. Energy Policy 64 (January): 313–23. https://doi.org/10.1016/j.enpol.2013.08.065.

Buylova, Alexandra, Mathias Fridahl, Naghmeh Nasiritousi, Indra Overland, and Gunilla Reischl. 2022. 'Climate Action in the Making: Business and Civil Society Views on the World's First Carbon Border Levy'. Climate Action 1 (1): 17. https://doi.org/10.1007/s44168-022-00015-4.

California. 2010. 'Subchapter 10 (Climate Change), Article 5, Sections 95800 to 96023, Title 17, California Code of Regulations: California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms'. https://ww3.arb.ca.gov/regact/2010/capandtrade10/finalrevfro.pdf?_ga=2.188648168.1586526258.1615199457-1765356218.1615199457.

Canada, Government of. 2021. 'Consultation on Border Carbon Adjustments'. 2021. https://www.canada.ca/en/department-finance/programs/consultations/2021/border-carbon-adjustments.html.

Carbone, Jared C., and Nicholas Rivers. 2017. 'The Impacts of Unilateral Climate Policy on Competitiveness: Evidence From Computable General Equilibrium Models'. Review of Environmental Economics and Policy 11 (1): 24–42. https://doi.org/10.1093/reep/rew025.

Caron, Justin, Sebastian Rausch, and Niven Winchester. 2015. 'Leakage from Sub-National Climate Policy: The Case of California's Cap-and-Trade Program'. The Energy Journal 36 (2): 167–90.

Chichilnisky, Graciela. 1994. 'North-South Trade and the Global Environment'. The American Economic Review 84 (4): 851–74.

Condon, Madison, and Ada Ignaciuk. 2013. 'Border Carbon Adjustment and International Trade: A Literature Review'. Paris: Organisation for Economic Co-operation and Development (OECD). https://doi.org/10.1787/5k3xn25b386c-en.

Coons, Christopher A., and Scott H. Peters. 2021. Fair, Affordable, Innovative, and Resilient Transition and Competition (FAIR) Act. https://www.congress.gov/bill/117th-congress/senate-bill/2378/text.

Davis, Steven J., and Ken Caldeira. 2010. 'Consumption-Based Accounting of CO_2 Emissions'. Proceedings of the National Academy of Sciences 107 (12): 5687. https://doi.org/10.1073/pnas.0906974107.

Dechezleprêtre, Antoine, Daniel Nachtigall, and Frank Venmans. 2023. 'The Joint Impact of the European Union Emissions Trading System on Carbon Emissions and Economic Performance'. Journal of Environmental Economics and Management 118 (March): 102758. https://doi.org/10.1016/j.jeem.2022.102758.

Dechezleprêtre, Antoine, and Misato Sato. 2017. 'The Impacts of Environmental Regulations on Competitiveness'. Review of Environmental Economics and Policy 11 (2): 183–206. https://doi.org/10.1093/reep/rex013.

Demarais, Agathe. 2022. Backfire: How Sanctions Reshape the World Against U.S. Interests. Center on Global Energy Policy Series. New York, NY: Columbia University Press. https://books.google.com/books?id=WG9sEAAAQBAJ.

Dwyer, Guy. 2022. '"Market Substitution" in the Context of Climate Litigation'. Climate Law 12 (1): 1–31. https://doi.org/10.1163/18786561-12010001.

Eicke, Laima, Silvia Weko, Maria Apergi, and Adela Marian. 2021. 'Pulling up the Carbon Ladder? Decarbonization, Dependence, and Third-Country Risks from the European Carbon Border Adjustment Mechanism'. Energy Research & Social Science 80 (October): 102240. https://doi.org/10.1016/j.erss.2021.102240.

European Union. 2023. Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 Establishing a Carbon Border Adjustment Mechanism. Vol. PE/7/2023/REV/1. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R0956.

Felbermayr, Gabriel, and Sonja Peterson. 2020. 'Economic Assessment of Carbon Leakage and Carbon Border Adjustment'. Briefing PE 603.501. Strasbourg: European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/603501/EXPO_BRI(2020)603501_EN.pdf.

Felder, Stefan, and Thomas F. Rutherford. 1993. 'Unilateral CO2 Reductions and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials'. Journal of Environmental Economics and Management 25 (2): 162–76. https://doi.org/10.1006/jeem.1993.1040.

Fischer, Carolyn, and Alan K. Fox. 2007. 'Output-Based Allocation of Emissions Permits for Mitigating Tax and Trade Interactions'. Land Economics 83 (4): 575–99. https://doi.org/10.3368/le.83.4.575.

———. 2012. 'Comparing Policies to Combat Emissions Leakage: Border Carbon Adjustments versus Rebates'. Journal of Environmental Economics and Management 64 (2): 199–216. https://doi.org/10.1016/j.jeem.2012.01.005.

Forganni, Antonella, and Heidi Reed. 2019. 'Circumvention of Trade Defence Measures and Business Ethics'. Journal of Business Ethics 155 (1): 29–40.

G7. 2022. 'G7 Statement on Climate Club'. Group of Seven. https://www.g7germany.de/resource/blob/974430/2057926/2a7cd9f10213a481924492942dd660a1/2022-06-28-g7-climate-club-data.pdf.

Gallagher, Kelly Sims, John P. Holdren, and Ambuj D. Sagar. 2006. 'Energy-Technology Innovation'. Annual Review of Environment and Resources 31 (1): 193–237. https://doi.org/10.1146/annurev.energy.30.050504.144321.

GATT. 1970. 'Report by the Working Party on Border Tax Adjustment, L/3464'. General Agreement on Tariffs and Trade. https://docs.wto.org/gattdocs/q/GG/L3799/3464.PDF.

Germany. 2021. 'Steps towards an Alliance for Climate, Competitiveness and Industry: Building Blocks of a Cooperative and Open Climate Club'. Berlln: Federal Ministy of Finance. https://www.bundesfinanzministerium.de/Content/EN/Downloads/Climate-Action/key-issues-paper-international-climate-club.pdf?__blob=publicationFile&v=4.

Gillingham, Kenneth, and James H. Stock. 2018. 'The Cost of Reducing Greenhouse Gas Emissions'. Journal of Economic Perspectives 32 (4): 53–72. https://doi.org/10.1257/jep.32.4.53.

Golombek, Rolf, Catherine Hagem, and Michael Hoel. 1995. 'Efficient Incomplete International Climate Agreements'. Resource and Energy Economics 17 (1): 25–46. https://doi.org/10.1016/0928-7655(94)00022-C.

Green, Fergus, and Harro van Asselt. 2022. 'COP27 Flinched on Phasing out "All Fossil Fuels". What's next for the Fight to Keep Them in the Ground?' The Conversation (blog). 21 November 2022. http://theconversation.com/cop27-flinched-on-phasing-out-all-fossil-fuels-whats-next-for-the-fight-to-keep-them-in-the-ground-194941.

Green, Fergus, and Richard Denniss. 2018. 'Cutting with Both Arms of the Scissors: The Economic and Political Case for Restrictive Supply-Side Climate Policies'. Climatic Change 150 (1): 73–87. https://doi.org/10.1007/s10584-018-2162-x.

Harstad, Bård. 2012. 'Buy Coal! A Case for Supply-Side Environmental Policy'. Journal of Political Economy 120 (1): 77–115. https://doi.org/10.1086/665405.

Hasanbeigi, Ali, and Aldy Darwili. 2022. 'Embodied Carbon in Trade: Carbon Loophole'. St. Petersburg, FL: Global Efficiency Intelligence. https://www.globalefficiencyintel.com/2022-embodied-carbon-in-trade-carbon-loophole.

Hoel, Michael. 1991. 'Global Environmental Problems: The Effects of Unilateral Actions Taken by One Country'. Journal of Environmental Economics and Management 20 (1): 55–70. https://doi.org/10.1016/0095-0696(91)90023-C.

———. 1994. 'Efficient Climate Policy in the Presence of Free Riders'. Journal of Environmental Economics and Management 27 (3): 259–74. https://doi.org/10.1006/jeem.1994.1038.

———. 1996. 'Should a Carbon Tax Be Differentiated across Sectors?' Journal of Public Economics 59 (1): 17–32. https://doi.org/10.1016/0047-2727(94)01490-6.

Höhne, Niklas, Takeshi Kuramochi, Carsten Warnecke, Frauke Röser, Hanna Fekete, Markus Hagemann, Thomas Day, et al. 2017. 'The Paris Agreement: Resolving the Inconsistency between Global Goals and National Contributions'. Climate Policy 17 (1): 16–32. https://doi.org/10.1080/14693062.2016.1218320.

Holmes, Peter, Tom Reilly, and Jim Rollo. 2011. 'Border Carbon Adjustments and the Potential for Protectionism'. Climate Policy 11 (2): 883–900. https://doi.org/10.3763/cpol.2009.0071.

IEA. 2021. 'Net Zero by 2050: A Roadmap for the Global Energy Sector'. Paris: International Energy Agency. https://www.iea.org/reports/net-zero-by-2050.

IPCC. 2006. '2006 IPCC Guidelines for National Greenhouse Gas Inventories'. Vol. 1: General Guidance and Reporting. Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_1_Ch1_Introduction.pdf.

———. 2007. Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

———. 2018. 'Global Warming of 1.5ºC'. Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/sr15.

———. 2022. 'Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report'. Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3.

Ismer, Roland, and Karsten Neuhoff. 2007. 'Border Tax Adjustment: A Feasible Way to Support Stringent Emission Trading'. European Journal of Law and Economics 24 (2): 137–64. https://doi.org/10.1007/s10657-007-9032-8.

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins. 2005. 'A Tale of Two Market Failures: Technology and Environmental Policy'. Technological Change and the Environment 54 (2): 164–74. https://doi.org/10.1016/j.ecolecon.2004.12.027.

Jakob, Michael. 2021. 'Climate Policy and International Trade – A Critical Appraisal of the Literature'. Energy Policy 156 (September): 112399. https://doi.org/10.1016/j.enpol.2021.112399.

Jenkins, Stuart, Margriet Kuijper, Hugh Helferty, Cécile Girardin, and Myles Allen. 2023. 'Extended Producer Responsibility for Fossil Fuels*'. Environmental Research Letters 18 (1): 011005. https://doi.org/10.1088/1748-9326/aca4e8.

Jenkins, Stuart, Eli Mitchell-Larson, Matthew C. Ives, Stuart Haszeldine, and Myles Allen. 2021. 'Upstream Decarbonization through a Carbon Takeback Obligation: An Affordable Backstop Climate Policy'. Joule 5 (11): 2777–96. https://doi.org/10.1016/j.joule.2021.10.012.

Jing, Liang, Hassan M. El-Houjeiri, Jean-Christophe Monfort, Adam R. Brandt, Mohammad S. Masnadi, Deborah Gordon, and Joule A. Bergerson. 2020. 'Carbon Intensity of Global Crude Oil Refining and Mitigation Potential'. Nature Climate Change 10 (6): 526–32. https://doi.org/10.1038/s41558-020-0775-3.

Kanemoto, Keiichiro, Daniel D. Moran, Manfred Lenzen, and Arne Geschke. 2014. 'International Trade Undermines National Emission Reduction Targets: New Evidence from Air Pollution'. Global Environmental Change 24 (January): 52–59. https://doi.org/10.1016/j.gloenvcha.2013.09.008.

Karstensen, Jonas, Glen P. Peters, and Robbie M. Andrew. 2018. 'Trends of the EU's Territorial and Consumption-Based Emissions from 1990 to 2016'. Climatic Change 151 (2): 131–42. https://doi.org/10.1007/s10584-018-2296-x.

Kavlak, Goksin, James McNerney, and Jessika E. Trancik. 2018. 'Evaluating the Causes of Cost Reduction in Photovoltaic Modules'. Energy Policy 123 (December): 700–710. https://doi.org/10.1016/j.enpol.2018.08.015.

Kortum, Samuel S., and David Weisbach. 2017. 'The Design of Border Adjustments for Carbon Prices'. National Tax Journal 70 (2): 421–46. https://doi.org/10.17310/ntj.2017.2.07.

Krishnan, Mekala, Hamid Samandari, Jonathan Woetzel, Sven Smit, and Daniel Pacthod. 2022. 'The Net-Zero Transition: What It Would Cost, What It Could Bring'. Washington, DC: McKinsey Global Institute. https://www.mckinsey.com/business-functions/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring#.

Kuik, Onno, and Reyer Gerlagh. 2003. 'Trade Liberalization and Carbon Leakage'. The Energy Journal 24 (3): 97–120.

Law, Abhishek. 2023. 'India to Raise at WTO EU's Plan to Levy Carbon Tax on Imports'. The Hindu BusinessLine, 27 January 2023, sec. Economy. https://www.thehindubusinessline.com/economy/india-may-raise-eus-carbon-tax-issue-at-wto/article66440036.ece.

Levinson, Arik. 2010. 'Offshoring Pollution: Is the United States Increasingly Importing Polluting Goods?' Review of Environmental Economics and Policy 4 (1): 63–83. https://doi.org/10.1093/reep/rep017.

Li, Shanjun, Lang Tong, Jianwei Xing, and Yiyi Zhou. 2017. 'The Market for Electric Vehicles: Indirect Network Effects and Policy Design'. Journal of the Association of Environmental and Resource Economists 4 (1): 89–133. https://doi.org/10.1086/689702.

Lowe, Sam. 2021. 'The EU's Carbon Border Adjustment Mechanism: How to Make It Work for Developing Countries'. London: Centre for European Reform. https://www.cer.eu/publications/archive/policy-brief/2021/eus-carbon-border-adjustment-mechanism-how-make-it-work.

Margolis, Robert M., and Daniel M. Kammen. 1999. 'Underinvestment: The Energy Technology and R&D Policy Challenge'. Science 285 (5428): 690–92.

Markusen, James R. 1975. 'International Externalities and Optimal Tax Structures'. Journal of International Economics 5 (1): 15–29. https://doi.org/10.1016/0022-1996(75)90025-2.

Masnadi, Mohammad S., Hassan M. El-Houjeiri, Dominik Schunack, Yunpo Li, Jacob G. Englander, Alhassan Badahdah, Jean-Christophe Monfort, et al. 2018. 'Global Carbon Intensity of Crude Oil Production'. Science 361 (6405): 851–53. https://doi.org/10.1126/science.aar6859.

Meckling, Jonas O., and Gu Yoon Chung. 2009. 'Sectoral Approaches for a Post-2012 Climate Regime: A Taxonomy'. Climate Policy 9 (6): 652–68. https://doi.org/10.3763/cpol.2009.0629.

Mehling, Michael A., Harro van Asselt, Kasturi Das, and Susanne Droege. 2018. 'Beat Protectionism and Emissions at a Stroke'. Nature 559 (7714): 321–24. https://doi.org/10.1038/d41586-018-05708-7.

Mehling, Michael A., Harro van Asselt, Kasturi Das, Susanne Droege, and Cleo Verkuijl. 2019. 'Designing Border Carbon Adjustments for Enhanced Climate Action'. American Journal of International Law 113 (3): 433–81. https://doi.org/10.1017/ajil.2019.22.

Mehling, Michael A, and Robert A Ritz. 2023. 'From Theory to Practice: Determining Emissions in Traded Goods under a Border Carbon Adjustment'. Oxford Review of Economic Policy 39 (1): 123–33. https://doi.org/10.1093/oxrep/grac043.

Moens, Barbara, and Steven Overly. 2023. 'Trump's Tariff Time Bomb Threatens to Blow up Transatlantic Trade'. Politico, 5 April 2023. https://www.politico.eu/article/donald-trump-steel-tariffs-europe-time-bomb-transatlantic-trade-united-states/.

Naran, Baysa, Jake Connolly, Paul Rosane, Dharshan Wignarajah, Githungo Wakaba, and Barbara Buchner. 2022. 'Global Landscape of Climate Finance: A Decade of Data 2011-2020'. San Francisco, CA: Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-a-decade-of-data.

Nemet, Gregory F. 2019. How Solar Energy Became Cheap: A Model for Low-Carbon Innovation. London: Routledge. https://www.routledge.com/How-Solar-Energy-Became-Cheap-A-Model-for-Low-Carbon-Innovation/Nemet/p/book/9780367136598.

Neuhoff, Karsten, William Acworth, Roland Ismer, Oliver Sartor, and Lars Zetterberg. 2015. 'Leakage Protection for Carbon-Intensive Materials Post-2020'. DIW Weekly Report 28/29. Berlin: Deutsches Institut für Wirtschaftsforschung (DIW). https://www.diw.de/de/diw_01.c.511048.de/publikationen/ecomomic_bulletins/2015_28_3/leakage_protection_for_carbon-intensive_materials_post-2020.html.

Newell, Peter, and Andrew Simms. 2020. 'Towards a Fossil Fuel Non-Proliferation Treaty'. Climate Policy 20 (8): 1043–54. https://doi.org/10.1080/14693062.2019.1636759.

Nordhaus, William D. 2015. 'Climate Clubs: Overcoming Free-Riding in International Climate Policy'. American Economic Review 105 (4): 1339–70. https://doi.org/10.1257/aer.15000001.

Overland, Indra, and Rahat Sabyrbekov. 2022. 'Know Your Opponent: Which Countries Might Fight the European Carbon Border Adjustment Mechanism?' Energy Policy 169 (October): 113175. https://doi.org/10.1016/j.enpol.2022.113175.

Parry, Ian W.H., Simon Black, and James Roaf. 2021. 'Proposal for an International Carbon Price Floor among Large Emitters'. 2021/001. IMF Staff Climate Notes. International Monetary Fund. https://www.imf.org/-/media/Files/Publications/Staff-Climate-Notes/2021/English/CLNEA2021001.ashx.

Pauer, Stefan U. 2018. 'Including Electricity Imports in California's Cap-and-Trade Program: A Case Study of a Border Carbon Adjustment in Practice'. Special Issue: Energy Policy Institute's Eighth Annual Energy Policy Research Conference 31 (10): 39–45. https://doi.org/10.1016/j.tej.2018.11.005.

Perdana, Sigit, and Marc Vielle. 2022. 'Making the EU Carbon Border Adjustment Mechanism Acceptable and Climate Friendly for Least Developed Countries'. Energy Policy 170 (November): 113245. https://doi.org/10.1016/j.enpol.2022.113245.

Persson, Sofia. 2010. 'Practical Aspects of Border Carbon Adjustment Measures: Using a Trade Facilitation Perspective to Assess Trade Costs'. Issue Paper 13. Geneva: International Centre for Trade and Sustainable Development. https://www.files.ethz.ch/isn/138391/persson-ictsd-practical-aspects-of-border-carbon-adjustment-measures.pdf.

Pethig, Rüdiger. 1976. 'Pollution, Welfare, and Environmental Policy in the Theory of Comparative Advantage'. Journal of Environmental Economics and Management 2 (3): 160–69. https://doi.org/10.1016/0095-0696(76)90031-0.

Prest, Brian C. 2022. 'Partners, Not Rivals: The Power of Parallel Supply-Side and Demand-Side Climate Policy'. 22–06. Washington, DC: Resources for the Future. https://www.rff.org/publications/reports/partners-not-rivals-the-power-of-parallel-supply-side-and-demand-side-climate-policy/.

Quick, Reinhard. 2011. 'The Debate Continues: Are Border Adjustments of Emission Trading Schemes a Means to Protect the Climate or Are They "Naked" Protectionism?' In Trade and Competition Law in the EU and Beyond, edited by Inge Govaere, Reinhard Quick, and Marco Bronckers, 119–43. Cheltenham: Edward Elgar.

———. 2020. 'Carbon Border Adjustment: A dissenting view on its alleged GATT-compatibility'. Zeitschrift für Europarechtliche Studien 23 (4): 549–96. https://doi.org/10.5771/1435-439X-2020-4-549.

Rayner, Steve. 2010. 'How to Eat an Elephant: A Bottom-up Approach to Climate Policy'. Climate Policy 10 (6): 615–21. https://doi.org/10.3763/cpol.2010.0138.

Rayner, Tim. 2021. 'Keeping It in the Ground? Assessing Global Governance for Fossil-Fuel Supply Reduction'. Towards a Sectoral Perspective on Global Climate Governance 8 (June): 100061. https://doi.org/10.1016/j.esg.2020.100061.

Richter, Philipp M., Roman Mendelevitch, and Frank Jotzo. 2018. 'Coal Taxes as Supply-Side Climate Policy: A Rationale for Major Exporters?' Climatic Change 150 (1): 43–56. https://doi.org/10.1007/s10584-018-2163-9.

Rossetto, Daniel. 2023. 'The Long-Term Feasibility of Border Carbon Mechanisms: An Analysis of Measures Proposed in the European Union and the United States and the Steel Production Sector'. Sustainable Horizons 6 (June): 100053. https://doi.org/10.1016/j.horiz.2023.100053.

Sanchez, Felipe, and Linus Linde. 2023. 'Turning out the Light: Criteria for Determining the Sequencing of Countries Phasing out Oil Extraction and the Just Transition Implications'. Climate Policy, April, 1–15. https://doi.org/10.1080/14693062.2023.2197854.

Sawyer, Dave, and Renaud Gignac. 2022. 'Border Carbon Adjustments: The Case for a Cooperative, Principles-Based Approach'. Ottawa, ON: Canadian Institute for Climate Choices. https://climatechoices.ca/wp-content/uploads/2022/01/Border-Carbon-Adjustments-scoping-paper.pdf.

Schaufele, Branden. 2021. 'Conceptual Framework for Benchmarking Leakage When Certifying Carbon Credits from Avoided Oil and Gas Extraction'. London, ON: Western University.

Semieniuk, Gregor, Philip B. Holden, Jean-Francois Mercure, Pablo Salas, Hector Pollitt, Katharine Jobson, Pim Vercoulen, Unnada Chewpreecha, Neil R. Edwards, and Jorge E. Viñuales. 2022. 'Stranded Fossil-Fuel Assets Translate to Major Losses for Investors in Advanced Economies'. Nature Climate Change 12 (6): 532–38. https://doi.org/10.1038/s41558-022-01356-y.

Seto, Karen C., Steven J. Davis, Ronald B. Mitchell, Eleanor C. Stokes, Gregory Unruh, and Diana Ürge-Vorsatz. 2016. 'Carbon Lock-In: Types, Causes, and Policy Implications'. Annual Review of Environment and Resources 41 (1): 425–52. https://doi.org/10.1146/annurev-environ-110615-085934.

Shapiro, Joseph S. 2021. 'The Environmental Bias of Trade Policy*'. The Quarterly Journal of Economics 136 (2): 831–86. https://doi.org/10.1093/qje/qjaa042.

Shell and BCG. 2023. 'The Voluntary Carbon Market: 2022 Insights and Trends'. London: Shell. https://www.shell.com/shellenergy/othersolutions/carbonmarketreports/_jcr_content/root/main/section/simple_1854223447/simple/call_to_action/links/item0.stream/1678304843217/3312c86506af1c43a3eb05e11bfdab50ce388d16/shellbcg-the-voluntary-carbon-market-2022-insights-and-trends-eight-march-2023.pdf.

Siebert, Horst. 1977. 'Environmental Quality and the Gains from Trade'. Kyklos 30 (4): 657–73. https://doi.org/10.1111/j.1467-6435.1977.tb02694.x.

Sijm, Jos, Karsten Neuhoff, and Yihsu Chen. 2006. 'CO2 Cost Pass-Through and Windfall Profits in the Power Sector'. Climate Policy 6 (1): 49–72. https://doi.org/10.1080/14693062.2006.9685588.

Sinn, Hans-Werner. 2012. The Green Paradox: A Supply-Side Approach to Global Warming. Cambridge, MA: MIT Press. https://mitpress.mit.edu/books/green-paradox.

Sovacool, Benjamin K., and Joseph Scarpaci. 2016. 'Energy Justice and the Contested Petroleum Politics of Stranded Assets: Policy Insights from the Yasuní-ITT Initiative in Ecuador'. Energy Policy 95 (August): 158–71. https://doi.org/10.1016/j.enpol.2016.04.045.

UNCTAD. 2021. 'A European Union Carbon Border Adjustment Mechanism: Implications for Developing Countries'. United Nations Conference on Trade and Development. https://unctad.org/system/files/official-document/osginf2021d2_en.pdf.

United Kingdom, Government of. 2022. 'Update on Carbon Leakage Mitigations. Statement Made on 16 May 2022'. 16 May 2022. https://questions-statements.parliament.uk/written-statements/detail/2022-05-16/hcws26.

Verde, Stefano F. 2020. 'The Impact of the EU Emissions Trading System on Competitiveness and Carbon Leakage: The Econometric Evidence'. Journal of Economic Surveys 34 (2): 320–43. https://doi.org/10.1111/joes.12356.

Ward, John, Paul Sammon, Guy Dundas, Grzegorz Peszko, and Pauline Kennedy. 2015. 'Carbon Leakage: Theory, Evidence and Policy Design'. Technical Note 11. Partnership for Market Readiness. Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/22785/K8516.pdf.

Weisbach, David, Samuel S. Kortum, Michael Wang, and Yujia Yao. 2022. 'Trade, Leakage, and the Design of a Carbon Tax'. Working Paper 30244. Working Paper Series. National Bureau of Economic Research. https://doi.org/10.3386/w30244.

Weitzman, Martin L. 2014. 'Can Negotiating a Uniform Carbon Price Help to Internalize the Global Warming Externality?' Journal of the Association of Environmental and Resource Economists 1 (1/2): 29–49.

Welsby, Dan, James Price, Steve Pye, and Paul Ekins. 2021. 'Unextractable Fossil Fuels in a 1.5 °C World'. Nature 597 (7875): 230–34. https://doi.org/10.1038/s41586-021-03821-8.

Whitehouse, Sheldon. 2022. Clean Competition Act. https://www.congress.gov/bill/117th-congress/senate-bill/4355/text.

Wood, Richard, Michael Grubb, Annela Anger-Kraavi, Hector Pollitt, Ben Rizzo, Eva Alexandri, Konstantin Stadler, Daniel D. Moran, Edgar Hertwich, and Arnold Tukker. 2020. 'Beyond Peak Emission Transfers: Historical Impacts of Globalization and Future Impacts of Climate Policies on International Emission Transfers'. Climate Policy 20 (sup1): S14–27. https://doi.org/10.1080/14693062.2019.1619507.

World Bank. 2019. 'Report of the High-Level Commission on Carbon Pricing and Competitiveness'. Washington, DC: World Bank. https://doi.org/10.1596/32419.

Zachmann, Georg, and Ben McWilliams. 2020. 'A European Carbon Border Tax: Much Pain, Little Gain'. Policy Contribution 5/2020. Brussels: Bruegel. https://www.bruegel.org/policy-brief/european-carbon-border-tax-much-pain-little-gain.

Zickfeld, Kirsten, Deven Azevedo, Sabine Mathesius, and H. Damon Matthews. 2021. 'Asymmetry in the Climate–Carbon Cycle Response to Positive and Negative CO2 Emissions'. Nature Climate Change 11 (7): 613–17. https://doi.org/10.1038/s41558-021-01061-2.

Ziegler, Micah S., Juhyun Song, and Jessika E. Trancik. 2021. 'Determinants of Lithium-Ion Battery Technology Cost Decline'. Energy & Environmental Science 14 (12): 6074–98. https://doi.org/10.1039/D1EE01313K.

Zimmer, Markus, and Arne Holzhausen. 2020. 'EU Carbon Border Adjustments and Developing Country Exports: Saving the Worst for the Last'. Allianz Research. Munich: Allianz. https://www.allianz.com/en/economic_research/publications/specials_fmo/2020_11_17_EU_CBAM_and_develping_country_exports.html.