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WORKING PAPER

THE CASE FOR A CARBON BORDER ADJUSTMENT: WHERE DO ECONOMISTS STAND?

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On 14 July 2021, the European Commission formally adopted a proposal for a Carbon Border Adjustment Mechanism to mitigate the risk of carbon leakage caused by its increasingly ambitious environmental policies. There is a gap between the ways in which this issue is discussed in political spheres and the evidence provided by economic literature on it. The aim of this paper is to bridge this gap by presenting the context and policy debate surrounding carbon leakage and CBAs in the EU, reviewing the state of the economic literature on this topic, and discussing further research that is necessary to answer remaining policy concerns and unresolved research questions.

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1 Introduction

As the EU has progressively established its Emissions Trading System (ETS), it has had to grapple with the ways in which this system impacts its economic ties with non-EU countries. Under the ETS, producers must buy or be allocated emissions allowances, which they can trade with other participants. At the end of each year, they must turn in enough allowances to cover the greenhouse gas (GHG) emissions from their annual production. This system acts as a price on carbon, which increases participants' production costs.

If the additional cost is high enough to put them at a competitive disadvantage compared to foreign producers, EU producers could lose parts of their market shares. They might also choose to relocate their activity outside the EU to avoid paying this additional cost. Both of these effects would decrease production within the EU, and boost production outside the EU. Not only would this undermine the EU's emission reduction efforts – since any internal reduction in emissions would be compensated by an external increase in emissions – it would also harm its economy and labor markets.

This problem is known as carbon leakage, which is defined in the literature as a displacement of carbon emissions from a region with stringent climate policies towards a region with less stringent climate policies (Naegele & Zaklan, 2019). Carbon leakage is most commonly understood as we have described it above – a mechanism through which regulated domestic firms lose their competitive edge to unregulated foreign firms. However, this is only one of three channels through which carbon leakage can occur. It is known as the competition channel.

The second channel is the energy channel. It is an indirect leakage channel working through global energy markets. As a regulated region reduces its demand for fossil fuels, the price of these goods will drop on international markets. This price drop can create an incentive for firms in the unregulated region to increase their fossil fuel consumption, consequently also increasing their GHG emissions.

Finally, the third channel is the innovation channel, which has an opposite effect to the other two channels. More stringent environmental regulation encourages firms in the regulated region to invest in R&D, innovate, and adopt carbon-abating technologies. Innovations resulting from this may then be diffused to other regions, including those without any environmental regulation. This channel is not discussed much in policy circles, despite its potential for generating negative carbon leakage, i.e., to reduce carbon emissions both in the regulated and the unregulated region.

Up until now, the EU has dealt with the threat of leakage by lowering the stringency of the ETS. This was accomplished by freely allocating emissions allowances to firms covered by the ETS and by allowing the use of international carbon offsets to comply with requirements. However, a new policy option is now being considered to replace free allocations; on 14 July 2021, the European Commission (EC) formally adopted a proposal for a Carbon Border Adjustment Mechanism (CBAM), as part of its Fit for 55 program (European Commission, 2021c). The CBAM imposes a carbon price on foreign goods imported to the EU which should level the playing field between foreign and domestic producers and reduce the risk of leakage. The current proposal foresees a gradual implementation of the CBAM starting in 2023.

The aim of this paper is threefold. First, we will present the context and policy debate surrounding carbon leakage and Carbon Border Adjustments (CBAs) in the EU. Second, we will discuss the state of the economic literature on carbon leakage and CBAs. This will be a broader literature review than in already existing publications, as it will include all three channels of carbon leakage and will cover empirical, as well as theoretical and structural strands of the literature. Finally, we will include discussions on further research that is necessary in this field to answer policy concerns and unresolved research questions.

In this paper, we highlight the discrepancy between the economic literature and policy debates about CBAs. Policymakers tend to focus on the competition channel when designing leakage-prevention measures, without taking into account the potential impacts of the energy and innovation channel. To address this discrepancy, we recommend that policymakers also aim to minimize the impact of the energy channel by developing cooperation with unregulated countries and taking foreign carbon pricing and regulation initiatives into account in the CBA. Additionally, they should work to maximize the impact of the innovation channel by promoting green technology diffusion to unregulated countries and reinvesting CBA funds into an international technology fund.

The paper is structured as follows. Section 2 anchors the problem of carbon leakage in the EU's political and institutional context, discussing the bloc's history of carbon leakage mitigation measures, as well as the debate surrounding the proposal for a CBA. Sections 3, 4 and 5 review the literature on the competition, energy, and innovation channels of carbon leakage, respectively. This review includes discussions on further research that may be needed for each channel. Finally, section 6 presents existing literature on CBAs, and looks at the impact of such a policy on each of the three leakage channels. Section 7 concludes.

2 Political and institutional contexts

This section discusses the political and institutional contexts in which carbon leakage has been apprehended in the EU throughout the different phases of the ETS. We present the policy choices that have been considered over the years and give some insight into why free allocations and international offsets were preferred to CBAs until now. Our aim is to give a solid understanding of the political considerations linked to leakage mitigation policies so they can be put into perspective with the economic literature presented in sections 3, 4, and 5.

2.1 A brief history of leakage mitigation measures in the EU

Carbon leakage has been discussed in the EU policy sphere since the ETS' inception. However, it was not a central issue during the first two phases of the ETS (2005 to 2012). This is mostly due to three factors: first, most emissions allowances were freely given out to firms; second, firms were allowed to use international carbon credit offsets to comply with their obligations; and third, carbon prices remained low. As a result, complying with the ETS during its first two phases did not represent a large financial constraint on firms, which nullified the risk of leakage (Joltreau & Sommerfeld, 2019).

The ETS' first phase (2005 to 2007) was designed as a pilot phase, so producers could adapt to the new regulation and give feedback on its implementation. 95% of allowances were given out freely, based on a grandfathering approach[1]. To determine the total number of allowances needed on the market, countries were asked to develop National Allocation Plans, in which they estimated how many allowances their firms would need based on historical emission data. The goal was to develop an equitable, bottom-up approach to allowance distribution. In practice however, most countries overestimated their producers' needs to protect their national interests. This created an oversupply of allowances throughout the entire trading phase[2]. As soon as the oversupply was revealed, allowance prices dropped. They remained low and volatile until the end of the first trading period (Le Cacheux & Laurent, 2009).

[1]The grandfathering approach allocates emissions allowances proportionally to each installation's historical emissions. This means installations with historically higher levels of carbon emissions are given more emissions allowances than installations with historically lower levels of carbon emissions (European Commission, 2015).

[2]At the end of the first trading period, it was estimated that verified GHG emissions in 2005 totaled 2 billion tons, while the annual average allocation was far higher, totaling 2.2 billion tons (European Commission, 2006). However, Ellerman and Buchner (2008) argue that in 2005-2006, there was no significant over-allocation. In their opinion, the difference between total emissions allowances and total observed emis-

In the second phase (2008 to 2012), more allowances were auctioned off to producers, but the majority (90%) remained freely allocated using the same grandfathering approach as in the first phase. Allowance oversupply was avoided in this phase through a stricter oversight of National Allocation Plans by the EC (Kossoy & Ambrosi, 2010).

Despite this, allowance prices remained low during this phase for two main reasons. The first was a policy choice. The ETS was designed with a link to the UNFCCC's Clean Development Mechanism, which allowed EU firms to cover their carbon emissions not only by turning in ETS-issued allowances, but also by turning in international credits from the Clean Development Mechanism[3]. The possibility of complying with ETS obligations in this alternative manner, which could be cheaper than buying allowances, reduced demand for ETS allowances[4], thus lowering prices on the EU carbon market (Trotignon, 2011). There is also evidence that CDM credits were granted quite liberally, and that many projects that were awarded these credits would have been built without them (Calel et al., 2021). This implies there was a strong incentive for firms to invest in CDM projects - that were lucrative anyways - rather than invest in the decarbonization of their domestic production.

The second reason why prices remained low was circumstantial: the 2008-2009 financial crisis led to a collapse in production which caused a drop in demand for allowances, mechanically driving carbon prices down as well (de Perthuis & Trotignon, 2014).

While leakage itself was not an issue during this second phase of the ETS, the subject began taking up more space in policy debates as planning for the ETS' more ambitious third phase started. In 2008/2009, during the review period before the launch of the ETS' third phase (2013 to 2020), carbon leakage was more explicitly discussed, mostly in terms of the threat it posed to the competitiveness of EU industry. In this third phase, free allocations were to be gradually replaced with an auctioning mechanism, potentially increasing EU firms' compliance costs and making them more vulnerable to unregulated foreign competition.

This is when the idea of a CBA gained some traction for the first time – though it was not implemented at this stage. By imposing a carbon price on imports, equal to the

sions is not substantial, and could be the result of lower production levels and abatement strategies.

[3]These credits represent the amount of carbon removed from the atmosphere or reduced compared to a business-as-usual scenario as a result of a firm's project in a developing country. ETS participants have been allowed to use Certified Emission Reduction (CER) credits from Clean Development Mechanism projects since the first phase of the ETS. However, the two systems were only directly linked for accounting purposes in 2008, and the economic incentive to use this link was stronger in the second phase of the ETS. This meant that CER credits were only used for compliance with ETS obligations starting in the second phase (Ellerman et al., 2010).

[4]Participants used 1.058 billion tons of international credits in phase 2 to comply with their ETS obligations (European Commission, 2016).

EU's internal carbon price, a CBA was seen as an option to mitigate the risk of carbon leakage and of loss of competitiveness.

A first proposal for a CBA on imports and exports of goods "subject to significant risk of carbon leakage or to international competition" was included in a draft proposal amending the ETS[5]. Additionally, the French government published a non-paper promoting a "Carbon Inclusion Mechanism" in 2009 and pushed for this policy in Brussels (Simon, 2010). However, the idea was not taken up and the final amendment proposal did not include any mention of a CBA. Instead, it included the use of targeted free allocations for sectors at risk of carbon leakage. A list of these sectors was drawn up in 2010 and amended in 2014 on the basis of their carbon intensity and exposure to international trade. They received a higher share of free allocations than other sectors. On top of this, international carbon offsets remained available to firms who wished to use them for compliance.

The debate over a CBA replacing free allocations was taken up again during the review period for the ETS' fourth phase (2021 to 2030). In 2016, a second French non-paper proposed a CBAM that would only be applied to the cement sector as a test. However, this was rejected in the European Parliament in favor of keeping targeted free allocations.

Breaking with its previous policy line, the EC announced in its 2020 Green Deal that it would be putting forward a proposal for a CBA to gradually replace free allocations in the fourth phase of the ETS. Published on 14 July 2021, this proposal provides for a CBAM that would cover imports from 5 sectors: cement, electricity, fertilizers, iron and steel, and aluminium. Importers would have to buy CBAM certificates from a pool mirroring - but separate from - the ETS and surrender enough of these certificates to cover the total embedded emissions of their yearly imports. These certificates would be priced at the level of the weekly average of ETS certificate closing prices. The regulation is expected to enter into force in 2023, with a transition period running until 2026 (European Commission, 2021c).

The idea of introducing a CBA instead of free allocations is not new, but until now, it had not been taken up by policymakers for implementation. Why did the EU not take up this option before? And why might it now consider a CBA to be viable? The following subsection aims to answer these questions.

[5]Draft Proposal 2007/XXXX (COD) for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the EU greenhouse gas emission allowance trading system.

2.2 Has a CBA become a viable policy option?

Up until now, the EU had rejected the idea of a CBA, in part because of the complexity of its implementation. It is unclear whether a CBA could be designed to comply with WTO law as well as with the UNFCCC's principle of Common but Differentiated Responsibilities. Additionally, such a policy could expose the EU to retaliation from trade partners who view it as a protectionist measure. We discuss each of these issues here.

Compliance with WTO law is uncertain for several main reasons. The first is that certain principles of WTO rules might not be compatible with a CBA, depending on how it is designed. The principles of Most Favored Nation[6] and of National Treatment[7] could be challenging in this regard. The second reason is that certain technical aspects of WTO rules might not allow for a CBA to be implemented at all – namely the fact that a CBA would tax CO2, an intangible and not easily measurable output in the production of a good. Both of these issues could be overcome if the EU can successfully argue the necessity and proportionality of a CBA for the protection of the environment. However, this is also a challenge given that preliminary studies on CBAs do not clearly indicate that the policy would have strong environmental benefits (see section 3). For a full discussion on WTO-compliance issues, see Mehling et al. (2019). The main takeaway from the legal debate on CBAs is that the design of the policy should focus on ensuring environmental benefits can be obtained from it. This would make it more likely to be WTO-compliant.

Another issue which makes designing a CBA so complex is the necessity of complying with the UNFCCC's principle of Common but Differentiated Responsibility. The principle states that while all countries are commonly responsible for addressing climate change and environmental destruction, each country's contribution to this cause should be proportional to its capacity to act and to its share of responsibility in historical global emissions. This means that developed countries are expected to contribute more than developing countries, the latter being responsible for a small share of historical global emissions and having more limited means of action. Böhringer et al. (2018) show that a CBA in OECD countries shifts the burden of decarbonization from developed countries onto developing countries, due to an adverse terms-of-trade effect caused by higher export prices. Additionally, Espagne and Magacho (forthcoming) highlight that some developing countries are particularly exposed to the costs of an EU CBAM given their heavy reliance on exports of

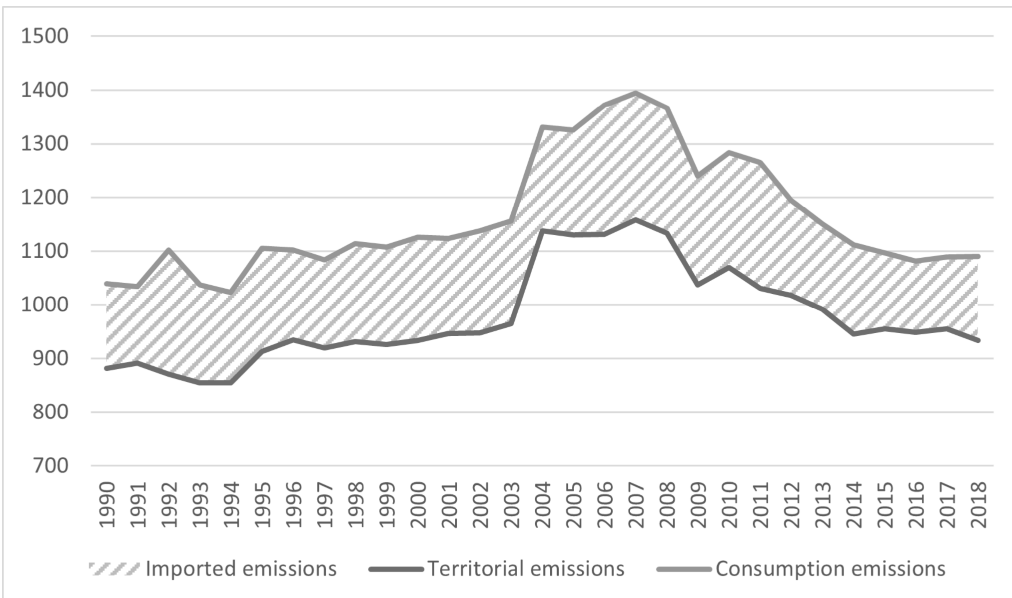
[6] In WTO law, the Most-Favored-Nation clause forbids countries from implementing trade policies that discriminate between different WTO member nations.

[7] In WTO law, the National-Treatment clause forbids countries from implementing trade policies that favor their domestic producers over foreign producers.

products that will be covered by the regulation. This is especially salient when looking at the weight of these exports in some countries' total exports and GDP. As such, this policy could unduly shift burden onto developing countries, making it non-compliant with the UNFCCC's principle of Common but Differentiated Responsibility.

Given that the EU is a net carbon importer (see figure 1), a CBA would also create adverse terms of trade for its main trading partners. To avoid shifting this burden onto developing countries, they could be excluded from the CBA's scope, or compensated with the revenue from the CBA. However, this would create more complications for WTO compliance.

Figure 1: The EU's carbon loophole



Note: EU changing composition
Source: Authors' visualization based on The Global Carbon Project[8]

Finally, the last major argument used against implementing a CBA is the fear of retaliation from trade partners. The EU's carbon imports mostly come from China, the US, India, and Russia (Peters et al., 2011). These would be the countries most capable and inclined to retaliate with their own trade measures. This risk is especially present given the frayed state of the current international trade environment, and the fact that a CBA's environmental benefits are not yet certain.

[8]For territorial emissions: Friedlingstein et al. (2020)
For consumption emissions: updated from Peters et al. (2011), 2011. Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the National Academy of Sciences 108, 8903-8908. http://www.pnas.org/content/108/21/8903.abstract

Each of the three points presented above have stopped the EU from implementing a CBA until now. The bloc's recent shift in policy preference could be explained by several factors. One of them is that the current global geopolitical environment is very different from what it was when a CBA was first proposed. Some of the world's largest international players – the US first and foremost – have turned to more protectionist and unilateral trade policies. In such an environment, if the EU were to impose its own unilateral trade policy, not only would the opportunity cost be lower, but there would also be less risk of a coordinated retaliation from its trade partners. Another factor which might sway the EU towards a CBA is the internal pressure EU countries are facing from their population as the bloc's environmental ambition increases. In order to be socially acceptable, the EU cannot let its producers bear the full brunt of compliance with environmental regulation while competing with unregulated foreign producers, nor can it let its consumers pay for fully passed-through compliance costs.

Beyond these geopolitical considerations, a CBA may be preferred now because free allocations have proven to have significant flaws. There are two main questions which policymakers and researchers have tried to answer to assess the effectiveness of free allocations. First, have they effectively protected EU firms from unregulated foreign competitors? Second, have they also inadvertently muted the ETS' price signal and reduced its environmental effectiveness?

While current evidence seems to indicate that EU firms have not suffered competitiveness losses as a result of participating in the ETS (Joltreau & Sommerfeld, 2019), most studies only look at the first, second, and beginning of the third phase due to data availability. In this period, free allocations appear to have been effective at protecting EU firms from competition with unregulated foreign firms. However, as discussed above, the absence of competitiveness losses could also be the consequence of low carbon prices in this period, and of the possibility of using international carbon credits.

To understand the impact of free allocation on environmental outcomes, researchers have studied how this mode of allocation impacts firms' incentives to abate their emissions. In theory, there should be no difference in firms' abatement decisions whether allowances are freely allocated or auctioned, because the opportunity cost of an allowance is the same in both cases. If allowances are freely allocated, a firm deciding not to abate its emissions will lose out on potential income it could have received from selling its allowance. This lost income is the same amount as what it has to pay to buy an allowance if they are auctioned.

In practice however, the hypothesis of neutrality of the mode of allocation does not seem to hold. Evidence from De Vivo and Marin (2018) points to a difference in behavior between firms freely receiving allocations and those subject to auctioning. There could be two main reasons for this. The first is that firms may not be making fully rational decisions; they may choose to change their abatement decisions based on a false sense that auctioning is more burdensome than free allocations. The second is that while the method of allocation may be neutral on firms' opportunity cost, auctioning has an impact on a firm's total compliance burden, while free allocations do not. The opportunity cost determines a firm's abatement decisions (i.e., whether or not to reduce its production to meet emission goals) while the total compliance burden determines its investment strategy (i.e., long-term investments to improve the efficiency of production). As a result, switching to auctioning could have an effect on firms' investment decisions. This possibility would have to be confirmed with further empirical research as the data currently available does not allow a validation of either of these hypotheses.

This is a particularly important research question, since the EU's carbon price is set to gradually increase, and with it, the long-term incentive for firms to invest in decarbonizing processes. If free allocations mute this incentive, then the environmental efficacy of the ETS is at risk. It is crucial to ensure that firms receive strong and long-term price signals so they can make investment decisions that take environmental factors into account. Firms will only invest in long-term technology and process transformations to decarbonize their production if they feel that the alternative – buying enough allowances to cover their emissions – is more expensive. As such, free allocations risk causing a high-carbon technology lock-in.

This section has described the most important issues surrounding the EU ETS' effectiveness with regards to environmental and competition goals. The crux of the problem is carbon leakage, a mechanism which can result from unevenly ambitious environmental regulation in different countries. We now look at the evidence of carbon leakage in the academic literature, through each of the three channels we have presented in section 1. Our aim is to bridge the gap between the policy debates we have just described, and the risks and opportunities identified in the academic literature.

3 The competition channel

As stated in the first section, most EU policy debates surrounding carbon leakage center on the competition channel[9]. This section aims to give an in-depth understanding of

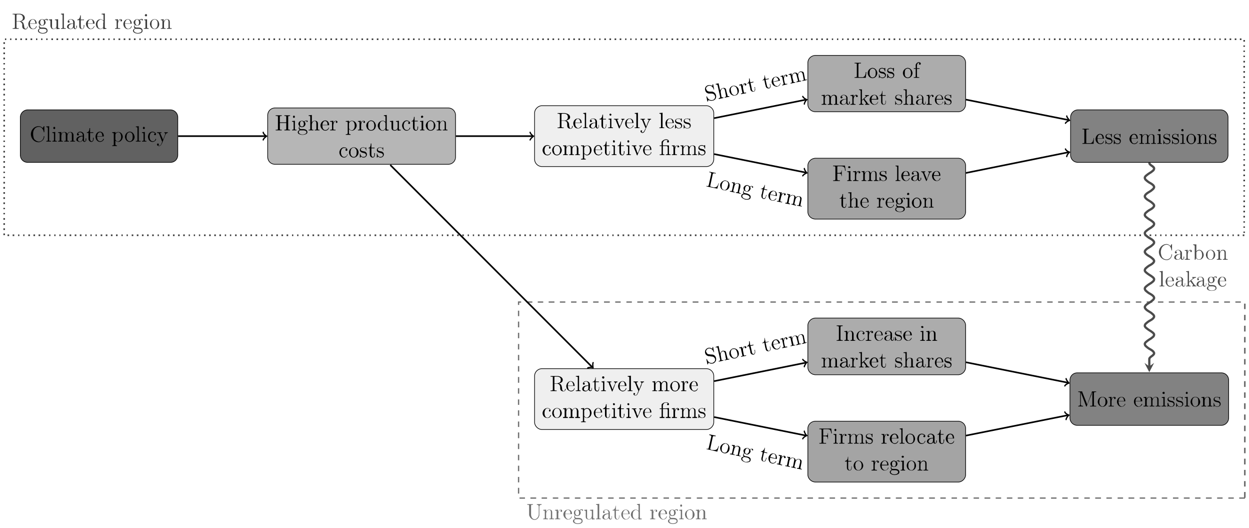
[9]An illustration of this can be found in the EU's Impact Assessment Report of a CBAM (European Commission, 2021a). In this document, carbon leakage is defined as "increasing emissions outside the Union through relocation of production or increased imports of less carbon-intensive products", implying

the workings of this channel, highlighting major findings from different strands of the academic literature. We first present the basic functioning of the competition channel through its roots in game theory, before turning to empirical evidence from the ex-post literature and finishing with partial and general equilibrium models. The choice of organizing this literature by methodology is driven by the fact that both quantitative and qualitative results greatly depend on the methodology used in each study.

3.1 How does the competition channel work?

Carbon leakage through the competition channel occurs when a region implements constraining environmental policies on its territory. Its domestic producers face additional costs to comply with the regulation, which puts them at a competitive disadvantage compared to foreign producers who supply the same markets but are not subject to the additional compliance costs (see figure 2).

Figure 2: A schematic view of the competition channel



Source: Authors

In a perfect competition setting, there are two possible consequences to this loss of a competitive edge. First, in the short run, domestic producers may lose market shares to unregulated foreign competitors. Second, in the long run, domestic producers may choose

the official stance is to consider leakage only through the competition channel. It is also the only channel which is discussed by third parties in the consultations led by the EC. On the other hand, the energy channel is briefly mentioned just twice in the whole document, in the technical section describing the CGE model they use to estimate the impact of a CBAM.

to relocate part or all of their activity to countries with less stringent climate policies. This second consequence is also known as investment leakage.

While classical economic theory and most CGE models use a perfect competition setting, carbon leakage has also been modeled in the context of more realistic settings with strategic interactions and imperfect competition. The competition channel was in fact first formalized using game theory, which models international trade as a game between trade partners that may exhibit strategically motivated behaviors. Within game theory, two foundational strands exist: one at the country level and one at the firm level.

Hoel's (1991) seminal paper is at the core of the first, country-level strand. He sets up a two-country model, in which each country aims to maximize its benefit function and can decide on the quantity of emissions it abates domestically as well as its level of production. Its cost function increases with the amount of emissions it decides to abate domestically, while its benefit function increases with the sum of emissions both countries decide to abate. In this setup, and in the absence of an international agreement on emissions reductions, both countries will always choose not to abate their emissions. If one country were to abate its emissions unilaterally, the other country would mechanically increase its emissions to reduce its cost function, without any loss to its benefit function. This is an expression of carbon leakage at the country level as an uncooperative and non-Pareto efficient Nash equilibrium. Emissions are simply shifted from one country to the other, without any global reductions.

The second, firm-level strand of game theory literature on carbon leakage was developed by Markusen et al. (1993). In their model, if one region decides to implement constraining environmental regulation, firms in this region decide to relocate their activity to an unregulated region and export part of their production back into the regulated region. Many firms may relocate at once if the constraint from the new environmental policy exceeds the fixed cost of relocating production. As such, there is also only a redistribution of emissions between countries, rather than a global decrease in emissions.

The analytical conclusions derived from these early works are the foundation for empirical tests and structural models that have been developed since then to evaluate the risk of carbon leakage. In the case of the ETS, the question is therefore to understand whether the financial constraint of compliance has been large enough to induce a leakage effect. According to theoretical models, this should be the case. The following subsection discusses empirical testing of this hypothesis.

3.2 Has the ETS caused carbon leakage?

Different strategies have been adopted to empirically test for carbon leakage caused by the ETS. Most studies find no evidence of carbon leakage so far. Verde (2020) surveys the econometric literature on this topic and concludes that very little, if any, carbon leakage can be causally linked to the ETS. The author identifies four major strands of research.

The first comprises of microeconomic studies of firm-level or sector-level competitiveness indicators such as value added, employment or total factor productivity. The ETS' short-run impact on these indicators depends on the specific measure that is used. However, most of the effects are either null or weakly negative – and in some cases even positive, meaning the ETS has actually improved EU firms' competitiveness. This could be because some carbon cost passthrough may be occurring or because firms are investing in carbon-abating innovations which are also productivity-enhancing.

The second strand Verde identifies is composed of studies looking at long-term investment leakage. The ETS' long-run impacts have been studied less than its short-run impacts and results are consequently not as clear cut. Two studies looking at investment leakage find that the ETS may have increased multinational firms' FDI towards non-EU countries. However, they look only at Italian and German firms respectively (Borghesi et al., 2020; Koch & Mama, 2019) and find a relatively small effect.

The third strand of the literature tries to find direct evidence of carbon leakage rather than looking at indicators of competitiveness. Only a few studies follow this approach. Naegele and Zaklan (2019) study the carbon content of trade to and from the EU using a gravity model, while Dechezleprêtre et al. (2019) study carbon leakage within multinational firms. The latter study has been updated and extended in Dechezleprêtre et al. (2020), which covers the first two years of the ETS' third phase. Each of these studies finds no evidence of carbon leakage resulting from the ETS. A recent study by Eskander and Fankhauser (2021) looks more broadly into the impact of climate regulation on carbon imports and exports. Interestingly, they find that legislation from 3 years ago and older has in fact led to a small, but significant, negative leakage effect. However, this is not an ETS-specific result.

Finally, Verde discusses a last, more distinct, strand of the literature which studies the effect of ETS allowance prices on participating companies' stock returns. The papers in this strand aim to measure the impact of carbon pricing on investors' beliefs about a firm's future profitability, rather than its present profitability. Their results do not measure how much leakage has occurred, but rather how much investors believe ETS prices affect the firm's profitability, which may in turn lead to leakage – although this is not tested for.

Two main results emerge from this literature. First, the relationship between carbon prices and stock prices is generally found to be positive in the ETS' first phase and negative in the second and third phases. This suggests the mode of allocation has an effect on investors' perception of firm profitability. Second, more carbon-intensive firms' stock prices tend to be negatively correlated with ETS prices, while less carbon-intensive firms' stock prices tend to be positively correlated with them.

The common conclusion from all four strands is that carbon leakage does not seem to have materialized as a result of the ETS. However, an important caveat should be highlighted: due to data availability, most of the surveyed literature looks only at the first two phases of the ETS – and the first years of the third phase for a few of them. During this period, free allocation was the general rule and carbon prices remained low. Researchers exploited breaks in this general rule to study leakage, but this may not accurately reflect the current situation in which prices have tripled, and free allocations have gradually been replaced by auctioning[10]. As a result, the ETS' financial impact on firms is likely greater than it was during the period that is studied in the literature, which could imply more carbon leakage is occurring than previously measured.

Additionally, there may be a stronger risk of within-firm leakage than of between-firm leakage inside the EU. Since the ETS regulates only installations whose emissions are above a certain level, certain firms with multiple installations may be switching some of their production from regulated installations to unregulated installations - thus artificially reducing emission levels in the regulated installations. While this phenomenon has not yet been studied in depth in the ETS' context, it has been observed in the context of environmental regulations in the US (Gibson, 2019; Soliman, 2020). The only study looking at this in the ETS context finds no evidence of within-firm leakage. However, this is once again using data which does not go further than the second phase (Wagner et al., 2014).

While observed leakage remains quite low for now, the EU is planning on tightening the ETS to become gradually more stringent. Free allocations will be fully phased out for sectors that do not have a high risk of leakage by 2030 and the ETS' cap will be tightened by reducing the overall number of allowances on the market by 2.2% each year from 2021 onwards, instead of 1.74% as is currently the case. This should increase the price of carbon over time as well as the financial constraint on participants that do not receive free allocations. This might in turn increase the risk of leakage.

[10]As of 2013, 100% of allowances were auctioned in the power sector. In the manufacturing sector, 20% of allowances were auctioned in 2013. This was gradually increased to 70% in 2020, excluding sectors on the list of high leakage risk. In the aviation sector, 15% of allowances were auctioned in the third phase. Overall, 57% of allowances were auctioned in this phase.

The impacts of this policy tightening cannot yet be tested empirically. As such, *ex ante* models can provide valuable insights into the potential impacts of a more constraining ETS. We now turn to the description of these models and their main conclusions about carbon leakage through the competition channel.

3.3 What drives carbon leakage according to *ex ante* general equilibrium models?

Computable General Equilibrium (CGE) models have been the workhorse models used to quantitatively assess the risk of carbon leakage linked to different policy scenarios. These models identify the conditions under which significant carbon leakage can occur, the policy choices that can mitigate this risk, and the behavioral and contextual parameters which can exacerbate or reduce the problem. Most of them use data from the Global Trade Analysis Project (GTAP) to calibrate behavioral parameters and elasticities, which are then used in *ex ante* policy simulations, generally imposing a carbon price on a given region. To avoid any distortionary effects, most of these studies include revenue recycling for this carbon price, in the form of a lump-sum transfer back to consumers (Carbone & Rivers, 2017).

Though these models provide quantitative results on the amount of carbon leakage which can be expected given certain assumptions – which we briefly discuss below –, these results are quite sensitive to the calibration choices made in each model. As such, the qualitative insights from this literature are more important to understand leakage.

Branger and Quirion (2014) perform a meta-analysis of CGE studies on the topic of carbon leakage and find that estimates of the leakage ratio[11]range from 5 to 25%. This means that up to one quarter of the emission reductions a climate policy induces in the region where it is implemented are compensated by an increase of emissions in the unregulated region.

Carbone and Rivers (2017) review the CGE literature specifically studying the impact of environmental policies on competitiveness indicators. They find that the literature identifies an average 5% reduction in the output of energy-intensive and trade exposed (EITE) sectors resulting from a 20% unilateral emission abatement objective. This seems to indicate that in a scenario where carbon pricing becomes more stringent, there could be a higher risk of carbon leakage, especially for EITE sectors. However, the magnitude of this phenomenon is not clear and highly depends on the parametrization of each CGE model.

[11]The carbon leakage ratio is the measure most often used in CGE models to assess the amount of carbon leakage linked to a policy scenario. It is generally measured as the increase in emissions outside the regulated region divided by the decrease in emissions inside the regulated region.

Some of the parameters that are used in CGE models have a particularly large influence on the size of the estimated carbon leakage ratio. The most determining parameters are the Armington elasticity[12], the size of the abating coalition, and market structure assumptions. This is somewhat problematic given that there is uncertainty surrounding the value of these parameters, as described below.

Estimates of the Armington elasticity, which measures the degree of substitutability between foreign and domestic products, can vary substantially; differences in estimates are largely driven by the level of data aggregation, as well as data size, frequency, and dimension (Bajzik et al., 2020). Despite the uncertainty surrounding the real value of this elasticity, Branger and Quirion (2014) note in their meta-analysis that the choice of a high Armington elasticity has a positive and statistically significant impact on a model's estimate of the carbon leakage ratio. To get around this, some studies carry out sensitivity analyses using relatively higher and lower values of the Armington elasticity to produce a range of leakage estimates. However, this does not remove all of the uncertainty related to this parameter.

Another parameter which influences the magnitude of leakage found in CGE models is the size of the abating coalition – i.e., how many countries are jointly implementing a carbon price. There is more certainty about the value of this parameter given that it is an observable policy choice. Additionally, there is also more of a consensus over the fact that it has a large negative impact on the leakage ratio. This means that the larger the coalition is, the less leakage occurs. Branger and Quirion (2014) estimate that there is a 12-percentage point difference between the carbon leakage ratio if Europe unilaterally abates its emissions and the carbon leakage ratio if a coalition made up of all Kyoto protocol Annex 1 countries and China, excluding Russia, jointly abates its emissions.

Finally, market structure assumptions can also influence the amount of leakage that models find. Most CGE models assume perfectly competitive Armington structures of international trade. However, Babiker (2005) and Balistreri and Rutherford (2012) show that departing from this structure can lead to much higher leakage estimates. Babiker adopts an oligopolistic structure and assumes energy-intensive goods are Heckscher-Ohlin in structure – meaning that goods produced in different countries are perfectly substitutable. In this scenario, the leakage ratio exceeds 100%. Babiker (2005) explains this surprising result by the fact that unexploited economies of scale in energy-intensive industries could be unlocked when production is relocated to developing countries. Balistreri and Rutherford

[12]Armington structures of trade assume that identical products from different countries are imperfect substitutes. The extent to which products are differentiated by country of origin is measured by Armington elasticities, which are cross-elasticities between two identical products from different countries (Armington, 1969).

(2012) apply Melitz's (2003) "New" New Trade theory, a monopolistic competition structure, to an otherwise standard CGE model. They find that adding firm heterogeneity to their model exacerbates the problem of carbon leakage through the competition channel because resources are reallocated to the most productive firms in the unregulated region, which do not have any incentive to reduce their emission intensity.

Mathiesen and Mœstad (2004) make the argument that the broad scope of general equilibrium models does not allow for enough sectoral specificities when estimating the carbon leakage ratio. Their paper focuses on the steel sector. They use a partial equilibrium framework and show that adding substitution possibilities between different types of steel production and between inputs to steel production halves the leakage ratio compared to what general equilibrium models – which do not include these specificities – generally find. Another potential source of effect overestimation is that most CGE models apply an economy-wide carbon tax, without any sectoral exemptions. This does not reflect the ETS's functioning, as the regulation only applies to certain industries and thus has a more restricted perimeter which should create a smaller risk of leakage.

The main takeaway from the CGE literature is that while the magnitude of leakage caused by the ETS is uncertain, there is a general consensus around the fact that the more constraining carbon pricing is, and the smaller the abating coalition is, the more of a problem carbon leakage may become.

3.4 What are the remaining gaps in the literature for the competition channel?

As we have seen, the economic literature is inconclusive about how much of a problem leakage through the competition channel actually is. While the empirical literature shows that leakage has not been a problem in the first phases of the ETS, it does not yet give results about the more constraining recent phases of the system. On the other hand, *ex ante* literature points to a higher risk of leakage, the magnitude of which is uncertain.

This literature could therefore be completed with empirical assessments of more recent phases of the ETS, once data becomes available. Concerning *ex ante* modelling, more work could be done on the impact of the ETS on value-chains inside and outside the EU, and how network effects could exacerbate leakage.

Additionally, non-price competition is not taken into account in existing models, despite the fact that it may have a significant impact on international trade patterns (Bas et al., 2015). Vertical competition through quality or branding could significantly affect the leakage ratio if consumers have a strong preference for higher quality products. For example, if EU steel producers manage to successfully decarbonize their production, they will likely be able to pass on higher production costs to construction companies which face increasing pressure and mounting regulatory standards to include environmental criteria in their production decisions.

4 The energy channel

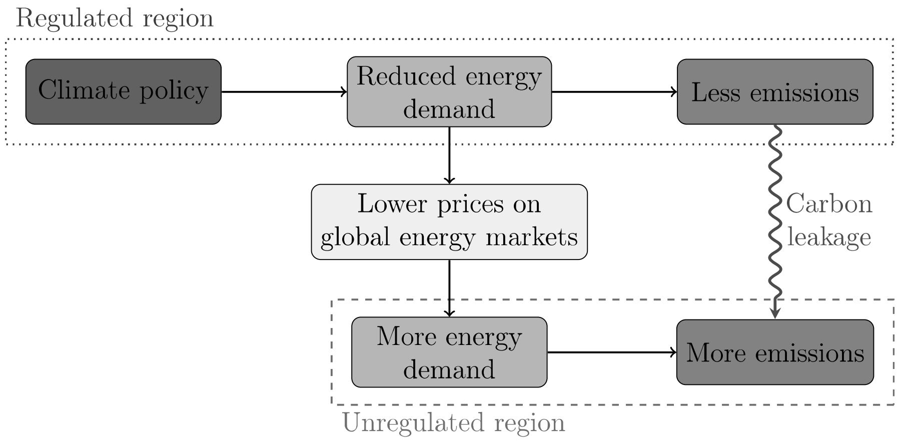
The energy channel is less discussed than the competition channel in policy circles, but it has been identified in the economic literature as a potentially large, long-term threat to the effectiveness of a region's environmental policy. In this section, we first discuss the mechanism underlying this channel, before reviewing the literature studying the magnitude of leakage that could occur through it. This is generally studied using CGE models. We also discuss the empirical evidence that can be linked to this channel, before highlighting research areas that should be explored in the future.

4.1 How does the energy channel work?

Carbon leakage through the energy channel is a macroeconomic phenomenon resulting from a price change on international energy markets (see figure 3). As a region increases the stringency of its environmental policies and transitions its energy system away from fossil fuels, its domestic demand for fossil fuels should decrease and tend towards zero in the long run. The region's lower demand for fossil fuels puts a negative pressure on the price of these products on global markets. As a result, producers in unregulated regions have an incentive to increase their fossil fuel consumption as these fuels get cheaper. They do this either by substituting them into their production process, or by increasing their output. The regulated region's lower demand for fossil fuels, and consequent decrease in emissions, are therefore compensated by an increased demand in unregulated regions (Arroyo-Currás et al., 2015).

From a policy perspective, it is important to understand the relative weight of the energy channel compared to the competition channel. Policy instruments like free allocations and CBAs are only effective to tackle leakage through the competition channel but have no impact on energy markets and prices. As such, they are not adequate policies to tackle leakage through the energy channel. If the energy channel is larger in magnitude than the competition channel, other policy instruments should be developed to deal with this second leakage channel.

Figure 3: A schematic view of the energy channel



Source: Authors

4.2 What is the magnitude of leakage through the energy channel?

To get an initial idea of the potential risk the EU faces from leakage through the energy channel, we first need to understand how much sectors covered by the ETS weigh in the bloc's overall final demand for fossil fuels. We estimate that the ETS covers sectors that account for roughly 15% of the bloc's final consumption of fossil fuels[13]. Sectors like road transport and households account for much larger shares of final fossil fuel consumption (44% and 20% respectively), so it seems doubtful that the regulation as it stands would induce a large shock on energy markets, even if it does induce deep decarbonization in the sectors it covers. The mirror ETS which has been proposed to cover these higher-consumption sectors (European Commission, 2021b) could generate more of a risk of leakage through the energy channel.

This channel has almost exclusively been studied through *ex ante* structural models. Empirical methods have not been used due to the absence of observable country-specific demand shocks on fossil fuel markets resulting from stringent environmental policies. The *ex ante* literature does not decisively converge on the relative importance of the energy

[13]This estimate does not account for the energy sector, which is covered by the ETS but is counted as an intermediary consumption in energy balances, rather than final consumption. These figures were calculated based on the EU's energy balances, available at https://ec.europa.eu/eurostat/web/energy/data/energy-balances.

channel compared to the competition channel, mostly because of the sensitivity of estimates to certain parameters. For instance, the EC's own estimates of carbon leakage under different policy scenarios includes effects from the energy channel, but their study does not discuss the decomposition between the energy and the competition channel - or of how the former channel affects leakage rates under a CBAM scenario (European Commission, 2021a).

By far the most determining parameter in energy channel leakage estimates is the elasticity of fossil fuel supply (Burniaux & Oliveira Martins, 2012). This channel hinges on the effect of a downward price pressure on global fossil fuel markets. If fossil fuel suppliers cannot adapt their production levels to a negative demand shock (low supply elasticity), lower prices should incentivize producers in unregulated regions to increase their consumption of fossil fuels. This will generate high levels of leakage. However, if suppliers can adapt their production levels when faced with a negative demand shock (high supply elasticity), they can drive prices back up by cutting supply, which would significantly limit leakage.

Another factor which may influence leakage estimates is the Armington elasticities of fossil fuels, which measure the degree of substitutability between foreign and domestic fuels. Indeed, even for one fossil fuel type, like oil for instance, different grades and variants extracted from different regions of the world may not be perfectly substitutable – although empirical evidence seems to indicate that substitution elasticities between different regions are still quite high (Balistreri et al., 2010).

In their study, Burniaux and Oliveira Martins (2012) run sensitivity analyses on a simplified static CGE model to determine which parameters have a significant influence on the value of leakage estimates. Aside from highlighting the importance of the elasticity of fossil fuel supply, they also note that the Armington elasticity, which largely determines leakage through the competition channel but does not impact leakage through the energy channel, has a smaller influence on the overall leakage ratio. This could indicate that the energy channel makes up a larger share of the overall leakage ratio than the competition channel does.

Boeters and Bollen (2012) further explore the question of the relative importance of each channel of leakage. To disentangle leakage through the energy channel from leakage through the competition channel, the authors compare dynamic CGE models in which they fix the price of fossil fuels at their business-as-usual levels (thus removing leakage through the energy channel) with dynamic CGE models in which they do not. They fix fossil fuel prices by adding a compensatory output tax in the system of equations modeling supply and demand responses to a demand shock. The tax adjusts to stabilize the buyer's price and allows for the stock of natural resources to remain untouched in the case of a negative demand shock. The authors include two different model specifications for the redistribution of revenue from their tax: one in which the revenue is redistributed to exporters from the unregulated region, and one in which it is redistributed to importers from the regulated region. These alternative specifications do not impact the results related to leakage, but allow the authors to demonstrate that welfare in the regulated region is larger when revenue is redistributed to importers. Their results show that the energy channel causes a larger share of leakage than the competition channel does, especially if Europe unilaterally abates its emissions without partnering with other Annex 1 countries.

Huppmann and Egging (2014) find a similar result using a dynamic bottom-up energy system model rather than a top-down elasticity of substitution model, as is common in CGE models. They conclude that tightening the EU ETS could lead to a leakage ratio of 60 to 70% via the energy channel.

Contrary to these findings, Arroyo-Currás et al. (2015) argue that leakage through the energy channel might be more restricted than is commonly thought because demand for fossil fuels in unconstrained regions will eventually saturate. They argue that substitution possibilities between fossil fuels are also not infinite. Their dynamic model thus imposes an upper bound on the amount of leakage that is possible through global energy markets. It includes transport costs for international fossil fuel trade, as well as low carbon prices even in unconstrained regions, which further lowers their leakage estimates. The overall leakage ratio their model finds does not exceed 15%.

A separate but related strand of the literature focuses on inter-temporal carbon leakage, a mechanism which also operates through global energy market prices and is founded on the Hotelling rule[14]. In this literature, stringent climate policies only change the temporal profile of the extraction and consumption of fossil fuels, but not the total, long-term amount that is ultimately extracted and consumed. When prices are low (high), producers extract and sell more (less). As a result, implementing gradually increasing carbon prices may actually incentivize forward-looking fossil fuel producers to increase their present extractions and sales in anticipation of higher future production costs. This is a mechanism known as the green paradox, developed by Sinn (2012). For a full literature review on this topic, see Jensen et al. (2020).

As we have seen, CGE models tend to indicate that the energy channel causes more leakage than the competition channel, with some notable exceptions such as the study by

[14] In its most basic form, the Hotelling rule implies that for an infinite time span there will always be an initial price and a price pathway which guarantees market equilibrium in each period and ensures that the stock of non-renewable natural resources is never exhausted. This rule assumes that supply is perfectly elastic, and that producers are indifferent between selling in one period or another.

Arroyo-Currás et al. (2015). However, there are some significant caveats attached to this conclusion due to the modelling characteristics we have discussed.

4.3 Can the energy channel be tested through empirical methods?

To our knowledge, no empirical studies exist testing for the presence of cross-country carbon leakage through the energy channel, whether caused by the ETS or any other environmental regulation. This is because there has not yet been a large unilateral shock to fossil fuel demand in any region as a result of environmental policy. However, there are a few empirical studies of inter-temporal leakage through this channel, related to Sinn's (2012) concept of the green paradox.

While most studies looking into the green paradox have been theoretical and analytical, some authors have been able to exploit data related to policy shocks in the US and China to provide empirical analyses of this phenomenon. Jensen et al. (2020) discuss some of this literature in the US context. Zhang et al. (2017) both review the empirical literature and contribute to this strand of research in the Chinese context. Overall, there is limited evidence of any effect in the US, and some evidence that there is a small green paradox effect in China. It should be noted that authors studying both cases highlight that their results are very context-dependent and cannot be generalized to other countries and/or policies.

One other study is of note in relation to the energy channel - more specifically in relation to cross-country rather than inter-temporal leakage through this channel. Though derived from a different context, the conclusions from Knittel et al. (2018) are relevant and potentially insightful. The authors study the impact of the Shale Revolution on international coal trade. The Shale Revolution came from the discovery of hydraulic fracturing and horizontal drilling technologies in 2010-2011. These new technologies very rapidly made natural gas cheaper than coal in the US. This acted as a fairly sharp negative demand shock on the coal industry in this country, which the authors take as an object of study. They find that the total amount of coal traded on international markets before and after the Shale Revolution are more or less the same, but US coal producers displaced other suppliers. Indeed, they were able to fully replace the domestic demand that disappeared as a result of the Shale Revolution with foreign demand. This seems to indicate that there could be 100% leakage through the energy channel for coal.

4.4 What are the remaining gaps in the literature for the energy channel?

The largest gap in the literature is of course empirical validation of the energy channel. While this channel is difficult for policymakers to apprehend because it does not yet present a tangible risk, it could invalidate the policy choice of implementing a CBA. Empirical testing will only be possible if a large enough and fast enough country-specific demand shock occurs on fossil fuel markets. The EU's Green Deal will have to be closely monitored for this type of an effect.

The intertemporal aspect of this channel could also be further explored. Existing studies look at the effect of intertemporal leakage on overall leakage, but do not consider the impact the energy channel could have on intertemporal leakage.

5 The innovation channel

Finally, the last of the three channels through which carbon leakage can occur is the innovation channel. It works in an opposite manner compared to the first two we have discussed, in the sense that it generates negative carbon leakage; when a region imposes a stringent environmental regulation, emissions are reduced in the unregulated region as well. We first describe how this channel works, before turning to the way it is represented in CGE models. We then review the empirical evidence related to it and conclude by identifying remaining gaps in the literature focused on this channel.

5.1 What is the innovation channel?

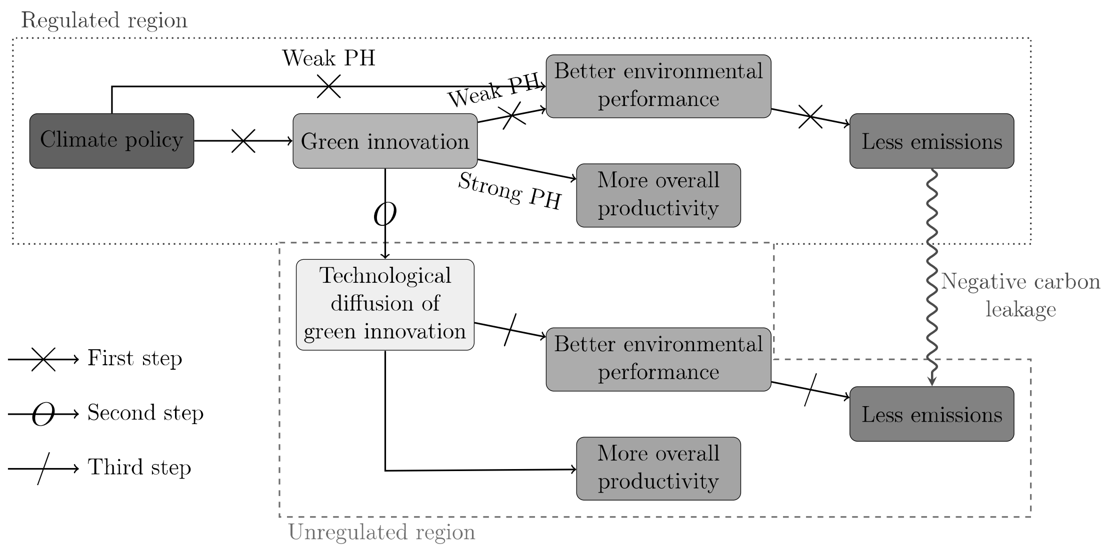
Carbon leakage through the innovation channel can be described as a three-step process (see figure 4). The *first step* is that climate policies make existing low-carbon processes and technologies more economically viable, which induces firms to switch to them. Additionally, firms have more of an incentive to invest in low-carbon research and innovation, which also improves their environmental performance in the long run. As a result, emission levels in the regulated country are brought down. This first step is known as the weak form of the Porter hypothesis (Porter, 1991; Porter & van der Linde, 1995)[15].

[15] Some argue that these green innovations also improve firm competitiveness, leading to higher productivity as well as environmental benefits. This is known as the strong form of the Porter hypothesis (Ambec et al., 2013) and is an argument used to improve the acceptability of climate regulation.

The *second step* is when these low-carbon innovations are diffused to countries that do not have climate policies in place. In practice, this diffusion may be hindered by the lack of a market for low-carbon products in unregulated countries, as well as lax intellectual property laws and barriers to trade. On the other hand, this channel can be encouraged through international innovation funds and technology transfer initiatives.

Finally, the *third step* occurs when these innovations are used by firms in the unregulated region and successfully reduce the carbon intensity of their production, thus bringing down overall emission levels.

Figure 4: A schematic view of the innovation channel



Note: PH = Porter Hypothesis

Source: Authors

This is the only leakage channel that has a clearly negative leakage effect. Through this channel, stringent climate policies in one region can decrease emissions in other unregulated regions, instead of increasing them like the competition and energy channels. As such, policies that target the development of this channel could have significantly positive impacts on the global climate. The innovation channel increases the efficiency of unilateral climate policies. It is therefore important to understand the magnitude and drivers underlying this channel to design policies aimed at developing it.

5.2 How is the innovation channel modeled in general equilibrium models?

To better understand the functioning of the innovation channel, we first turn to CGE models, which can give some insight into the potential magnitude of the channel. Most of these models include technical change as a fixed exogenous parameter and consequently do not account for the innovation channel. However, some studies argue that this omission can lead to a significant overestimation of the overall leakage ratio.

Di Maria and Van Der Werf (2008) build a theoretical framework exploring this argument. They compare a baseline two-sector, two-country model in which technological change is endogenous and undirected with a model which has exactly the same characteristics except that technological change is directed in the sense given by Acemoglu et al. (2012). In the latter model, stringent climate policies direct technological innovation towards climate-friendly innovations in the regulated country. Allowing for directed technological change leads to a significant reduction in the overall leakage ratio. As a result, the authors argue that most CGE models may be overstating the risk of leakage because they fail to account for the green innovation that stringent climate policies should induce. It is worth noting that in this model, innovations are diffused from one country to another immediately and at no cost, which could lead to overstated numerical results compared to a more realistic diffusion scenario. Qualitatively however, the argument stands.

Gerlagh and Kuik (2014) test Di Maria and van der Werf's theoretical framework in a CGE model which includes endogenous and directed technological progress. In their setup, the elasticity of substitution between a carbon energy input and a non-carbon energy input is constituted of a technology parameter and a non-technology parameter. Both parameters sum to the total elasticity of substitution between the two inputs. A price increase for either of the inputs induces investments in input-saving technological innovation which modifies the technology parameter of the elasticity of substitution. If the carbon energy input becomes relatively more expensive than the non-carbon input for instance, technology will improve so that less of the carbon energy input is required for the same level of output. Interestingly, the authors find that the leakage ratio can be negative, even at moderate levels of technological diffusion between countries. This is because the innovation channel has the potential to induce large amounts of negative leakage, which can trigger large emission reductions both in the regulated and the unregulated region. To verify the validity of the CGE results we have discussed, we now turn to existing empirical evidence studying the innovation channel.

5.3 Is there any empirical evidence pointing to the existence of the innovation channel?

As we have described in section 5.1, the innovation channel operates as a three-step mechanism: climate policies create incentives for firms in the regulated country to improve their environmental performance through process improvements and low-carbon innovation (step 1). The technology they develop is then diffused to unregulated countries (step 2), thereby reducing their overall carbon emissions as well (step 3). In this section, we sequentially review empirical evidence for each of these three steps.

There is a general consensus in the literature concerning the *first step* of the innovation channel, which is closely related to the weak form of the Porter hypothesis. Indeed, most studies find a positive and statistically significant relationship between environmental policies and green innovation (see Ambec et al. (2013) for a complete literature review on this topic).

There is also evidence that the EU ETS, specifically, has led to low-carbon innovative activity (Teixidó et al., 2019). Of particular note in this strand of literature is the paper by Calel and Dechezleprêtre (2014), due to the robustness of its methodology and findings. The authors use a matched diff-in-diff specification to compare the innovative behavior of firms regulated under the ETS with the innovative behavior of firms not regulated under the ETS. They find that regulated firms started patenting more low-carbon innovations than their unregulated counterparts in 2005, when the ETS was first implemented. In a more recent study, Calel (2020) found further evidence that the ETS has increased low-carbon patenting and R&D in regulated UK firms by 20-30% compared to unregulated UK firms. Though insightful, the approach developed by Calel and Dechezleprêtre is somewhat limited for two reasons. First, it only considers technological progress as innovative activity and not the adoption of new technologies, which can lead to an underestimation of the ETS' effect through the innovation channel. Second, if carbon-abating innovation is occurring in sectors that are not directly covered by the ETS, but instead in sectors upstream of covered sectors, there can also be an underestimation of the innovation channel's effect.

Borghesi et al. (2015) take a different approach to explore this question, exploiting data from the 2006-2008 Italian Community Innovation Survey to test whether manufacturing firms covered by the ETS adopt more environmental innovations than those not covered by the ETS. This avoids one of the problems mentioned above since the authors are not measuring innovative activity as a proxy for technological progress, but measure technological adoption instead. Their results show that participating in the ETS makes firms more likely to adopt environmental innovations. Given that their study uses data from the first and second phases of the ETS, when free allocations were the general rule and prices were low and volatile, this could mean that firms were anticipating higher future prices and acting accordingly. If this is true, firms' anticipation of future regulatory pathways could be as important in determining their innovative behavior as current regulation is.

Fewer studies look into the impact of this low-carbon innovative activity on firms' environmental performance, measured both as carbon intensity and overall carbon emissions. Baudry and Faure (2021) adopt a technological frontier framework which allows for a classification of firm-level technology based on its carbon intensity. They show that while the ETS has led to technological progress which reduces firms' carbon intensity, there has also been a rise in overall carbon emissions as a result of higher production levels. Their findings highlight the fact that even when firms covered by the ETS reduce the carbon intensity of their production, they can still have higher overall baseline (or Business As Usual) emissions.

Two further elements should be noted. First, there could be a time component affecting this channel. Environmental regulation could initially have a negative effect on innovative activity, which turns positive in the long run (Dechezleprêtre & Kruse, 2018). Second, the type of green innovation that is developed could matter. Innovations improving firms' resource efficiency seem to provide positive returns to profitability, while innovations improving other parts of the production process do not (Rexhäuser & Rammer, 2014; van Leeuwen & Mohnen, 2017).

A related strand of literature looks at the strong version of the Porter hypothesis, which posits that environmental regulation improves firm productivity. Proving its validity can be an important factor to improve the social acceptability of environmental regulation. Cohen and Tubb (2018) conduct a broad meta-analysis of studies on this topic and find considerable heterogeneity in the sign and significance levels of results. They find that the most likely conclusion is that environmental regulation is neither significantly correlated with higher productivity levels nor significantly detrimental to productivity.

Empirical studies of the innovation channel's *second step* study technological diffusion from regulated to unregulated countries. One strand of these studies provide descriptive analyses of the geography of green innovation activity. These works point to a concentration of patented green innovations in very few countries, namely the US, Japan, Germany, and, more recently but to a lesser extent, China. Innovations patented in high-income countries are mostly transferred[16]to other high-income countries. The small amount that is transferred to middle-income countries (roughly one third of total transfers) mostly goes to China (around 72% of transfers from high- to middle-income countries). Virtually no transfers are made to low-income countries (Dechezleprêtre et al., 2011; Probst et al., 2021)). This is a first indication that there may not be perfect diffusion of technology between all countries as modeled by Di Maria and Van Der Werf (2008).

Another strand of this literature looks at the role of technology transfers in specific low-carbon sectors, such as wind and solar power generation. Many papers study the case of China, a country where expertise in both of these fields was developed in large part thanks to strong flows of foreign direct investments and technological transfers. In the case of wind turbines for instance, large parts of Chinese demand were developed through the sale of Clean Development Mechanism credits on the ETS (Baudry and Dumont, mimeo). In the case of photovoltaic cells, technology transfers from Western countries, especially Germany, were key to develop China's manufacturing expertise (Huang et al., 2016). This underlines the potential strength of the innovation channel if diffusion is made more widespread.

Finally, empirical evidence concerning the *third step* of the innovation channel is quite sparse. To our knowledge, there are no studies looking specifically at the ways in which low-carbon technology transfers to unregulated countries improve these countries' environmental performance and/or productivity. The most closely related paper is a recent study by Eskander and Fankhauser (2021) which measures carbon leakage as the impact of climate policies on the import and export of carbon emissions. The authors take a macro perspective and find that climate legislation passed more than 3 years ago has generated small negative leakage rates. Without getting into any analysis on technology development and diffusion, they note that this result matches the hypothesis of the innovation channel. Some literature also looks at the impact of technology transfers on the receiving country's knowledge base, but results are mixed and do not allow for a general conclusion on the success or failure of technology transfers as a method of knowledge sharing (Kirchherr & Urban, 2018).

It is also worth highlighting evidence from two further papers, which are more indirectly related to this issue. First, Barrows and Ollivier (2021) look at the impact of foreign demand shocks on the carbon emissions of a third country - India. They find that while positive foreign demand shocks drive reductions in emission intensity, they also generate a strong, positive scale effect - meaning firms produce more - leading to overall greater carbon emissions in India. Jaraite et al. (2021) also note a similar effect when studying the impacts of the Clean Development Mechanism (CDM) on Indian manufacturing firms. This is an important result in our context, since it underlines the fact that even if environmental

[16] In the paper by Dechezleprêtre et al. (2011), technology transfers are patents that were originally patented in another country then extended to the transfer country.

regulation does lead to more diffusion of carbon-abating technologies in third countries, it might not lead to overall emission reductions if there is also a scale effect.

To summarize, papers studying the innovation channel seem to indicate that it does not yet have a large magnitude but could in the future. Green innovation remains highly concentrated in a few, mainly OECD countries and diffusion is quite limited beyond OECD borders. While policy-induced innovations do seem to improve the environmental performance of firms in the regulated region, their impact on firms in unregulated countries has not yet been studied.

5.4 What are the remaining gaps in the literature?

This topic has garnered a lot of attention in the economic literature, in part due to its close relation to the Porter hypothesis. However, many questions remain unanswered. Further studies of the ETS' impact on innovative activity within the EU should be conducted, especially with a focus on the environmental impact of these innovations. Research on policies which could act to avoid a rebound effect should also be prioritized as the ETS becomes increasingly stringent.

Another area of interest could be to look at the ETS' impact on the innovative behavior of sectors that are not directly covered by it, but that are upstream or downstream of sectors that are. For instance, in the sector of wind power generation, most innovation occurs in sectors upstream of those covered by the ETS, so it would be interesting to study how the policy is affecting these sectors. This could complement works such as those by Calel (2020) which give insights into the innovative activity of firms directly covered by the ETS.

To better understand the innovation channel's third step, studies could also focus on the ways in which green innovation is absorbed by unregulated countries' production processes once it is transferred there. Testing whether innovations are well-absorbed and whether they effectively reduce emissions in unregulated countries would be particularly important to quantify the innovation channel's environmental impact.

6 Designing a Carbon Border Adjustment

Policies aiming to minimize overall carbon leakage can target any or all three of the channels we have described. They should try to minimize positive leakage (i.e., emissions increasing in the unregulated region) through the competition and energy channels, while maximizing negative leakage (i.e., emissions decreasing in the unregulated region) through the innovation channel. Our interest in this section is to explore whether a CBA can achieve these objectives. We present the economic literature on this topic and aim to answer the two following questions:

1. Is a CBA an appropriate instrument to minimize leakage?
2. How can it be designed to best reduce overall leakage?

Most of the literature on designing a CBA is focused on mitigating positive leakage through the competition channel. Our contribution is to add considerations about the other two channels based on our previous discussions on their functioning. Given that a CBA has not been implemented on a large scale anywhere in the world, the evidence we present is mostly based on theoretical and CGE models.

6.1 How can a CBA reduce leakage through the competition channel?

The idea that a country with domestic carbon pricing could impose an import tariff to avoid carbon leakage was first put forward by Markusen (1975) in a two-good, two-country game-theory model. It was then generalized by Hoel (1996) in a game-theory model with N number of goods. The results from these seminal works indicate that the optimal tariff to avoid leakage is always non-zero and below the domestic (Pigouvian) carbon tax rate. The reason it is lower than the domestic rate is that a carbon tariff decreases the relative price of the polluting good in the unregulated region, mechanically increasing demand for it. This is sub-optimal both from an environmental and a competition perspective, implying the tariff should be lower than the domestic carbon price. One important element to note is that this holds only when the country or coalition of countries that imposes the carbon price is large enough to have some market power at the international level. If it does not, its tariff will have no effect on the foreign price of the polluting good or on production decisions in the unregulated region.

More recently, Balistreri et al. (2019) modified Markusen's framework to align it with the current WTO context. In Markusen's model, the optimal tariff rate is a function of the domestic carbon price, a strategic element, and an environmental element. Balistreri et al. (2019) neutralize the strategic element, in line with WTO law which states that countries cannot impose import tariffs for strategic reasons. Even in this setup, the optimal tariff is not zero, and remains below the Pigouvian tax. Testing their model in a numerical simulation, the authors find that if a coalition of Kyoto protocol Annex 1 countries were to implement a domestic carbon price, the optimal tariff for imports to this coalition would be roughly 40% of the domestic price. Theoretical works clearly indicate that a tariff could be an effective manner of reducing carbon leakage through the competition channel.

CGE models tend to confirm these theoretical results. Branger and Quirion (2014) provide a meta-analysis of 25 studies looking at CBAs, and find that all else being equal, CBAs reduce the leakage ratio by an average 6 percentage points. This is a 6 percentage-point reduction in already relatively small leakage rates (5-25% in most CGE models). While CBAs do seem to decrease leakage risk, the CGE-predicted magnitude of this reduction appears quite small compared to the burden of such a complex legislation.

Some studies point to possible differences in the effect of a CBA depending on the sector that it is applied to. For instance, Kuik and Hofkes (2010) find that CBAs can significantly reduce leakage in the iron and steel industries, while the effect is smaller in sectors such as mineral products, including cement. This difference can mostly be explained by the differences in carbon intensity between sectors. The most carbon intensive sectors, namely iron and steel, are more protected by a measure targeting carbon intensity in imported products.

It appears from these general analyses that a CBA may not be a highly effective policy for carbon leakage prevention. However, there are some design elements which could maximize a CBA's leakage reduction effect on the competition channel. Table 1 summarizes the different design choices which policymakers have to make when implementing a BCA.

These design choices need to be carefully weighed based on their capacity to mitigate leakage as well as their administrative costs and legal feasibility. Böhringer et al. (2022) provide a helpful summary of the issues related to this.

Böhringer et al. (2012) compare the cost-effectiveness of CBA designs in a CGE setup. They test variations of a CBA's design along three dimensions: the emissions scope (direct, direct plus indirect emissions from electricity, and all embodied carbon), the sectoral coverage (only energy-intensive and trade-exposed sectors, versus all sectors), and the determination of embodied carbon in products (domestic emissions benchmark, foreign emissions benchmark, and regional emissions benchmark). They find that the most cost- and environmentally effective design for a CBA is one which targets all embodied emissions (direct and indirect), which uses a benchmark for carbon content based on foreign emissions, and which

Table 1: Design choices for a CBA

Category	**Examples of policy options**
Type of policy instrument	**Price-based** (tax or custom duty) or **quantity-based** instrument
Scope and coverage	**Coverage of trade flows** (imports and/or exports), **geographic scope** (all foreign countries or only some trade partners, developing countries excluded…), **sectoral scope** (only carbon intensive industries, electricity and energy sources, ETS sectors, …), **emissions scope** (direct and/or indirect)
Determination of embedded carbon	**Based on domestic average**, **foreign average**, **regional/country-level average**, **sectoral or product-level** benchmark
Calculation of crediting for policies	Adjusting for **foreign carbon pricing or not**, choice of **including foreign emission standards**
Use of revenue	**General budget, earmarked for decarbonization projects, lump-sum transfers to affected developing trade partners, international clean technology fund**, ….

Source: Marcu et al. (2020)

covers all sectors.

The literature review by Branger and Quirion (2014) confirms that most studies find that including all sectors rather than only carbon-intensive ones in the scope of the CBA greatly increases its effectiveness. A larger sectoral scope reduces the risk of reshuffling – a practice through which foreign exporters circumvent the regulation by exporting products not covered by the CBA, namely products that are more downstream in the value chain. For example, if a CBA is applied to steel, but not cars, exporters can choose to stop exporting steel to car manufacturers in the regulated region and instead produce cars outside the regulated region then export the cars into the region. This allows them to avoid paying the CBA tariff. However, the authors also find that the inclusion of indirect emission in the accounted emissions is not statistically significant in all studies, contradicting findings from Böhringer et al. (2012).

Böhringer et al. (2017) add to this with their own CGE analysis, which highlights that a CBA targeting firm-level carbon intensity can limit leakage through the competition channel considerably more than a CBA targeting industry-level carbon intensity, while also mitigating adverse distributional effects of an industry-level CBA. The intuition behind this is that the more targeted a CBA is, the more it protects truly carbon-efficient firms. With industry-level benchmarks, dirty producers would pay exactly the same tariff as clean producers in the same industry, which reduces their incentive to invest in less carbon-intensive modes of production.

Finally, Fischer and Fox (2012) explore the environmental and cost efficiency of four types of policies: a border tariff on imports, border rebates on exports, a full border adjustment (including both a tariff and rebates), and domestic output-based rebating. Using a numerical simulation, they find that while none of these policies reduce global emissions, a full border adjustment is the most effective at reducing leakage rates.

To summarize the evidence found in the CGE literature, there is a consensus around the fact that a CBA would reduce carbon leakage through the competition channel. However, the magnitude of this reduction is not predicted to be very significant by CGE models. Some design elements can nonetheless increase a CBA's effectiveness at reducing leakage through the competition channel: covering all sectors in the economy, using a foreign benchmark for the carbon content of products, targeting carbon intensity at the firm or sub-industry level, and including export rebates as well as an import tariff.

6.2 Is a CBA ineffective at reducing leakage through the energy channel?

CGE models generally find that while a CBA can have an effect on the competition channel, it cannot impact the energy channel and is therefore not effective if most leakage is transmitted through this channel (Kuik & Hofkes, 2010).

However, a CBA can be used as a strategic tool to encourage unregulated countries to impose environmental regulations of their own. Böhringer et al. (2016) study this possibility in a numerical game theory set-up. They find that the threat of a carbon tariff can act as a strong incentive for unregulated countries to impose their own environmental regulation, especially if the coalition of regulated countries is large and has strong market power. This is important for the energy channel because cross-country leakage would be avoided if other countries also implement environmental policies that limit carbon emissions and the use of fossil fuels. The more countries have regulations which restrict demand for fossil fuels, the less leakage can occur through the energy channel.

If a CBA is implemented for strategic purposes as described above, two design elements can accentuate its power to incentivize other countries to impose their own domestic environmental policies. First, a CBA can take into account carbon pricing initiatives and climate policies in other jurisdictions. This could mean for instance that goods produced in Japan, covered by the country's domestic carbon tax, only pay a tariff at the rate of the difference between the EU's carbon price and Japan's carbon price. Countries exporting to the EU would be more strongly incentivized to have a domestic pricing system since their producers would not be doubly penalized, and they would receive the additional revenue instead of the EU. Further, if regulations other than carbon pricing, such as emission standards for instance, are also taken into account, there would be more flexibility for countries to regulate in ways that correspond to their particular context.

Second, the implementation process of the CBA is also important in itself. The more collaborative the process is, the more the EU will be able to take foreign legislation into account, potentially incentivizing trade partners to impose their own carbon pricing.

6.3 How can a CBA be designed to encourage spillovers through the innovation channel?

Finally, we look at the potential impact of a CBA on the innovation channel. To our knowledge, there is no literature looking into this question, so we put forward some preliminary considerations which should be further explored to maximize a CBA's positive impact on the innovation channel.

One interesting consideration is to ask whether the weak form of the Porter hypothesis could hold true in the context of a CBA. Since a CBA imposes a cost on carbon emissions for foreign producers exporting to the regulated region, it could create an incentive for these producers to invest in carbon-abating technological innovation and adoption. The emissions reductions induced by this could then be multiplied by a diffusion of these technologies to other producers within the unregulated region which are not exporting to the regulated region.

A more indirect channel through which a CBA could impact the innovation channel is through trade. There is evidence in the innovation literature that trade is a very strong channel for technology diffusion between countries (Xu & Wang, 2000). If it is imposed by a large enough trading bloc such as the EU, a CBA should restrict trade in carbon-intensive goods, while encouraging trade in low-carbon goods. As a result, it is possible that a CBA would increase technology diffusion through the trade channel. However, this would only be the case if the CBA is based on actual carbon content, or foreign content benchmarks rather than domestic content benchmarks. This hypothesis would have to be tested when a CBA is fully implemented. It would likely take some time for this type of technology diffusion to occur.

Additionally, policymakers could push for further green innovation and international technology diffusion by reinvesting the revenues from the CBA into an international green innovation fund. This fund could be focused on investing in projects transferring low-carbon technologies to producers in unregulated, and especially developing, countries. This would strengthen the innovation channel and mitigate the risk of burden shifting onto developing countries.

7 Conclusion

This paper has presented the state of the economic literature on the issue of carbon leakage and CBAs. We have first discussed the EU's political and institutional contexts to ground this literature in concrete policymaking problems. Second, we have given an in-depth review of the ways in which each of the three leakage channels – competition, energy, and innovation – function and where research should be focused in the future. Finally, we have linked this to a discussion on a CBA's role in minimizing carbon leakage by minimizing the effect of the competition and energy channels and maximizing the effect of the innovation channel.

There is a discrepancy between the economic literature and policy debates about CBAs. The latter do not consider how such a policy could impact leakage through the energy and innovation channels. However, both channels could have a strong impact on overall leakage rates in the future, depending on the ways in which a CBA is implemented. Policymakers should therefore aim to minimize the impact of the energy channel by developing cooperation with unregulated countries and taking foreign carbon pricing initiatives into account in the CBA. They should also work to maximize the impact of the innovation channel by promoting green technology diffusion to unregulated countries and reinvesting CBA funds into an international technology fund.

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