Carbon Leakage in a Small Open Economy: The Importance of International Climate Policies*

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Abstract

The literature offers estimates on carbon leakage effects of subglobal climate policies for large countries and climate coalitions. However, little is known about carbon leakage effects for small open economies. To fill this gap in the literature, we incorporate international climate policies relevant for a small open economy - like EU climate policies - into the general equilibrium model GTAP-E. We estimate carbon leakage effects for Denmark, but our framework could be employed on any EU member state. We find that a national economy-wide carbon tax is associated with a leakage rate of around 70 pct. Hence the global CO_2e emission reduction is about 30 pct. of the domestic reduction. We show that this is due to EU climate policies. We also present leakage rates for different sectors of the Danish economy and find large sectoral differences. These findings may have important policy implications, as an efficient leakage-adjusted climate policy imposes more lax regulation on leakage sensitive sectors.

Keywords: Carbon leakage, Trade and the environment, Climate policy, Computable general equilibrium

JEL Classification: F18, H23, Q54

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1 Introduction

The global climate is equally affected by a unit of greenhouse gas (GHG) emission no matter where it occurs. Hence the effectiveness of unilateral climate policies is reduced if they result in increased GHG emissions in other countries, for instance, through a shift in international production patterns. This phenomenon is typically referred to as carbon leakage.

The literature on carbon leakage is substantial. However, most studies analyse carbon leakage issues for a coalition of countries (e.g., Antimiani et al. 2013, Böhringer et al. 2018) or a large country like the US (e.g., Fischer and Fox 2012). There are only a limited number of studies dealing with carbon leakage issues for small open economies, all building on single country partial or general equilibrium models (e.g., Bohlin 2010). As these studies only explicitly model the national economy, the actual leakage effects result directly from simplifying assumptions about the foreign production technology and response to domestic policies.

The main contribution of this study is to estimate carbon leakage effects both on the aggregate and sector level for a small open economy. To the best of our knowledge, we are the first to do so using a global CGE model (the GTAP-E model) with relevant international climate policies in place. Most importantly, we incorporate EU climate policies like the EU Emissions Trading System (ETS) into the CGE model. A small open economy must take these political systems and agreements as given when designing its national climate policies. We compute carbon leakage rates for Denmark, but our approach can, with some appropriate country specific adjustments, be extended to any economy, and it is particularly suitable for EU member states.

One can of course object that the climate change issue cannot be solved by a small economy. On the other hand, if national policymakers care about the global emission effect of their policies, it is necessary to know the carbon leakage effects to design optimal unilateral climate policies (Hoel 1996; Kruse-Andersen and Sørensen 2019). We illustrate this in a simple model in Section 3.

A natural question is then: do national policymakers care about carbon leakage? One recent example is the broad political agreement on the Danish Climate Act of 2020. It commits Denmark to reduce national GHG emissions by 70 pct. by 2030 compared to the emission level of 1990. Importantly, the Danish Climate Act also states that the emission reduction measures may not simply move the emissions abroad. Thus the policymakers clearly care about the global impact of their policies.

In addition, a small economy may contribute more to climate change mitigation than suggested by its domestic emission cuts (Greaker et al. 2019). It is sometimes argued that the greatest impact a small nation can have on the climate is to be an example to follow.[1] Indeed, the Danish Climate Act explicitly states this demonstration effect as a policy goal. Carbon leakage may play an important role for such a demonstration effect. If an economy simply reduces it GHG emissions by outsourcing polluting activities, it does not really demonstrate anything about pollution abatement costs, and the potential demonstration effects highlighted by Greaker et al. (2019, p. 178-179) will not apply. Hence an effective demonstration effect requires climate policies that at least partly deals with the leakage issue. Implementing such policies requires knowledge about carbon leakage effects.

To operationalize the concept *carbon leakage*, we follow the literature and define the leakage rate denoted L. If a country reduced its GHG emissions by some amount through some policy action, the leakage rate expresses how much of this domestic reduction is replaced by additional foreign emissions. Formally, the leakage rate is given by:

$$L = -\frac{\Delta e_{\text{foreign}}}{\Delta e_{\text{domestic}}},$$

where $\Delta e_{\text{foreign}}$ and $\Delta e_{\text{domestic}}$ are changes in foreign and domestic GHG emissions, respectively.

There are several channels of carbon leakage. Firstly, carbon leakage may occur through international trade and production patterns. A tighter climate policy in the domestic economy reduces the competitiveness of GHG intensive industries. This may result in transfers of both production and emissions for these industries.

Secondly, carbon leakage may occur through the international market for fossil fuels. Reducing domestic fossil fuel consumption also reduces the fossil fuel price which increases fossil fuel use in the rest of the world. This effect may also be important when considering a small economy. Although small scale climate actions have small price effects these effects occur on a large market.

Thirdly, carbon leakage effects are build into certain political systems and agreements. A prime example is an international cap-and-trade system like the EU ETS. If the emission cap is fixed, national policies that overlap with the cap-and-trade system have no long-run

[1] Hoel (2012) explains this demonstration effect.

effect on emissions in the system, implying a leakage rate of 100 pct. And even in systems where the effective cap is no longer fixed like in the current version of the EU ETS, there is still a leakage effect built into the system (see Perino 2018; Beck and Kruse-Andersen 2020). Nevertheless, political systems can also block carbon leakage. If a country has a binding emission commitment through the Paris Agreement, emissions cannot leak to that country. Likewise, the EU non-ETS emission reduction obligations may block emission leakage to countries with binding obligations.

The first two leakage channels have been emphasized in much of the previous literature, whilst the third (leakage through political agreements and institutions) is often partly or fully ignored (potentially due to the scope of the coalitions considered). When considering leakage effects for a small economy, carbon leakage effects caused by political agreements and systems are crucial. A small EU country will, for instance, be substantially affected by the climate policy of the EU. We, therefore, do a substantial effort to take relevant international climate policies into account. We also show that the computed leakage rates are sensitive to the in- or exclusion of these international policies.

Finally, technological spillover effects may reduce carbon leakage as emphasized by Gerlagh and Kuik (2014). As an example, assume that the EU decides to tighten its climate policy. This expands the market for renewable energy technologies and energy-efficiency technologies, resulting in a greater incentive to develop such technologies. This directs research efforts toward these technologies spurring innovation in that direction. As the resulting climate friendly technologies can, in principle, be employed everywhere, the EU policy may lead to more climate friendly production outside of Europe. This lowers foreign emissions and thereby dampens the carbon leakage effects associated with the policy.

We do not include this directed technical change effect in our study for two reasons. Firstly, it is difficult to estimate this directed technical change effect, and thus, it is not straightforward to implement it in our numerical model. Secondly, a small economy has little impact on the global market for climate friendly technologies. Thus, the impact on the global technological frontier is arguably negligible. However, it should be emphasized that the exclusion of this effect will bias our results upwards.

Inspired by typical climate policy recommendations by economists we examine the leakage rates associated with economy-wide or sector specific carbon taxes. Our results suggests that carbon leakage rates are higher for Denmark compared to those found in the previous literature for large countries and country coalitions. Specifically, we find that the macroeconomic leakage rate is around 70 pct. for Denmark, while typical estimates for large coalitions are between 10 and 30 pct. This result is to a large extend driven by leakage through the EU ETS, while other political agreements like the Paris Agreement have little effect. In fact, the macroeconomic leakage rate is estimated to around 20 pct. in absence of international climate policies. We also find substantial discrepancies between sector specific leakage rates. Sectors covered by the EU ETS and agriculture have high leakage rates: 68 pct. or higher. Meanwhile, with the exception of the land transportation sector, the remaining sectors have leakage rates that range from negative numbers to below 20 pct.

The remaining part of the paper is organized as follows. Section 2 reviews the theoretical and empirical literature on carbon leakage. It is then shown in Section 3 that knowledge about sector specific leakage rates is crucial for the implementation of optimal unilateral climate policies if policymakers value global emission reductions. Section 4 describes our model and the employed database. The policy experiments are described in Section 5, while the simulation results are presented and explained in Section 6. Finally, Section 7 offers some concluding remarks.

2 Literature review

The fact that carbon leakage may substantially reduce the effectiveness of unilateral climate action has long been recognized in the literature (e.g., Hoel 1991). It is also well established that optimal unilateral climate actions involve a uniform domestic carbon price mechanism as well as border carbon adjustments (BCAs) that is export rebates and import tariffs (Hoel 1996). However, this result is derived under the assumption that the implementation of BCAs does not trigger a trade war. If BCAs cannot be employed or if employing them would trigger a costly trade war, the second-best unilateral policy involves a large number of instruments including sector specific carbon taxes (Kruse-Andersen and Sørensen 2019). In particular, more leakage exposed sectors should pay a lower emission tax.[2] However, in both the first-best and second-best cases, it is necessary to know domestic leakage effects to implement the efficient policy. In the next section, we use a toy model to illustrate that

[2] Hoel (1996) also find that taxes should be differentiated across sectors if emission taxes are the only instruments available to the government. However, Kruse-Andersen and Sørensen (2019) show that if import tariffs and export rebates are the only unavailable instruments, the second-best policy also involves subsidies to renewable energy, abatement subsidies in fossil-based electricity production, a tax on internationally traded goods, and sector specific electricity taxes. The second-best policy investigated by Hoel (1996) can, therefore, be considered a third-best policy option, where only the tax instrument is available.

this point also holds in a setting with a domestic emission target and a cost associated with carbon leakage.

A substantial literature investigates the leakage issue using CGE models.[3] These studies typically investigate the effects of unilateral climate actions by a coalition of developed countries using world-wide CGE models.

Table 1 shows the estimated leakage rates in the baseline scenarios from selected studies from this literature published since 2010. As indicated by the table, most studies in the literature find carbon leakage rates between 10 and 30 pct. for large coalitions (Carbone and Rivers 2017). There are some notable outliers. Babiker (2005) finds leakage rates above 100 pct. when deviating from standard assumptions on returns to scale and market structure. At the other end of the scale, Gerlagh and Kuik (2014) find that the leakage rate can be close to zero if there are sufficiently strong technological spillover effects from developed to developing countries. The idea is that an unilateral action by a coalition of developed countries will push the technological frontier of abatement technologies, and this can reduce emissions in developing countries if there are strong technological spillover effects.

Some authors argue that the leakage rate is generally decreasing in the size of the coalition (Burniaux and Martins 2012). As an example, OECD (2009) finds that the leakage rate is 12 pct. if only the EU reduced emissions by 50 pct. in 2050 compared to 2005, while the leakage rate decreases to less than 2 pct. if the absolute reduction is conduced by Annex I from the Kyoto Protocol. Intuitively, there will be fewer countries were emissions can leak to, when the coalition size increases.

However, there are also examples going in the opposite direction. Böhringer et al. (2010) find that the leakage rate is 10 pct. for the US, 28 pct. for the EU, and 15 pct. for a coalition of both regions. Hence it is not generally such that larger climate coalitions result in lower leakage rates. As a consequence, it is unclear what we should expect the leakage rate to be for a small open economy.

A substantially smaller literature deals with the carbon leakage issue for a small economy. These studies are based on partial equilibrium models or single country CGE model.

Bohlin (2010) estimates carbon leakage effects in a CGE model for Sweden. It is assumed that foreign consumption is unaffected by developments in Sweden, and that Swedish production technologies are employed by the foreign economy for all goods. The only exception

[3]This literature includes - but is not limited to - Babiker (2005), Elliott et al. (2010), Böhringer et al. (2010), Kuik and Hofkes (2010), Böhringer et al. (2012b), Böhringer et al. (2012a), Fischer and Fox (2012), Antimiani et al. (2013), Gerlagh and Kuik (2014), and Böhringer et al. (2018).

is electricity, where the Danish production technology is employed. Bohlin (2010) also includes the EU ETS in some simulations. The leakage rate is set to 100 pct. for commodities produced by the ETS sector. Bohlin (2010) finds long-run leakage rates ranging from 48 to 100 pct. in simulations including the EU ETS.

TABLE 1: Baseline carbon leakage estimates from selected studies published in peer-reviewed journals since 2010

Study	Leakage rate	GHG reduction[g)]	Coalition
Antimiani et al. (2013)	12-13 pct.	14 pct.	Annex I from Kyoto
Böhringer et al. (2018)	14 pct.	20 pct.	OECD
Böhringer et al. (2012b)[a)]	15-21 pct.	10-30 pct.	EU and EFTA countries
Böhringer et al. (2010)[b)]	10-28 pct.	20 pct.	USA and/or EU
Elliott et al. (2010)[c)]	15-25 pct.	3-15 pct.	Annex B from Kyoto
Fischer and Fox (2012)[d)]	7 pct.	-	USA (selected sectors)
Gerlagh and Kuik (2014)[e)]	3-10 pct.	11 pct.	EU
Kuik and Hofkes (2010)[f)]	11 pct.	-	EU (only ETS sector)

Notes: Generally, the reported figures are taken from the baseline scenarios, where the regulation is typically conducted using a carbon tax or a cap-and-trade system. Yet, the reported studies often feature leakage rates from other types of regulation which seeks to reduce carbon leakage.
a): A unilateral GHG reduction of 10 (30) pct. results in a leakage rate of 15 (21) pct.
b): The leakage rate for the US is 10 pct., while the leakage rate of 28 pct. is for the EU. A GHG reduction by both regions results in a leakage rate of 15 pct.
c): The numbers are based on a reading of figure 1 in Elliott et al. (2010), where the GHG reduction of 3 (15) pct. corresponds to the lowest (highest) tax rate and lowest (highest) leakage rate.
d): The scenario involves a carbon tax of 14 US-dollars per ton for energi intensive and trade exposed industries. It is not reported how much this tax reduces GHG emissions.
e): The leakage rate is taken from table 3 in Gerlagh and Kuik (2014), where the leakage rates 3 and 10 pct. are with and without technological spillovers, respectively. However, the authors also show that the leakage rate can become negative, if the spillover effects are sufficiently strong.
f): The scenario involves a fixed emission allowance price of 20 euro per tonne of CO2. It is not reported how much this allowance price reduces GHG emissions.
g): The GHG reduction referrers to that of the coalition, not the net effect on global GHG emissions.

Copenhagen Economics (2011) estimates carbon leakage rates for energy-intensive industries in Denmark using a partial equilibrium model. The model only accounts for leakage through the trade channel, and it is based on a simple calibration procedure. The study finds a leakage rate of 88 pct. from a particular tax reform in Danmark.

Roson (2001) estimates carbon leakage effects using a dynamic CGE model for Italy. It is assumed that the goods are produced with the same emission intensity in the domestic and foreign economy. The carbon leakage estimates are around 23 pct. and vary little.

To our knowledge, the present study is the first attempt to estimate leakage effects for a small open economy using a global CGE model including relevant international climate policies. In comparison with the studies mentioned above, our approach has two important advantages. Firstly, the foreign economy in our study is directly modelled and it includes the entire global economy. Further, the model is calibrated to a global database ensuring plausible parameter values. Secondly, our model includes leakage through international agreements and institutions which a small open economy must take as given. The inclusion of these international climate policies turns out to be crucial for the estimated leakage rates.

3 Illustrative model

The theoretical literature on carbon leakage investigates how different instruments can be employed to obtain cost-effective regulation seen from a unilateral perspective. A common feature of these studies is that the implementation of the optimal policy requires knowledge about sector specific leakage effects. This section presents a simple model that illustrates this point.[4]

The economy consists of N production sectors indexed by $i = 1, 2, ..., N$. The carbon emission abatement cost of sector i is given by the function $c_i(e_{0,i} - e_i)$, where $e_{0,i}$ is the emission level without regulation and e_i is the actual emission level. Accordingly, emission abatement amounts to: $e_{0,i} - e_i$. The function $c_i(\cdot)$ is strictly increasing and convex, reflecting that the cheapest abatement options are employed first.

Carbon leakage reduces the global impact of domestic emission reductions. Specifically, reducing the domestic emission of sector i by one unit results in a global emission reduction of $(1 - L_i)$ units, where L_i is the leakage rate of sector i. Leakage rates are restricted to be between zero and one, $0 < L_i < 1$, such that domestic emission reductions always exceed global emission reductions, while domestic emission reductions still benefit the climate. This seems like the plausible case, cf. Section 2.

The government wants to reduce emissions to the level $\bar{E}$. This target mimics the domestic emission reduction targets of many countries. Yet, the policymakers also care about carbon leakage. In particular, the policymakers assign a value p on each unit of emission leakage. Thus the cost of leakage is the difference between the domestic emission reduction target and global emission reductions.

[4]The model shows that the optimal policy can be implemented using differentiated carbon taxes only. In more advanced settings, it is necessary to employ additional instruments beside carbon taxes like subsidies and BCAs to obtain the first-best allocation. Nevertheless, in all cases the policymakers need knowledge on sector specific leakage effects to obtain the first-best allocation.

The problem of the government is to reduce the cost of emission abatement and leakage, while ensuring that the domestic emission target is met. Mathematically, the problem is formulated as:

$$\min_{\{e_i\}_{i=1}^N} \sum_{i=1}^{N} c_i(e_{0,i} - e_i) + p\left(\sum_{i=1}^{N} L_i(e_{0,i} - e_i)\right) \quad \text{st.} \quad \bar{E} \geq \sum_{i=1}^{N} e_i.$$

Assuming that the domestic emission constraint is binding, the first-order condition implies that:

$$c_i'(e_{0,i} - e_i) + pL_i = \lambda,$$

where λ is the shadow cost of domestic emissions. The equation states that the cost of emission abatement in sector i - which is the abatement cost plus the cost of carbon leakage - must equal the shadow cost of domestic emissions. This implies that the total marginal abatement cost (including the cost of carbon leakage) is equalized across sectors.

In the market equilibrium, firms will abate emissions until the marginal abatement cost equals the price of emissions, that is, the carbon tax. The optimal solution can therefore be implemented by imposing the sector specific emission tax, τ_i, given by:

$$\tau_i = \tau^* - pL_i, \quad \tau^* = \lambda > 0,$$

where τ^* is a common emission tax term which is determined such that the domestic emission target is met.

The equation shows that the sector specific carbon tax is relatively lower for leakage sensitive sectors. Furthermore, the carbon price discrepancy between sectors increases with the cost of carbon leakage. Note that if policymakers do not care about carbon leakage, it is optimal to impose a uniform carbon tax. This is a well-know result from the literature (Baumol and Oates 1971). Additionally, it is worth noticing that if the policymakers increase the cost of leakage, p, the common tax term, τ^*, must increase to ensure the domestic emission target.

The intuition is as follows. The cost of emission abatement consists of two terms: the direct emission abatement cost and the cost of carbon leakage resulting from emission abatement. To ensure an equalization of marginal abatement costs across sectors, more leakage exposed sectors face a lower emission tax, resulting in a lower direct abatement cost.

This simple model illustrates that the implementation of an optimal unilateral climate policy requires estimates on sector specific leakage effects given that policymakers assign some cost to carbon leakage. This is also true in more advanced settings, where additional instruments are required to achieve the first-best allocation (see Hoel 1996; Kruse-Andersen and Sørensen 2019).

4 Model and data

The analysis is based on a modified version of the GTAP-E model (Truong et al. 2007). We give a brief overview of the GTAP-E model, the GTAP Data Base, and our aggregation before explaining our extentions to the model. For further details on the GTAP-E model we refer to Truong et al. (2007) and Truong (2007).

4.1 The GTAP-E model

The GTAP-E model is a comparative static CGE model for the entire world economy. The model consists of a series of CGE models: one for each region in the model. These CGE-models are connected via three markets: (1) the market for goods, (2) the market for savings, and (3) the market for international transport services.

Within each region there are a number of production sectors - each producing a specific good using a production function characterized by constant returns to scale. There are five primary input factors: land, capital, labor (skilled and unskilled), and natural resources. In addition, production requires intermediate inputs from other sectors. Separate sectors are producing oil, coal, gas and electricity, and the use of oil, coal and gas generates carbon emissions. The primary input factors are region specific and exogenous except for capital which is determined by aggregate saving and an equalization of returns across regions (see Corong et al. 2017).

Each region has a representative household that obtains utility from private and public consumption as well as saving. The last element is added to ensure that savings occur despite the static nature of the model. Trade is modelled via an Armington structure, where domestic and foreign goods are imperfect substitutes.

4.2 The GTAP database

This paper builds on the GTAP Database 10. The database includes macroeconomic statistics on 141 countries or country aggregates, covering 98 pct. of global GDP and 92 pct. of the global population. There are 65 sectors in each country (or region), and the base year for our analysis is 2014 (the latest available year in the database).

4.3 Aggregation

In order to have a model that can be solved in a reasonable amount of time, we need to aggregate the data. We aggregate to 30 regions based on Danish trade statistics (see Table 4 Appendix A). This means that the European economy remains relatively disaggregated, as Denmark trades more intensely with European countries. Meanwhile, Denmark trades little with Central and South American countries, and these countries are therefore aggregated into a single region.

We aggregate to 19 production sectors based on the economic and environmental significance of the sectors. Table 2 in Appendix A gives an overview. The aggregation is designed such that important substitution possibilities are not eliminated. The agricultural sector is, for instance, divided into three sectors: cattle, other animal, and vegetable farming. This allows for a shift from meat toward vegetable production as a response to higher emission taxes. It also allows for a shift within animal farming. This might be important given that cattle farming is relatively more pollution intensive. In the manufacturing sector, we distinguish between heavy and light manufacturing. But since there are several other production sectors (e.g., a services sector and a trade sector), production can shift away from heavy manufacturing in various ways as a response to a carbon tax.

4.4 Model extensions

We add four extensions to the GTAP-E model to improve its ability to estimate carbon leakage rates for a small open economy within the EU.

Firstly, we add non-CO_2 emissions from a GTAP satellite database. These emissions are in the database connected to the use of certain inputs (e.g., fertilizers in agriculture), the use of capital (mostly animal stocks in agriculture), and certain production outputs (e.g., chemical production processes). These primarily non-energy related emissions have been implemented in relevant sector and region aggregations. We add the output and capital related emissions.

The idea is that the agricultural sector cannot substitute away from capital (e.g., cows) to other production factors such as labor as a reaction to a tighter climate policy.

Second, we model the EU ETS system. Before the latest reform of the EU ETS system this could have been done by implementing an emission cap for the EU ETS sector. However, after the latest reform of the EU ETS system, the cap is no longer directly controlled by the EU policymakers (Perino 2018; Beck and Kruse-Andersen 2020). As a consequence, the EU ETS does not imply an intra-ETS leakage rate of 100 pct. We use the model developed by Beck and Kruse-Andersen (2020) to estimate the current intra-ETS leakage rate for the EU ETS. Specifically, we permanently reduce the demand for EU ETS allowances/emissions by 1.2 m. tonne of CO_2 per year from 2020, corresponding to 10 pct. of the yearly Danish demand. This shock reflects a permanent tightening of the Danish climate policy in the ETS sector. The shock is associated with an intra-ETS leakage rate of 83 pct. To ensure that our modified GTAP-E model satisfies this leakage rate for the ETS sector on the EU level, we add a subsidy - equal to zero in the absence of policy interventions - to fossil fuel consumption in the entire EU ETS sector. If a policy shock reduces Danish ETS sector emissions, the subsidy becomes positive and fossil fuel consumption in the ETS sectors of other EU member states increases, resulting in an intra-ETS leakage rate of 83 pct. Note that the data and model calibration already reflect the existence of the EU ETS, although the system is not directly modelled within the standard GTAP-E model. The subsidy modelled here should therefore be interpreted as changes to the EU ETS allowance price caused by Danish policy actions: a positive subsidy corresponds to an allowance price decrease.

It is important to emphasize that due to responses outside of the EU as well as within the EU non-ETS sector, leakage rates associated with sectors covered by the EU ETS are not hard wired by this assumption. In addition, we conduct robustness analysis to check the importance of the specific EU ETS leakage rate employed.

Third, the EU has imposed country specific non-ETS emission reductions on all EU member states. These reduction obligations hinder certain member states from increasing their non-ETS emissions as a response to changes in foreign production and emission patterns. We identify countries with binding emission reduction targets using the analysis by the Danish Council on Climate Change (2016). Specifically, we place an emission cap on non-ETS emissions for 13 EU member states. From a technical point of view, this is modelled by implementing an endogenous non-ETS emission tax in these countries. If non-ETS emissions were to increase in these countries due to a Danish climate policy, the country specific non-ETS emission taxes increase to ensure the domestic non-ETS reduction obligations of each country. Although this approach is simple, it reflects that if carbon emissions leak to these countries do to Danish policies, these countries will somehow need to tighten their climate policy to comply with their EU obligations.

Finally, we allow for emission constraints resulting from the Paris Agreement. More precisely, we impose binding emission constraints on almost all countries outside the EU. In line with the non-ETS sector constraint, we model this through an endogenous carbon tax. The EU commitment to the Paris Agreement is already modelled though the non-ETS and ETS constraints explained above. However, we allow the largest economies to have non-binding emission caps, that is China, the US, India, and Russia. See Table 4 in Appendix A for details.

5 Policy experiments

We consider two types of policy experiments. To estimate the macroeconomic leakage rate - the leakage rate associated with an economy-wide environmental policy - we impose a uniform tax on CO_2e emissions. The macroeconomic leakage rate reflects the overall leakage sensitivity of the economy. The tax is set to 10 US dollars per tonne of CO_2e. Yet, the estimated leakage rates seem insensitive to the exact size of the tax.

We do not tax air and water transportation in our policy experiments, as these sectors are difficult to regulate due to bunkering. In addition, the GTAP database reports global emissions by Danish ships and aircrafts. Emissions and tanking often take place far away from Danish territory, making them hard to regulate for the Danish government.

To estimate the sector specific leakage rates, we impose a sector specific tax on CO_2e emissions of the same magnitude as for the economy-wide experiment. Sectors are here divided into main sectors such as the agricultural sector which includes cattle, other animal, and vegetable farming. The main sectors are shown in Table 3 in Appendix A. We also estimate the leakage rate of private fossil fuel consumption using the same method.

The sector specific leakage rates reflect the leakage sensitivity of each main sector. To be specific, our estimates are an attempt to estimate L_i from the illustrative model from section 3. Nonetheless, one should keep in mind that leakage rates are case sensitive. For simplicity we ignored this issue in section 3. The estimates should therefore be interpreted with caution. Nevertheless, the estimated leakage rates seem insensitive to the size of the tax within reasonable bounds.

Importantly, we take all emissions into account when estimating the sector specific leakage rates. Other studies only consider leakage within the sector of interest, but that may be problematic if general equilibrium effects like changes in the sector composition are important. A tax on heavy industry in Denmark will not only push part of the heavy industry production out of Denmark. It will also increase Danish production in other sectors given the fixed supply of certain inputs including labor. This in turn reduces foreign production in these sectors. If Danish production in these sectors is relatively more environmentally friendly, this may dampen the overall leakage effect. Our study takes such general equilibrium effects into account when estimating sector specific leakage rates.

6 Results

6.1 Macroeconomic leakage rates

The main results for the economy-wide policy shock are presented in Figure 1. The estimated macroeconomic leakage rate is around 70 pct. Thus the global impact of economy-wide climate policies is about 30 pct. the domestic impact. Adding emission caps from the Paris Agreement has little effect on this result, as shown by the last bar in the figure.

The figure also shows that EU climate policies are crucial for the estimated macroeconomic leakage rate. Without any EU policies the leakage rate drops to 20 pct. Interestingly, this is well within the range of estimated leakage rates from the literature based on large countries and climate coalitions. This indicates that political agreements and institutions are much more important for estimated leakage rates compared to the size of the economy.

The main leakage driver is the EU ETS. Removing only this climate policy from the baseline scenario reduces the leakage rate from 70 to 18 pct., whilst only removing the non-ETS constraint results in a leakage rate of 74 pct.

The intra-ETS leakage rate is of course important and associated with a great deal of uncertainty (see Beck and Kruse-Andersen 2020). If the intra-ETS leakage rate is computed based on a 20-year horizon, it is reduced to 43 pct.[5] Employing this measure reduces the macroeconomic leakage rate to 42 pct.

[5]This number is also computed from the model developed by Beck and Kruse-Andersen (2020), but we estimate the intra-ETS leakage rate based on a 20-year instead of a permanent allowance demand reduction. This means that a larger part of the policy shock works while the Market Stability Reserve absorbs allowances, resulting in a lower intra-ETS leakage rate (see Beck and Kruse-Andersen 2020).

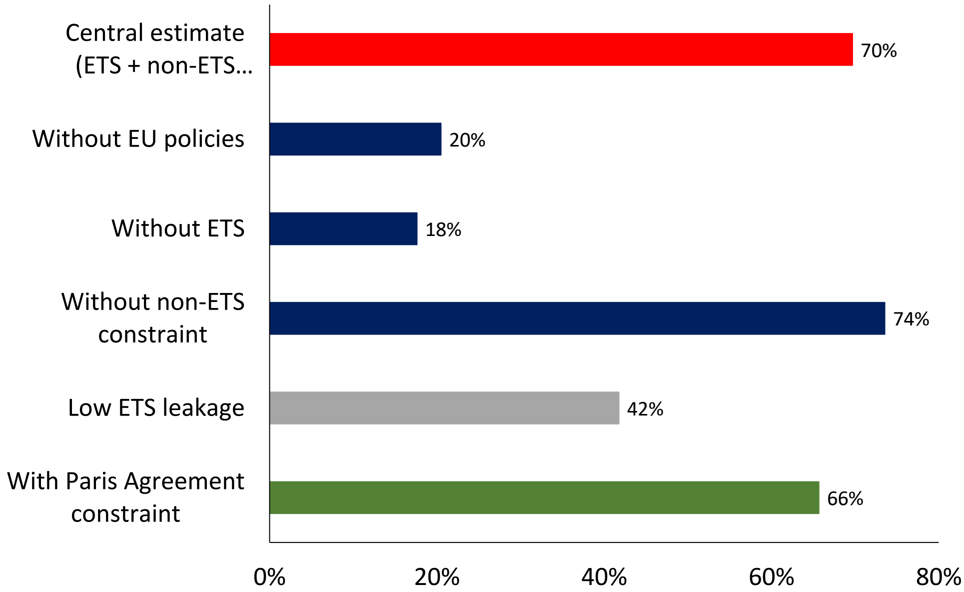

FIGURE 1: Macroeconomic carbon leakage rates.
Notes: The macroeconomic carbon leakage rate reflects the leakage sensitivity of the entire economy. It shows the increase in foreign emissions as a share of Danish emission reductions caused by an economy-wide CO_2e tax of 10 US dollars per tonne of emission. This emission tax is placed on top of the existing regulation.

6.2 Sector specific leakage rates

The estimated sector specific leakage rates are shown in Figure 2. Leakage rates in sectors covered by the EU ETS are above the macroeconomic leakage rate, while most of the non-ETS sectors have leakage rates much below the macroeconomic leakage rate. The exception is agriculture which has a high leakage rate even when compared to sectors covered by the ETS. One reason is that the demand elasticity for agricultural products is low. Hence domestic climate policies in this sector have a relatively smaller impact on global demand, resulting in a relatively stronger response by foreign producers.

ETS covered sectors have high leakage rates due to the leakage mechanism built into the EU ETS. The intra-ETS leakage rate is set to 83 pct. as described above. The leakage rates for the ETS sectors considered here (energy-intensive industry, electricity and heating, and oil and gas extraction) are higher or lower than that. This is due to general equilibrium effects. A reduction in Danish ETS sector production leads to an increase in Danish non-ETS sector production. This again leads to non-ETS production moving from the foreign economy to Denmark. This works in the opposite direction on the total leakage effect, explaining why the ETS sector leakage rate is below the intra-ETS leakage rate of 83 pct.

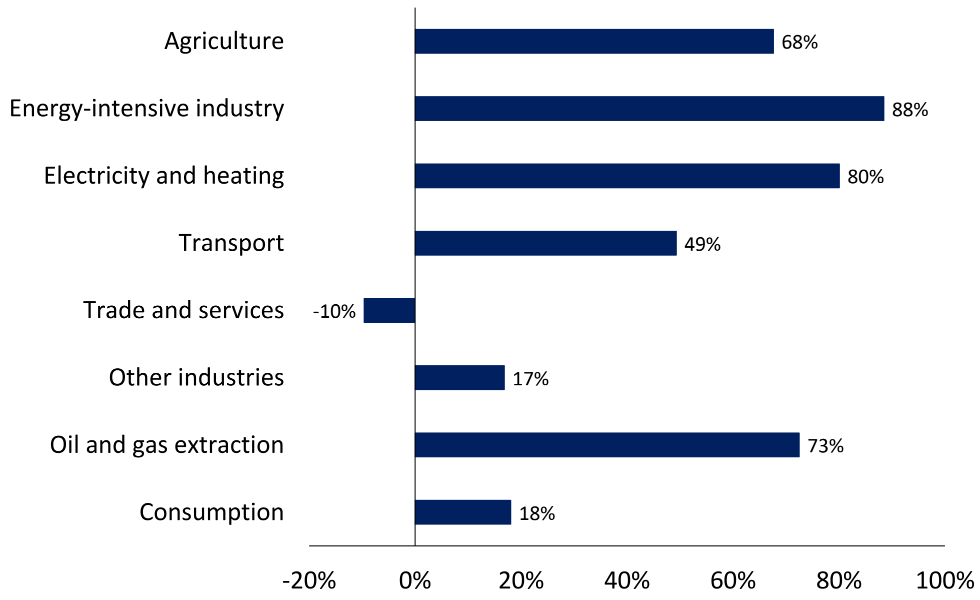

FIGURE 2: Sector specific carbon leakage rates.
Notes: The sector specific carbon leakage rates reflect the leakage sensitivity of the sectors. They show the increase in foreign emissions as a share of Danish emission reductions caused by a sector specific CO_2e tax of 10 US dollars per tonne of emission. This emission tax is placed on top of the existing regulation.

On the other hand, ETS sector production and emission may also leak to economies outside the EU which can push the leakage rate up.

Figure 2 reports a negative leakage rate for trade and services. The explanation is as follows. A stricter environmental policy for trade and services results in a Danish production shift from trade and services to other sectors including heavy manufacturing. The opposite specialization occurs in the foreign economy. Thus Danish production generally becomes more emission intensive, whilst the opposite is true in the foreign economy. Despite the higher Danish emission intensity, total Danish emissions decrease which is primarily a result of a smaller capital input (the returns to capital in Denmark decreases due to the policy). Meanwhile, emissions also decrease in the foreign economy due to the aforementioned specialization effect. Altogether, this results in a negative leakage rate.

Finally, the leakage rate associated with private (and public) fossil-fuel consumption mostly reflects leakage though the fossil fuel market, as the taxation of fossil-fuel consumption outside the production sectors only have second-order effects on trade patterns. This also explains the relatively small leakage effect. However, the model does not allow for private border trade like private citizens fuelling their vehicles on the other side of the Danish border. This leakage rate is therefore likely to be underestimated.

6.3 Sensitivity of sector specific leakage rates

To test the sensitivity of our estimates, we estimate the sector specific leakage rates under the assumption of a low intra-ETS leakage rate or that the Paris Agreement imposes binding emission constraints on most countries (see Table 4 in Appendix A).

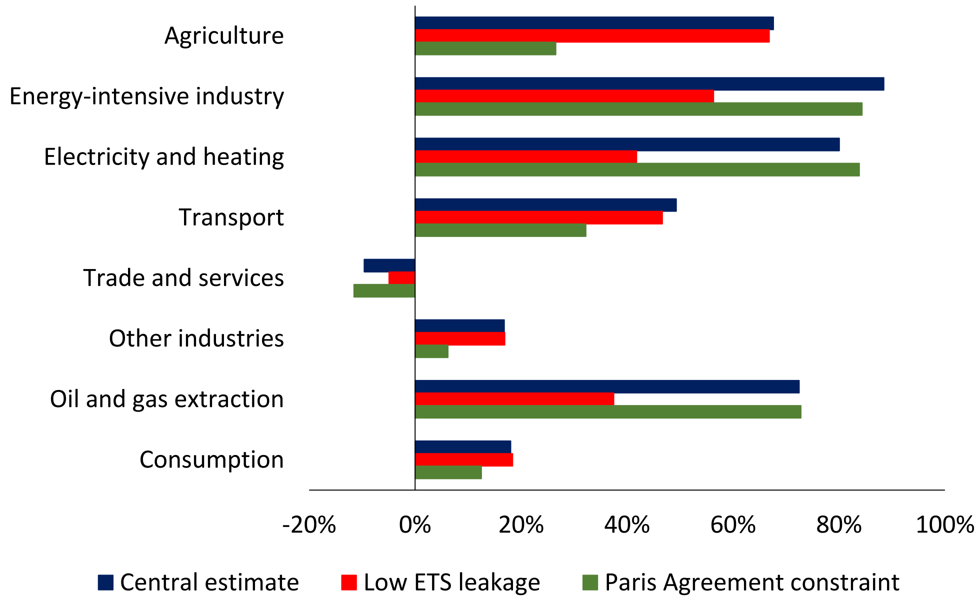

FIGURE 3: Sector specific carbon leakage rates under alternative assumptions.
Notes: Same policy experiments as in Figure 2. In the "Low intra-ETS leakage rate" scenario, the intra-ETS leakage rate is reduced from 83 to 43 pct. In the "With Paris Agreement constraint" scenario, binding emission caps are imposed on most non-EU countries with China, the US, India, and Russia as notable exceptions.

In the first case we reduce the intra-EU leakage rate from 83 to 43 pct. Figure 3 shows that a reduced intra-ETS leakage rate results in a substantial reduction in the estimated sector specific leakage rates for the ETS sectors. Meanwhile the assumption has little effect on the estimated leakage rates for the non-ETS sectors.

Introducing the Paris Agreement constraint has little effect on the estimated sector specific leakage rates as shown in Figure 3. The only exception is the agricultural sector. Here the estimated leakage rate is reduced from about 68 pct. to around 27 pct. The non-ETS constraints limit production effects within the EU of a Danish CO_2e tax in the agricultural sector. Thus the central leakage estimate for the agricultural sector is largely due to production shifts occurring outside of the EU. The Paris Agreement constraint limits these production shifts further, resulting in a much lower leakage rate. Nonetheless, the small effect of the Paris Agreement constraint on the macroeconomic leakage rate reflects that even though only a handful of large countries are left without emission caps, the global economy is still left with a substantial flexibility to change production patterns.

7 Concluding remarks

The main contribution of this study is to estimate economy-wide and sector specific carbon leakage rates for a small open economy using a global CGE model incorporating relevant international climate policies. We estimate leakage rates for Denmark, but the developed framework is applicable to any EU member state.

Our main finding is that the macroeconomic leakage rate for Denmark is around 70 pct. Thus the global CO_2 emission reduction of a Danish climate policy is only 30 pct. of the domestic reduction. We find that the Danish leakage rate is strongly affected by EU policies. Without any EU climate policy, our estimated leakage rate drops to about 20 pct. This is well within the typical range of leakage estimates found in the literature for large economies or climate coalitions. Imposing binding emission constraints from the Paris Agreement on most countries, but excluding the US, China, India, and Russia, has little effect on our macroeconomic leakage estimate.

We also provide sector specific leakage estimates. Our results indicate that carbon leakage rates vary substantially across sectors. Sectors covered by the EU ETS and agriculture have high leakage rates compared to the remaining sectors.

Our theoretical model shows that if national policymakers care about global emissions, then leakage sensitive sectors should face relatively more lax climate policies. In addition, one cannot implement the optimal leakage-adjusted policy without knowledge about the sector specific leakage rates. Thus our leakage estimates may have direct policy implications.

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A Aggregation

TABLE 2: Sector aggregation

Sectors			Sectors		
GTAP Data Base	**Aggregation**	**EU ETS**	**GTAP Data Base**	**Aggregation**	**EU ETS**
Paddy rice	Vegetable farming	No	Basic pharmaceutical products	Other industries	No
Wheat	Vegetable farming	No	Rubber and plastic products	Energy intensive sector	Yes
Cereal grains nec	Vegetable farming	No	Mineral products nec	Energy intensive sector	Yes
Vegetables, fruit, nuts	Vegetable farming	No	Ferrous metals	Energy intensive sector	Yes
Oil seeds	Vegetable farming	No	Metals nec	Energy intensive sector	Yes
Sugar cane, sugar beet	Vegetable farming	No	Metal products	Energy intensive sector	Yes
Plant-based fibers	Vegetable farming	No	Computer, electronic and optic	Other industries	No
Crops nec	Vegetable farming	No	Electrical equipment	Other industries	No
Bovine cattle, sheep and goats	Cattle farming	No	Machinery and equipment nec	Energy intensive sector	Yes
Animal products nec	Other animal farming	No	Motor vehicles and parts	Other industries	No
Raw milk	Cattle farming	No	Transport equipment nec	Other industries	No
Wool, silk-worm cocoons	Other animal farming	No	Manufactures nec	Other industries	No
Forestry	Raw materials sector	No	Electricity	Electricity sector	Yes
Fishing	Raw materials sector	No	Gas manufacture, distribution	Gas sector	Yes
Coal	Coal sector	No	Water	Other industries	No
Oil	Oil sector	Yes	Construction	Other industries	No
Gas	Gas sector	Yes	Trade	Trade sector	No
Minerals nec	Raw materials sector	No	Accommodation, Food and servic	Services sector	No
Bovine meat products	Animal food processing	No	Transport nec	Land transport sector	No
Meat products nec	Animal food processing	No	Water transport	Water transport sector	No
Vegetable oils and fats	Vegetable food processing	No	Air transport	Air transport sector	No
Dairy products	Animal food processing	No	Warehousing and support activi	Services sector	No
Processed rice	Vegetable food processing	No	Communication	Services sector	No
Sugar	Vegetable food processing	No	Financial services nec	Services sector	No
Food products nec	Vegetable food processing	No	Insurance	Services sector	No
Beverages and tobacco products	Vegetable food processing	No	Real estate activities	Services sector	No
Textiles	Other industries	No	Business services nec	Services sector	No
Wearing apparel	Other industries	No	Recreational and other service	Services sector	No
Leather products	Other industries	No	Public Administration and defe	Public sector	No
Wood products	Other industries	No	Education	Services sector	No
Paper products, publishing	Other industries	No	Human health and social work a	Services sector	No
Petroleum, coal products	Oil products	Yes	Dwellings	Services sector	No
Chemical products	Energy intensive sector	Yes			

TABLE 3: Main Sectors

Main Sector	Sectors	Covered by EU ETS
Agriculture	Vegetable farming	No
	Cattle farming	No
	Other animal farming	No
Transport, land-based	Other transport	No
Transport, sea and air	Air transport	No
	Sea transport	No
Energy-intensive industry	Energy intensive industry	Yes
	Oil products	Yes
Electricity and heating	Electricity and heat	Yes
Trade and services	Trade	No
	Service	No
	Public production	No
Other industry	Vegetable processing	No
	Animal processing	No
	Other industries	No
	Forestry and fishing	No
Oil and gas extraction*	Oil	Yes
	Gas	Yes
	Coal	No

*This main sector is simply named oil and gas extraction, as there is no coal production in Denmark.

TABLE 4: Regional aggregation and political constraints

	Region	Note	EU ETS member?	Binding non-ETS constraint	Paris Agreement constraint
1	Oceania	Incl. Australia and New Zealand	No	No	Yes
2	China	Incl. Taiwan	No	No	No
3	Japan		No	No	Yes
4	India		No	No	No
5	Asia	Rest of Asia	No	No	Yes
6	USA		No	No	No
7	Canada		No	No	Yes
8	North America	Primarily Mexico	No	No	Yes
9	Latin America	Central and	No	No	Yes
		South America	No	No	Yes
10	Austria		Yes	Yes	No
11	Belgium		Yes	Yes	No
12	Denmark		Yes	No	No
13	Finland		Yes	Yes	No
14	France		Yes	Yes	No
15	Germany		Yes	Yes	No
16	Ireland		Yes	Yes	No
17	Italy		Yes	Yes	No
18	The Netherlands		Yes	Yes	No
19	Poland		Yes	Yes	No
20	Spain		Yes	No	No
21	Sweden		Yes	Yes	No
22	Great Britain		Yes	Yes	No
23	ROEU	Rest of EU-28	Yes	No	No
24	Norway		Yes	No	Yes
25	Russia		No	No	No
26	Switzerland		No	No	Yes
27	Middle East and		No	No	Yes
	North Africa		No	No	Yes
28	Sub-Saharan Africa		No	No	Yes
29	RoEuropa	Rest of non-EU Europe	No	No	Yes
30	RoW	Small GTAP-regions (xtw)	No	No	No