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by

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

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## Abstract

A substantial literature investigates carbon leakage effects for large countries and climate coalitions. However, little is known about leakage effects for a small open economy within a climate coalition. To fill this gap in the literature, we incorporate international climate policies relevant for a small open EU economy into the general equilibrium model GTAP-E. We focus our analysis on Denmark, but we show that our framework can be applied to any EU economy. We find substantial leakage associated with an economy-wide CO<sub>2</sub>e tax. This result is strongly affected by EU climate policies. We also present sector-specific leakage rates and find large sectoral differences.

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

**JEL Classification:** F18, H23, Q54

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\*The present study is partly based on the background document Beck, Kruse-Andersen, and Stewart (2019) accompanying the report "Economy and the Environment 2019" by the Danish Economic Councils.

<sup>†</sup>The views expressed in this paper are solely my own, and not those of the secretariat of the Danish Council on Climate Change.

# 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, typically building on single country partial or general equilibrium models (e.g., Bohlin 2010). As these studies only explicitly model the national economy, the leakage effects result almost directly from simplifying assumptions about the foreign production technology.

The main contribution of this study is to estimate carbon leakage effects for a small open economy. To the best of our knowledge, we are the first to do so using a global CGE model (a modified version of the GTAP-E model) with relevant international climate policies in place. We focus our investigation on Denmark, but our model framework can be applied to any EU member state, and we verify the generality of our main findings by estimating leakage effects for all EU regions in our model. The literature typically focuses on carbon leaking from a climate coalition to non-coalition countries. In contrast, we investigate leakage effects of a single economy (Denmark) within a climate coalition (the EU), and we investigate how emissions leak to both coalition and non-coalition countries. We incorporate EU climate policies like the EU Emissions Trading System (ETS) into the CGE model. A small open economy must (to a large extent) take these political systems and agreements as given when designing its national climate policies.

Our analysis leads to several insights. Firstly, we show that carbon leakage substantially reduces the global impact of national policies. In our central case for Denmark, the global emission impact is at most 62 pct. of the domestic emission cut. Secondly, we show that EU climate policies are crucial for the leakage effects. This is mainly due to the EU

ETS which amplifies leakage effects within the EU despite the recent reform of the system (see Beck and Kruse-Andersen 2020). Thirdly, we show that the Paris Agreement has a limited effect on carbon leakage as long as major economies like the US, China, India, and Russia do not have binding Nationally Determined Contributions. Finally, we uncover large differences in the leakage sensitivity of different sectors. Sectors covered by the EU ETS and agriculture are relatively more leakage sensitive compared to the remaining part of the economy.

The policy implications and relevance of our study hinge on the political aversion to carbon leakage. If there is no aversion to leakage, policymakers should simply adopt uniform carbon taxation to minimize the cost of achieving national emission targets (Baumol and Oates 1971). However, if policymakers care about the global emission impact of their policies, this affects not only optimal emission targets, but also the optimal regulation associated with these targets. Our study provides a methodology that EU countries can use to estimate both the national leakage sensitivity that may guide national emission targets, and the leakage sensitivity of different sectors that are needed to implement leakage-reducing policies efficiently (see Hoel 1996; Kruse-Andersen and Sørensen 2019, 2021).

A natural question is then: do policymakers care about carbon leakage? One recent indication is the carbon border adjustment mechanism proposed by the EU Commission as part of the Fit for 55% package. Motivating the introduction of this mechanism, Commissioner for Economy, Paolo Gentiloni, stated that:

In full respect of our WTO commitments, this will ensure that our climate ambition is not undermined by foreign firms subject to more lax environmental requirements (European Commission 2021).

The commissioner emphasizes the environmental impact, and thereby the carbon leakage effect, rather than competitiveness as motivation for the mechanism.

Another 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 states that

the emission reduction measures may not simply move the emissions abroad. Thus the policymakers seem to care about the global impact of their policies, although the exact formulation in the law probably only prohibits measures resulting in leakage rates of 100 pct. or more.

The policymakers' preferences on leakage are also revealed more indirectly through the arguments of industry actors and lobbyists. These actors use carbon leakage as a core argument against tighter climate policies. For instance, the CEO of the Danish cement producer Aalborg Portland – the largest single GHG emitter in Denmark – made the following statement on the prospect of a substantial increase in the Danish carbon tax:

It simply means that we cannot compete... There will be a period where we might be able to compete domestically, but we are severely challenged even in that case, and we will therefore create a substantial leakage of carbon to other countries (Bach 2020).

The fact that industry actors and lobbyists use the leakage argument in their media appearances suggests that policymakers find the argument persuasive.

On top of this, it is sometimes argued that the greatest impact a small economy can have on the climate is to be an example to follow.<sup>1</sup> 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 its GHG emissions by outsourcing polluting activities, it does not really demonstrate anything about pollution abatement costs. Instead, the economy simply shows that it is possible to specialize in low-emission industries.<sup>2</sup> Hence an effective demonstration effect requires climate policies that at least partly deal with the leakage issue. Implementing such policies requires knowledge about carbon leakage effects.

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<sup>1</sup>Hoel (2012) explains this demonstration effect.

<sup>2</sup>In a formal analysis, Greaker et al. (2019) show how the demonstration effect works through a demonstration of abatement costs.

## 1.1 Carbon leakage: definition and channels

To operationalize the concept of *carbon leakage*, we follow the literature and define the leakage rate denoted  $L$ . If a country reduces its GHG emissions 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:

$$L = -\frac{\Delta e_f}{\Delta e_h},$$

where  $\Delta e_f$  and  $\Delta e_h$  are changes in foreign and domestic GHG emissions, respectively. The global emission impact per unit of domestic emission reduction is then:  $(1 - L)$ .

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 its climate actions have small price effects, these effects occur on a large world market. This mechanism may therefore be important in our context even if the international fossil fuel prices are only affected little by Danish policy actions.

Thirdly, carbon leakage effects are built 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 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). 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 carbon leakage effects for a small economy, effects caused by political agreements and systems are crucial. For instance, a small EU country will be substantially affected by the climate policy of the EU, so we make a substantial effort to take relevant international climate policies into account. We also show that leakage rates are highly 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.

Our study does not include this effect which is very difficult to quantify. This is a typical shortcoming in the carbon leakage literature. We recognize that the absence of this effect might bias our leakage estimates upwards.

## 1.2 Outline

The remaining part of the paper is organized as follows. Section 2 reviews the theoretical and empirical literature on carbon leakage. We build a conceptual framework in Section 3 which guides our numerical analysis. Section 4 describes the GTAP-E model and the employed database, and Section 5 describes our extensions to the standard GTAP-E model. We then explain the policy experiments in Section 6, and the simulation results are presented and explained in Section 7. Finally, Section 8 offers some concluding remarks.

## 2 Review of literature on carbon leakage

### 2.1 Optimal unilateral climate policy with carbon leakage

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. In addition, BCAs may not be an available tool for policymakers. BCAs may be challenged under WTO rules (Cosbey et al. 2019), and the internal market within the EU does not allow such border adjustments between EU member states.

Alternatively, the optimal unilateral climate policy can be implemented using a variety of instruments including differentiated carbon and consumption taxes. This equivalence is shown by Jakob et al. (2013) in a two-country two-sector model.

In a multi-sector partial-equilibrium model Kruse-Andersen and Sørensen (2019) show that the optimal policy for an economy that wants to achieve a global emission reduction includes differentiated carbon taxes and differentiated consumption taxes. They also explicitly model an electricity market, and the optimal policy involves taxes on electricity consumption and subsidies to renewable energy production.

Kruse-Andersen and Sørensen (2021) show in a general equilibrium model that if policy-makers have an aversion to carbon leakage, the optimal unilateral climate policy involves taxes on emissions as well as taxes on domestic consumption of energy and final goods. Kruse-Andersen and Sørensen (2021) distinguish between leakage at the extensive margin where firms relocate to a foreign economy, and leakage at the intensive margin where domestic firms lose world market shares. As a consequence, the optimal policy includes an output subsidy to deal with leakage at the intensive margin and a lump-sum location subsidy to deal with leakage at the extensive margin.

Hoel (1996) finds that taxes should be differentiated across sectors if emission taxes are the only instruments available to the government. Yet, in contrast to the first-best



policy schemes derived by Jakob et al. (2013) and Kruse-Andersen and Sørensen (2019, 2021), this results in a second-best allocation.

An important point is that although the optimal unilateral climate policy can be implemented without BCAs, the literature shows that knowledge on sector-specific leakage effects is necessary to implement efficient policies. The present study, therefore, includes sector-specific leakage rate estimates.

An alternative way to mitigate the leakage problem is output-based allocations of emission rights (e.g., Böhringer and Lange 2005; Hagem et al. 2020). The output-based approach may involve free emission allowances within a cap-and-trade system, or a tax refund within a tax system, proportional to output. The idea is to reduce the loss in competitiveness imposed by carbon pricing by subsidizing output. However, as shown by Kruse-Andersen and Sørensen (2021), output-based allocations alone cannot ensure the first-best allocation in general.

## 2.2 Empirical studies of carbon leakage

The empirical literature on competitiveness and environmental regulation is substantial. These studies typically find small effects of environmental regulation on competitiveness (Dechezleprêtre and Sato 2017; Venmans et al. 2020). Nonetheless, most of these studies do not deal directly with the leakage issues.

There are also empirical studies that tackle the leakage issue directly. The advantage of these ex-post studies is that they evaluate real-world developments, but they have three key limitations. Firstly, as the datasets are subglobal, researchers cannot detect all relevant effects. Leakage through the fossil fuel market is, for instance, a global effect. Secondly, the environmental policies that are evaluated may not provide sufficient variation in the environmental stringency to identify a significant leakage effect. The question is then how informative the results are when guiding more fundamental policy changes. Finally, the distinct details of the policy shocks considered complicate the interpretation of the results (e.g., scope, exemptions, and rebates).

Using an instrumental variable strategy, Aichele and Felbermayr (2012) find that the

ratification of binding Kyoto Protocol commitments lowered domestic emissions by 7 pct. However, they also find that the carbon footprint of committing countries is unchanged. Thus, they argue that the effect on global emissions is in the best case zero, implying substantial carbon leakage.<sup>3</sup>

Barker et al. (2007) use an econometric model to evaluate six environmental tax reforms of individual EU members over the period 1995-2005. They find virtually no carbon leaking from members introducing environmental tax reforms to other EU member states. However, their study does not include emissions by economies outside the EU.

Fowlie and Reguant (2020) utilize energy price variations to estimate carbon leakage effects of US manufacturing industries. The idea is that changes in energy prices mimic the impact of a domestic carbon tax. Their results suggest substantial leakage (median estimate of 46 pct.) in the absence of leakage-mitigating measures like output rebates.

In a related study, Misch and Wingender (2021) exploit sector-country-specific variation in energy prices to infer effects from carbon pricing on domestic carbon emissions and carbon embodied in trade flows. The study finds country-specific leakage rates ranging from around 7 to 47 pct. However, the leakage estimates are based on country-specific carbon embodied in trade flows, implying that not all leakage effects are taken into account. One example of a missing effect is leakage through the EU ETS.

Naegele and Zaklan (2019) estimate leakage effects of the EU ETS using changes in trade flows. They find no evidence of carbon leakage from the introduction of the EU ETS. However, their empirical assessment only covers years prior to EU ETS phase 3 (2013-2020). During the investigated period, the majority of allowances were allocated for free and the allowance price was low. The authors note that the direct cost of the EU ETS is negative for most sectors due to free allocations. Given the low carbon price imposed by the system, it is not surprising that the authors cannot find significant leakage effects.<sup>4</sup>

The empirical literature mentioned above finds mixed evidence of leakage effects. Some

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<sup>3</sup>Aichele and Felbermayr (2015) also find that the Kyoto Protocol lead to substantial carbon leakage.

<sup>4</sup>Colmer et al. (2020) investigate emission and production effects of the EU ETS. They find no evidence that firms outsource production due to the EU ETS. In line with Naegele and Zaklan (2019), their investigated period stops before Phase 3, implying a low cost imposed on firms by the system.

studies find sizeable leakage effects, while other studies do not find any significant effects. In addition, the different sources of exogenous variation make the studies difficult to compare. Venmans et al. (2020) argue that the insignificant effect of environmental policies on competitiveness found in the empirical literature is partly caused by low carbon prices, tax exemptions, and generous emission allowance allocations. Our review suggests that the same conclusion holds for empirical studies focusing more directly on carbon leakage. It is, therefore, difficult to evaluate leakage effects of more fundamental climate policy changes based on the existing empirical literature.

## 2.3 Model simulations and carbon leakage

### 2.3.1 CGE models: large economies and climate coalitions

A substantial literature investigates the leakage issue using computable general equilibrium (CGE) models.<sup>5</sup> 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 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.

The leakage rate is generally decreasing in the size of the coalition (Böhringer et al. 2010; Burniaux and Martins 2012). As an example, OECD (2009) finds that the leakage

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<sup>5</sup>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).

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

Study	Leakage rate	GHG reduction <sup>g)</sup>	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) <sup>a)</sup>	15-21 pct.	10-30 pct.	EU and EFTA countries
Böhringer et al. (2010) <sup>b)</sup>	10-28 pct.	20 pct.	USA and/or EU
Elliott et al. (2010) <sup>c)</sup>	15-25 pct.	3-15 pct.	Annex B from Kyoto
Fischer and Fox (2012) <sup>d)</sup>	7 pct.	-	USA (selected sectors)
Gerlagh and Kuik (2014) <sup>e)</sup>	3-10 pct.	11 pct.	EU
Kuik and Hofkes (2010) <sup>f)</sup>	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 energy-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 CO<sub>2</sub>. It is not reported how much this allowance price reduces GHG emissions.

g): The GHG reduction refers to that of the coalition, not the net effect on global GHG emissions.

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 conducted by the Annex I countries from the Kyoto Protocol. Intuitively, there will be fewer countries where emissions can leak to when the coalition size increases.

However, the leakage effect depends not only on the size but also on the characteristics of the regulated region. Böhringer et al. (2010) investigate a 20 pct. emission reduction for the EU, the US, and both regions simultaneously under different policy schemes. The EU has much higher leakage rates (up to 28 pct.) compared to the US (up to 10 pct.). The authors emphasize two reasons for this discrepancy: (1) the EU is a more open economy, and (2) energy-intensive industries in the EU are relatively less carbon intensive.

Exemplified by the study by Böhringer et al. (2010), leakage rates depend not only on the size of the abating region but also on the structure of the economies considered.

Furthermore, the literature typically finds that the leakage rate is increasing in the amount of abated emissions (see Carbone and Rivers 2017).

By construction, the leakage literature on large countries and climate coalitions does not provide much information on leakage effects of unilateral climate policies of small economies – and even less so for small economies within a climate coalition.<sup>6</sup>

### 2.3.2 Small economies

There are only a handful of model analyses dealing with the carbon leakage issue for a small economy. These studies are based on partial equilibrium models, single country CGE models, or subglobal power market models.

Bohlin (2010) estimates carbon leakage effects in a CGE model for Sweden. The core assumption is that Swedish production technologies are employed by the foreign economy for all goods. The only exception 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.

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 Denmark.

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

Frontier Economics (2018) analyses the effects of a carbon price floor and a ban on coal in the Netherlands. The study employs a multi-region but subglobal power market

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<sup>6</sup>Global CGE model studies examining the effects of unilateral climate coalitions sometimes provide emission effects divided into several countries (e.g., Lanzi et al. 2012). But these emission effects are not informative when it comes to leakage from a unilateral climate policy of a small economy, as the policy shock is completely different. Specifically, policy action by a climate coalition affects the competitiveness of multiple economies simultaneously, while a unilateral policy action by a single economy only affects the competitiveness of that economy.

model. The investigated policies are associated with leakage rates above 50 pct. in 2030. However, the analysis is limited by both the regional and sectoral coverage of the model.

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. This allows us to capture leakage effects occurring far from the regulated region. One would, for instance, expect carbon leakage through the fossil fuel market to occur all over the world. Secondly, our model includes leakage through international agreements and institutions which a small open economy must (to a large extent) take as given. The inclusion of these international climate policies turns out to be crucial for the estimated leakage rates.

### 3 Conceptual framework

This section introduces a conceptual framework that is used to interpret our results. We show that the total leakage effect can be decomposed into three leakage effects, and we refer to these effects when interpreting the model simulations. The conceptual framework developed here extends that of Perino et al. (2020) by adding leakage to countries outside the climate coalition (external leakage).

We consider an economy, denoted  $h$  for "home economy", that is part of a climate coalition. The remaining part of the climate coalition is denoted  $c$ , and the economy outside the climate coalition is denoted  $r$  for "rest of the world".

The climate coalition has a common climate policy that may partly or fully cover total GHG emissions from the coalition members. The variable  $\tau$  captures the strength of the coalition climate policy. It could, for instance, measure the allowance price within a common cap-and-trade system. Holding  $\tau$  fixed, a unilateral climate policy has the following emission effect in the three regions:  $\Delta e_j$ ,  $j = h, c, r$ . We refer to this as the direct emission effect.

However, the equilibrium emission effect may differ from the direct emission effect, as

$\tau$  is endogenous. One example is a textbook international cap-and-trade system where a reduction in emission demand in one country reduces the allowance price, while total emissions remain unaffected. In that case  $\tau$  is the emission allowance price which decreases as a response to policies that reduce emission demand. The reduction in  $\tau$  implies that the equilibrium emission reduction is lower than the direct emission reduction.

The equilibrium global emission change,  $\Delta e^*$ , resulting from a unilateral climate policy in the home economy, is given by:

$$\Delta e^* = \Delta e_h^* + \Delta e_c^* + \Delta e_r^*,$$

where  $\Delta e_j^*$  is the absolute equilibrium emission change in economy  $j = h, c, r$ .

The question is then how the direct emission effect of a domestic policy,  $\Delta e_h$ , translates into a global emission effect,  $\Delta e^*$ . To derive the relevant formula, we define three leakage effects.

The *internal leakage effect* is the emission leakage that occurs within the coalition holding the coalition climate policy ( $\tau$ ) constant. The internal leakage rate is given by:

$$L^{int} \equiv -\frac{\Delta e_c}{\Delta e_h}.$$

However, the coalition climate policy ( $\tau$ ) is endogenous. The *waterbed effect*,  $W$ , captures the leakage effect caused by the change in the climate policy of the coalition (changes to  $\tau$ ):

$$W \equiv 1 - \frac{\Delta e_h^* + \Delta e_c^*}{\Delta e_h + \Delta e_c}.$$

Finally, the *external leakage effect* captures carbon leaking from the climate coalition to the remaining part of the world. The external leakage rate is given by:

$$L^{ex} \equiv -\frac{\Delta e_r^*}{\Delta e_h^* + \Delta e_c^*}.$$

It follows that the global effect of a unilateral climate policy is given by:

$$\Delta e^* = (1 - L^{ex})(1 - W)(1 - L^{int})\Delta e_h. \quad (1)$$

The three leakage effects from this formula are directly related to the leakage rate as:

$$(1 - L)\Delta e_h^* = (1 - L^{ex})(1 - W)(1 - L^{int})\Delta e_h, \quad L \equiv -(\Delta e_c^* + \Delta e_r^*)/\Delta e_h^*.$$

Consider equation (1). Economists are typically able to come up with a good estimate of the direct domestic emission impact of a unilateral climate policy,  $\Delta e_h$ . And if the policy has a small effect on the policy stringency of the coalition (small effect on  $\tau$ ), the direct domestic impact is typically close to the domestic equilibrium effect,  $\Delta e_h^*$ .

However, it is much harder to estimate the three leakage effects present in (1). They all result from multiple general equilibrium effects that occur in multiple regions. The global emission impact is therefore difficult to quantify.

The present study develops a framework that can compute the total leakage effect of a unilateral climate policy and quantify the importance of the three leakage effects in (1). The waterbed effect is here of particular interest. While the internal and external leakage effects are largely determined by the economic structures, the waterbed effect is basically a political construction. If the waterbed effect is strong, the climate policy of the coalition deters members from pursuing more ambitious climate policies on their own. This might be seen as problematic, but it is also something the policymakers can do something about.

In our model simulations, we quantify the importance of the waterbed effect by removing all EU climate policies from the model. In addition, we analyse what parts of the EU climate policies contribute the most to the waterbed effect by removing policies separately. We also consider the size of the external leakage effect. This effect is directly observable in the model runs, while the internal leakage and waterbed effects are entangled.



## 4 The GTAP-E model and GTAP Database

The analysis is based on a modified version of the GTAP-E model. We give a brief overview of the GTAP-E model, the GTAP Data Base, and our aggregation before explaining our extensions 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 capital, 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 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

To ensure a reasonable solution 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 substitution 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.

## 5 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. In the following, we briefly describe the four extensions before going into the technical details in separate subsections.

Firstly, we add non-CO<sub>2</sub> emissions like methane emissions from agricultural production and N<sub>2</sub>O emissions from chemical industries. Bednar-Friedl et al. (2012) show that leakage effects are underestimated if these non-CO<sub>2</sub> emissions are not taken into account.

The second and third extensions introduce EU climate policies: the EU ETS, and non-ETS emission constraints. The EU ETS covers the power sector and the energy-intensive part of the manufacturing industry across the EU. Despite the latest reform of the EU ETS, there is still a waterbed effect embedded into the system (Perino 2018; Beck and Kruse-Andersen 2020) that we need to take into account.

The EU takes responsibility for emission reductions within ETS-covered sectors. Meanwhile, EU members are obligated to reduce GHG emissions within the non-ETS sector. Member states with binding emission obligations cannot increase their non-ETS emission in response to changes in Danish policies. We model this mechanism as well which dampens the waterbed effect.

The fourth and final extension is the inclusion of binding emission commitments from the Paris Agreement. We do not impose these binding commitments in our central case, but we want to analyse how the agreement affects our leakage estimates in a scenario where most countries have binding commitments.

## 5.1 Non-CO<sub>2</sub> emissions

We add non-CO<sub>2</sub> emissions using a GTAP satellite database (Chepeliev 2020). These emissions are in the database connected to the use of certain inputs (e.g., fertilizers in agriculture), the use of primary production factors in farming – mostly capital in the form of livestock – and certain production outputs (e.g., chemical production processes). We add emissions from primary factor inputs in farming to output-related emissions. This simplification eliminates the possibility that farmers substitute away from capital as a response to an emission tax. As capital in animal farming mostly consists of animals, this seems like a reasonable assumption. Still, farmers are able to substitute away from emission-intensive cattle farming to other animal farming or to vegetable farming, leaving plenty of emission abatement options.

## 5.2 The EU ETS

The EU ETS is a cap-and-trade system, where producers must surrender emission allowances proportional to their emissions. Firms receive and purchase allowances from the EU (via the member states), and they are allowed to trade allowances with each other. The system ensures a price on GHG emissions covered by the system. There is a waterbed effect built into international cap-and-trade systems like the EU ETS. If a member state reduces its allowance demand, the allowance price falls, and other member states increase

their emissions. As long as the total amount of emission allowances are unchanged, the intra-ETS leakage rate is 100 pct.

The introduction of the Market Stability Reserve (MSR) and the 2018 reform of the EU ETS reduced this intra-ETS leakage (Beck and Kruse-Andersen 2020). We now give a condensed description of the mechanism.<sup>7</sup> The MSR regulates the amount of allowances in circulation. If there is a large amount of allowances in circulation in excess of current emissions, the MSR absorbs allowances, and if there are few allowances in circulation, the MSR releases some of these allowances again. The original MSR was cap preserving in the sense that it did not affect the total amount of allowances in the EU ETS – only the intertemporal availability. Accordingly, the long-run intra-ETS leakage rate was still 100 pct.

However, the 2018 reform introduced a cap on the amount of allowances that can be contained within the MSR. If there are too many allowances in the MSR, excess allowances are permanently cancelled. This can affect the intra-ETS leakage rate. Consider a unilateral policy that reduces the allowance demand. The policy increases the amount of allowances in circulation, resulting in more allowances being placed in the MSR. If the MSR cap is binding, these allowances are then cancelled, resulting in a long-run intra-ETS leakage rate of less than 100 pct.

We want to incorporate the leakage effects of the current EU ETS into our model. This is complicated by the fact that our CGE model is static, while the dynamic aspect is crucial for computed intra-ETS leakage rates. To work around this issue, we deploy the EU ETS model by Beck and Kruse-Andersen (2020) to compute intra-ETS leakage rates. We introduce a permanent reduction in allowance demand to mimic the effect of a permanent unilateral economy-wide CO<sub>2</sub>e tax. Details are provided in Appendix B.

We then introduce 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. The subsidy ensures that the waterbed effect from the EU ETS model is reflected appropriately in the CGE model.

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<sup>7</sup>We refer to Beck and Kruse-Andersen (2020) for a more thorough exposition.

Note that the GTAP data, and thereby the CGE 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. Furthermore, 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.

For a permanent reduction in the allowance demand, the EU ETS model by Beck and Kruse-Andersen (2020) estimate an intra-ETS leakage rate of 41 pct. until 2030. The leakage rate increases to 66 pct. if we evaluate the leakage effect in 2050. We call these estimates the medium-run and long-run EU ETS leakage rates. On the one hand, it may be argued that the long-run estimate should be used as current policies have leakage implications far down the road. On the other hand, it is highly uncertain that the computed effect after 2030 will actually occur, as the EU ETS is reformed regularly. On top of this, economists typically discount the value of emissions, implying a low value of post-2030 leakage. We find both arguments valid, and our main results are therefore reported for both.

Finally, we note that our intra-ETS leakage rate is computed based on existing rules. Yet, the Fit for 55% package recently proposed by the European Commission includes additional changes to the EU ETS system (European Commission 2021), that may affect the intra-ETS leakage rate. These are not included given that the package has not been adopted at the time of writing. But we note that it is straightforward to incorporate changes in the intra-ETS leakage rate using our methodology.

### **5.3 Non-ETS constraints**

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, as shown in Table 4 in Appendix A.

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 due to Danish policies, these countries will somehow need to tighten their climate policy to comply with their EU obligations. We also note that our approach allows for sectoral shifts within the non-ETS sector for countries with binding non-ETS commitments.

## 5.4 Paris Agreement constraints

To reflect the potential effect of a functioning Paris Agreement, we impose binding emission constraints on almost all smaller countries outside the EU. In line with the non-ETS sector constraint, we model this through an endogenous CO<sub>2</sub>e tax. The EU commitment to the Paris Agreement is already modelled through 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, as well as a region consisting of non-EU countries in Eastern Europe and Western Asia (e.g., Ukraine, Georgia, Kazakhstan). See Table 4 in Appendix A for details. These regions are primarily selected based on business-as-usual emissions and official emission targets obtained from UN Environment (2018).

# 6 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<sub>2</sub>e emissions. The macroeconomic leakage rate reflects the overall leakage sensitivity of the economy. We focus on a tax rate of 50 US-dollars per tonne

of CO<sub>2</sub>e. We choose this tax rate, as it results in a Danish emission reduction of 8 mt. of CO<sub>2</sub>e. A linear emission reduction toward the Danish 2030 emission target requires an emission reduction of roughly 8 mt. in 2025 (see Appendix C for details). Thus the reduction seems realistic in size and it is a politically relevant case. Nevertheless, we also show that the leakage rate in our central case is insensitive to the tax rate.

We do not tax emissions from international transportation by air and water, as these emissions are not part of the Danish GHG emissions according to the UN accounting method. The GTAP database reports global emissions by Danish ships and aircraft. Yet, emissions and bunkering often take place far away from Danish territory, making them hard to regulate for the Danish government.

We also want to investigate the leakage sensitivity of different sectors. As mentioned above, an effective leakage-adjusted climate policy requires knowledge of sector-specific leakage effects. To estimate the sector-specific leakage rates, we divide our 19 sectors into main sectors like agriculture, energy-intensive industry, and trade and services. We also include private consumption of fossil fuels as a main sector. All main sectors are shown in Table 3 in Appendix A. We then impose CO<sub>2</sub>e taxes on one main sector at a time to compute the sector-specific leakage rate. The advantage of this approach is that the sector-specific leakage rates include all general equilibrium effects.

## 7 Results

This section presents our results. We start with the economy-wide policy shock. Our main findings are that: (1) the Danish leakage rate is substantial, and (2) EU policies (the waterbed effect) increase the Danish leakage rate considerably. We then investigate leakage effects in all our EU regions. This exercise confirms that our two main findings from the Danish case carry over more generally within the EU. We finish by computing sector-specific leakage rates for Denmark which reveals large sectoral differences.

## 7.1 Macroeconomic leakage rates

The main results for the economy-wide policy shock are presented in Figure 1. In our central case, the macroeconomic leakage rate is 38-56 pct., depending on the time horizon of the EU ETS leakage. If we remove all EU policies, the leakage rate drops to 26 pct., implying that the waterbed effect is substantial. Here it should be noted that the leakage rate without EU policies lies within the typical range found in the CGE literature of 10-30 pct.

The non-ETS constraints reduce the waterbed effect as they prohibit some EU member states from increasing their non-ETS emission as a response to Danish policies. However, as shown in Figure 1, the macroeconomic leakage rate only increases by 4-6 percentage points (pp) when the non-ETS constraint is dropped.

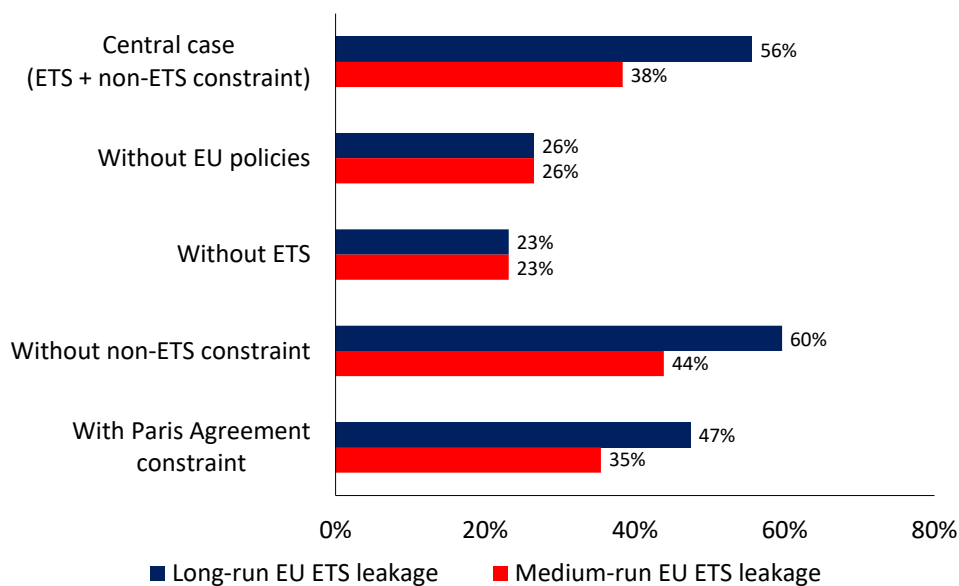
In contrast, the EU ETS imposes a substantial and positive waterbed effect. The macroeconomic leakage rate drops to 23 pct. when we remove the EU ETS from the model: a drop of 15-33 pp.

Introducing the Paris Agreement constraint reduces the leakage rate by 3-9 pp. The effect seems small given that most non-EU countries are constrained. There are two reasons why the effect is not larger. Firstly, since the large economies – China, India, the US, and Russia – are not constrained, there is still substantial flexibility in the global economic system. Secondly, the Paris Agreement reduces external leakage, but since most of the leakage occurs within the EU due to the waterbed effect, the agreement has a limited impact on the leakage rate.

Next, we want to examine the importance of the tax level. Figure 2 shows macroeconomic leakage rates as a function of the CO<sub>2</sub>e tax rate. The computed leakage rate is barely affected by the tax level in our central case (with long-run EU ETS leakage). The leakage rate decreases from around 58 pct. for a 10 dollar tax to 55 pct. for a 100 dollar tax. Removing all EU policies result in a gradually increasing leakage rate starting at 21 pct. for a 10 dollar tax and ending at 33 pct. for a 100 dollar tax.

The pattern observed for the case without EU policies is in line with the literature, where the leakage rate increases with the abatement effort. To explain the observed pat-



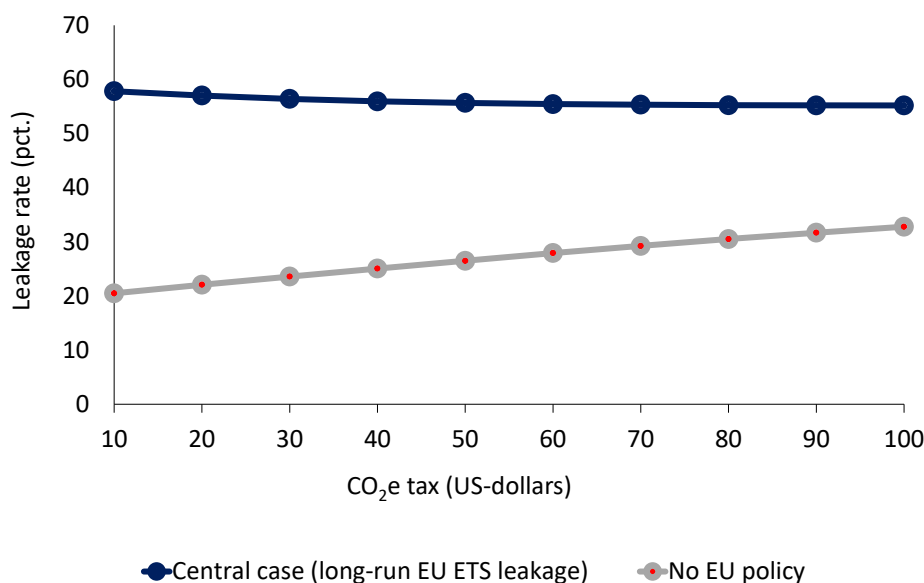


**FIGURE 1: Macroeconomic carbon leakage rates.**

*Notes:* The macroeconomic 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<sub>2</sub>e tax of 50 US-dollars per tonne of emission. This emission tax is placed on top of the existing regulation.

terns in Figure 2 consider the following two opposing effects. The first effect is an inverted MAC (marginal abatement cost) effect. It is well known in the environmental economics literature that (if abatement is conducted efficiently) marginal emission abatement costs are increasing in the abatement level. In equilibrium, firms abate until their MAC equals the CO<sub>2</sub>e tax rate. Inverting the relationship therefore implies that emission reductions are a decreasing function of the tax rate. This reduces the domestic emission impact from a tighter environmental policy which, all other things equal, increases the leakage rate. Meanwhile, a higher emission tax level erodes the competitiveness of emission-intensive industries which pushes this production – and thereby emissions – to the foreign economy.

The other effect is a sector composition effect. As the CO<sub>2</sub>e tax increases, the domestic economy loses competitiveness in emission-intensive industries, and activity shifts towards less emission-intensive industries. As a consequence, the emission share of emission-intensive sectors decreases. But these sectors are also the leakage-sensitive sectors (as shown below). Seen in isolation, this effect reduces the leakage-sensitivity of the economy, as the tax rate increases.



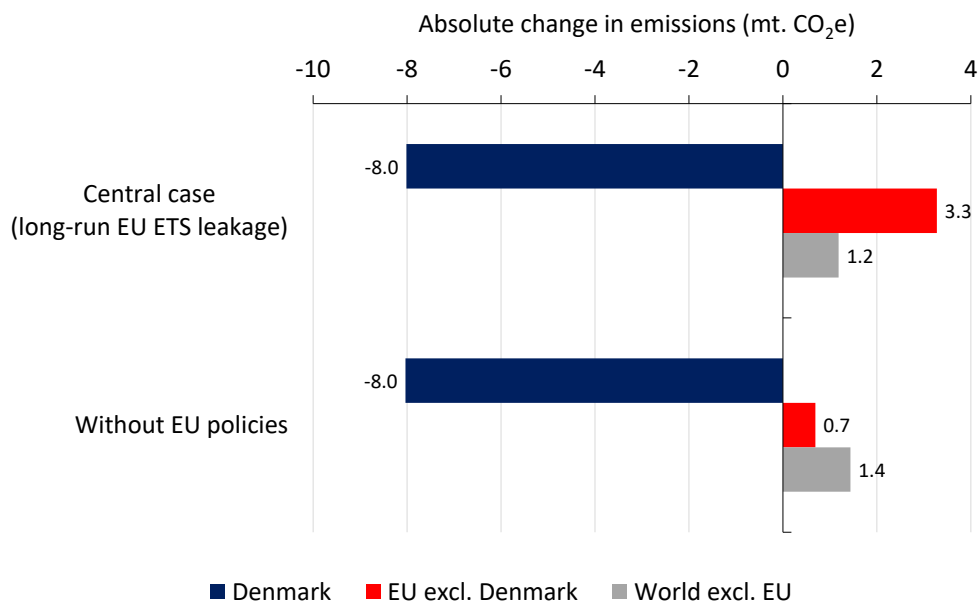
**FIGURE 2: Macroeconomic carbon leakage rates as a function of the CO<sub>2</sub>e tax rate.**

Without EU climate policies the inverted MAC effect dominates, while the sector composition effect dominates in our central case. This is because the EU ETS increases the leakage-sensitivity of emission-intensive sectors substantially, as we show below. On top of this, the non-ETS constraints weaken leakage effects in the non-ETS sector. This increases discrepancies in leakage sensitivities which amplifies the sector composition effect.

The main takeaway from Figure 2 is that the estimated leakage rate in our central case is not sensitive to the exact rate of the CO<sub>2</sub>e tax, while the leakage rate without EU policies is increasing in this tax rate.

The results presented in Figure 1 show that the waterbed effect is substantial. The next question is then where emissions leak to. If emissions stay within the climate coalition, domestic policymakers may advocate EU climate policies that reduce the waterbed effect. In case emissions mainly move outside the coalition, the leakage issue must be dealt with through global climate policy action which is much harder to affect.

Figure 3 shows the absolute change in emissions as a result of a Danish CO<sub>2</sub>e tax of 50 US-dollars. Domestic emissions decrease by 8 mt. of CO<sub>2</sub>e in both the central case (with long-run EU ETS leakage) and without EU policies. In the central case, emissions increase



**FIGURE 3: Absolute change in emissions as a result of a Danish CO<sub>2</sub>e tax of 50 US-dollars.**

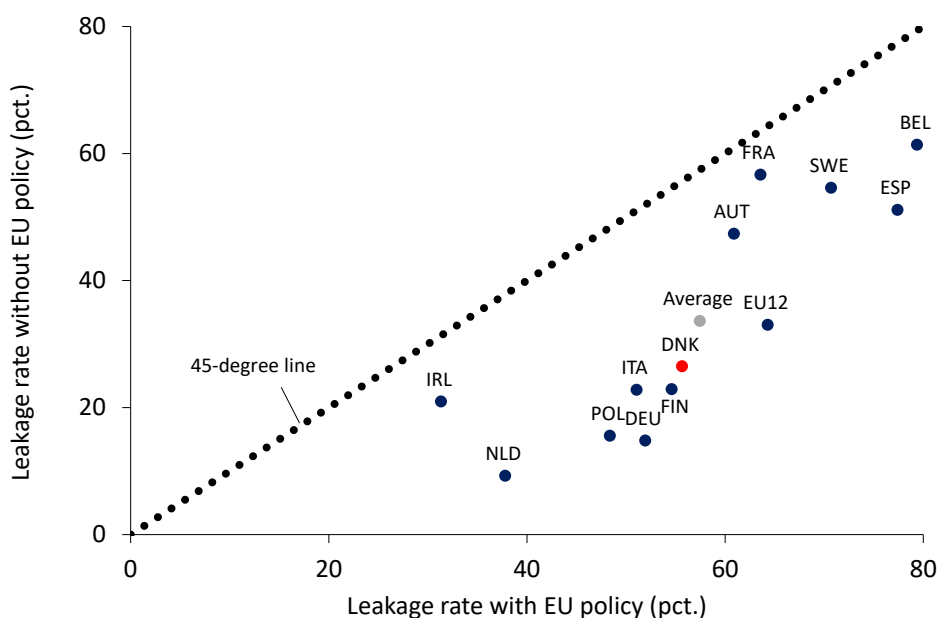
by 3.3 mt. in the rest of the EU, while emissions increase by only 1.2 mt. outside the EU. Thus, external leakage constitutes only one-quarter of the total leakage. The picture changes without EU policies. In that case, emissions increase by almost the same amount outside the EU (1.4 mt.), while emissions only increase by 0.7 mt. in the rest of the EU. Thus without the waterbed effect, the absolute emission leakage to the EU is reduced by almost 80 pct. As a consequence, the external leakage effect becomes dominant and constitutes almost 70 pct. of the total leakage, although the absolute external leakage effect is about the same.

Summing up, the simulations conducted here show that EU climate policies have a pronounced effect on carbon leakage in Denmark. We have also shown that the leakage rate is insensitive to the level of a uniform CO<sub>2</sub>e tax as long as the EU climate policies are in place. Finally, we have shown that emissions mainly leak to the EU, and that this is a consequence of EU policies.

## 7.2 Leakage in all EU regions

The results presented above show that the waterbed effect is substantial for the Danish economy. In addition, the macroeconomic leakage rate for Denmark is high (38-56 pct.), indicating that leakage reduces the global impact of domestic emission reductions substantially. To test the generality of these findings, we compute leakage rates for all EU regions in our model both with and without EU policies. One reservation is that our aggregation is based on the sectoral composition of the Danish economy. The aggregation might therefore not be ideal for all our EU regions. The results should be interpreted with this caveat in mind.

The results are shown in Figure 4. Most EU regions in our model have leakage rates with EU policies between 48 and 65 pct. Since all observations are located well below the 45-degree line, the leakage rate falls notably when the EU policies are removed from the model. We also note that Denmark is placed close to the (simple) average in both dimensions.



**FIGURE 4: Leakage in the EU resulting from a CO<sub>2</sub>e tax of 50 US-dollar: leakage rates with and without EU policies.**

*Note: Computations based on long-run EU ETS leakage rate.*

Figure 4 support some of our main findings. Firstly, it shows that leakage rates in the

EU are substantial: ranging from 31 to 79 pct. Secondly, it shows that the waterbed effect is sizeable. On average, the leakage rate drops by 24 pp. when EU policies are removed from the model. Nevertheless, the waterbed effect varies notably between EU regions.

A detailed explanation of the leakage rate differences is beyond the scope of this analysis, and we leave it for future research. Yet we note that simple explanations such as the share of emissions from ETS-covered sectors seem insufficient.

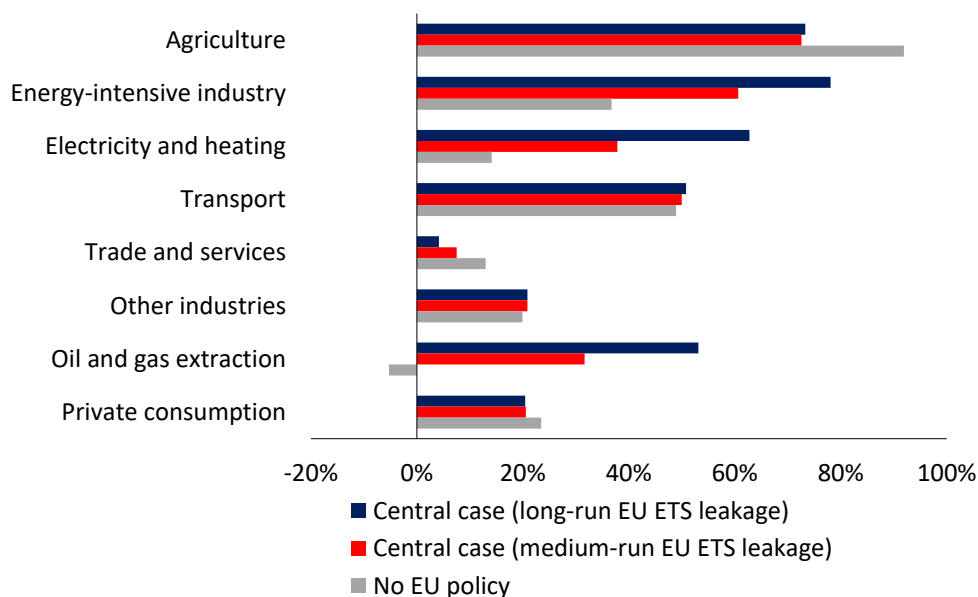
### 7.3 Sector-specific leakage rates

We now return to the Danish case and dive into the leakage-sensitivity of the main sectors of the economy. Figure 5 shows the sector-specific leakage rates. With EU policies in place, the leakage-sensitive sectors include the ETS sectors (energy-intensive industry, electricity and heating, and oil and gas extraction), agriculture, and (land-based) transport. The distinction between medium-run and long-run EU ETS leakage affects leakage rates in the ETS sectors notably, while the leakage is only marginally affected in the non-ETS sectors.

Taking the weighted average of the sector-specific leakage rates, where the weights are given by the initial emission levels, results in an approximated macroeconomic leakage rate of 54 pct. – only two pp. from the actual number. This suggests that the separately computed sector-specific leakage rates are informative about the sector-specific leakage effects under a uniform CO<sub>2</sub>e tax.

The leakage sensitivity of the agricultural sector is largely driven by a low demand elasticity for agricultural products. Domestic policies have a low impact on the global demand for agricultural goods, implying a strong foreign production response. We note that removing EU policies increases leakage in the agricultural sector. This is a consequence of the non-ETS constraints which restrict the non-ETS response by most EU economies.

ETS-covered sectors have high leakage rates due to the leakage mechanism built into the EU ETS. The leakage rates differ from the intra-ETS leakage rates (computed from the EU ETS model) due to general equilibrium effects. A reduction in Danish ETS production leads to an increase in Danish non-ETS production and thereby emission, as



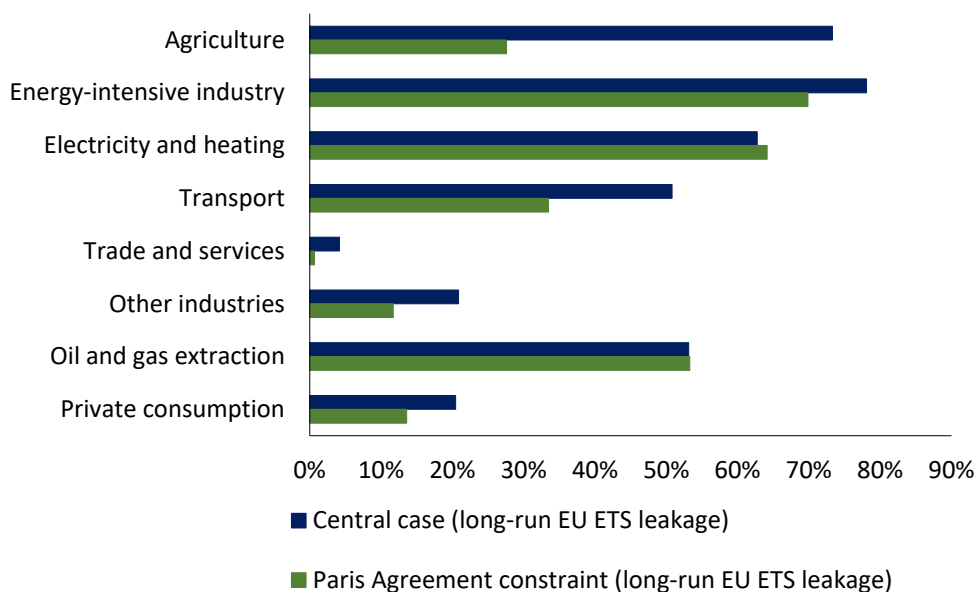
**FIGURE 5: Sector-specific carbon leakage rates.**

*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<sub>2</sub>e tax of 50 US-dollars per tonne of emission. This emission tax is placed on top of the existing regulation.

the primary input factors (e.g. labor) are reallocated within the Danish economy. The opposite occurs in the foreign economy where non-ETS production is reduced, while ETS production increases. This reduces the total leakage effect, explaining why ETS sectors can have leakage rates below the intra-ETS leakage rate. Furthermore, ETS production and emission may leak to economies outside the EU which can push the leakage rate up.

The ETS sector leakage rates drop significantly when EU policies – and the EU ETS in particular – are removed. An interesting case is oil and gas extraction, where leakage becomes negative. The reason is that the oil and gas producers reduce both their emissions and supply of fossil fuels. The reduction in the global supply of fossil fuels results in a reduction in foreign emissions, implying negative leakage.

The low leakage rate for trade and services as well as other industries can be attributed to the relatively low energy intensity of these sectors. Higher emission costs have a much lower impact on the competitiveness of these sectors compared to more energy-intensive sectors. The opposite is true for (land-based) transportation where the emission tax affects competitiveness notably, resulting in a higher leakage rate.



**FIGURE 6: Sector-specific leakage rates with and without the Paris Agreement constraint.**

Leakage from private consumption goes primarily through the fossil fuel market. Lower domestic demand for fossil fuels reduces the global price of fossil fuels, resulting in higher foreign demand.

The sector-specific leakage rates are not sensitive to the tax level. Table 5 in Appendix D shows sector-specific leakage rates for our central case with long-run EU ETS leakage for three tax rates: 25, 50, and 75 US-dollars. The leakage rates vary little with the tax rates, and – in line with the inverted MAC effect explained above – the leakage rates are in most cases increasing in the tax rate.

Figure 6 shows sector-specific leakage rates in our central case and with the Paris Agreement constraints in place. In both cases, we use the long-run EU ETS leakage rate for comparability. As expected, the Paris Agreement constraint limits leakage in almost all sectors. The effect is larger for non-ETS sectors, as the Paris Agreement does not affect leakage through the EU ETS.

The most striking effect of the Paris Agreement constraints is the reduction in leakage in the agricultural sector. The Paris Agreement limits the ability of most developing countries with large agricultural sectors to increase their emissions in response to Danish

policies. Agricultural production and emission actually increase almost everywhere in the world, as a response to a lower Danish agricultural production. But the Paris Agreement then forces most non-EU economies to reduce emissions elsewhere. The effect of the agreement is stronger for agriculture compared to other sectors as the production response for this sector is stronger given the low demand elasticity of agricultural products.

## 8 Concluding remarks

The present study develops a methodology to compute leakage effects for a small open economy within a climate coalition. We focus on the Danish economy, but as we demonstrate, our method can be applied to any EU economy. Our central estimates show that the Danish leakage rate is sizeable: 38-56 pct. Our analysis also reveals that EU climate policies have a pronounced impact on these leakage effects. Both findings seem to carry through more generally within the EU.

Given that some EU members want more ambitious climate policies than warranted by the EU, policymakers should think more carefully about how to reduce the leakage impact of EU climate policies. The latest EU ETS reform is a step in that direction, but the leakage effect through the EU ETS is still substantial for permanent policy changes.

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. If policymakers want to reduce leakage, this finding may motivate more lax climate policies for these leakage-sensitive sectors. Implementing optimal leakage-reducing climate policies requires sector-specific leakage estimates. The methodology developed in this analysis provides a useful tool in this regard.



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## References

- R. Aichele and G. Felbermayr. Kyoto and the carbon footprint of nations. *Journal of Environmental Economics and Management*, 63(3):336–354, 2012.
- R. Aichele and G. Felbermayr. Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *Review of Economics and Statistics*, 97(1):104–115, 2015.
- A. Antimiani, V. Costantini, C. Martini, L. Salvatici, and M. C. Tommasino. Assessing alternative solutions to carbon leakage. *Energy Economics*, 36:299–311, 2013.
- M. H. Babiker. Climate change policy, market structure, and carbon leakage. *Journal of International Economics*, 65(2):421–445, 2005.
- S. Bach. Aalborg Portland: Nye klimaråd kan få store konsekvenser for eksport. TV2 Nord <https://www.tv2nord.dk/aalborg/aalborg-portland-nye-klimaraad-kan-faa-store-konsekvenser-eksport>, 2020. Online 9 March 2020; accessed 17 March 2020.
- T. Barker, S. Junankar, H. Pollitt, and P. Summerton. Carbon Leakage from Unilateral Environmental Tax Reforms in Europe, 1995–2005. *Energy Policy*, 35(12):6281–6292, 2007.
- W. J. Baumol and W. E. Oates. The use of standards and prices for protection of the environment. *The Swedish Journal of Economics*, 73(3):42–54, 1971.
- U. Beck and P. K. Kruse-Andersen. Endogenizing the cap in a cap-and-trade system: Assessing the agreement on eu ets phase 4. *Environmental and Resource Economics*, 77:781–811, 2020.
- U. R. Beck, P. K. Kruse-Andersen, and L. B. Stewart. Dokumentationsnotat CO<sub>2</sub>e-lækage og dansk klimapolitik. *Danish Economic Councils, Background Document*, 2019.
- B. Bednar-Friedl, T. Schinko, and K. W. Steininger. The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment. *Energy Economics*, 34:S168–S180, 2012.
- L. Bohlin. Climate policy within an international emission trading system: a swedish case. *Örebro Studies in Economics* 19, 2010.
- C. Böhringer and A. Lange. On the Design of Optimal Grandfathering Schemes for Emission Allowances. *European Economic Review*, 49(8):2041–2055, 2005.
- C. Böhringer, C. Fischer, and K. E. Rosendahl. The global effects of subglobal climate policies. *The BE Journal of Economic Analysis & Policy*, 10(2), 2010.

- C. Böhringer, E. J. Balistreri, and T. F. Rutherford. The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29). *Energy Economics*, 34:S97–S110, 2012a.
- C. Böhringer, J. C. Carbone, and T. F. Rutherford. Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage. *Energy Economics*, 34:S208–S217, 2012b.
- C. Böhringer, J. C. Carbone, and T. F. Rutherford. Embodied carbon tariffs. *The Scandinavian Journal of Economics*, 120(1):183–210, 2018.
- J.-M. Burniaux and J. O. Martins. Carbon leakages: A general equilibrium view. *Economic Theory*, 49(2):473–495, 2012.
- J. C. Carbone and N. Rivers. The impacts of unilateral climate policy on competitiveness: Evidence from computable general equilibrium models. *Review of Environmental Economics and Policy*, 11(1):24–42, 2017.
- M. Chepeliev. Development of the Non-CO2 GHG Emissions Database for the GTAP 10A Data Base. *GTAP Research Memorandum No. 32*, 2020.
- J. Colmer, R. Martin, M. Muûls, and U. J. Wagner. Does Pricing Carbon Mitigate Climate Change?: Firm-level Evidence from the European Union Emissions Trading Scheme. 2020.
- Copenhagen Economics. Carbon leakage from danish energy taxation, 2011.
- E. L. Corong, T. W. Hertel, R. McDougall, M. E. Tsigas, and D. van der Mensbrugghe. The standard gtap model, version 7. *Journal of Global Economic Analysis*, 2(1):1–119, 2017.
- A. Cosbey, S. Droege, C. Fischer, and C. Munnings. Developing guidance for implementing border carbon adjustments: Lessons, cautions, and research needs from the literature. *Review of Environmental Economics and Policy*, 13(1):3–22, 2019.
- Danish Council on Climate Change. Danmark og EU’s 2030-klimamål: Analyse af Kommissionens forslag til reduktionsmål uden for kvotesektoren. 2016.
- Danish Energy Agency. Basisfremskrivning 2020: Klima- og energifremskrivning frem til 2030 under fravær af nye tiltag. 2020.
- Danish Energy Agency. Klimastatus og -fremskrivning, 2021. 2021.
- A. Dechezleprêtre and M. Sato. The impacts of environmental regulations on competitiveness. *Review of Environmental Economics and Policy*, 11(2):183–206, 2017.

- J. Elliott, I. Foster, S. Kortum, T. Munson, F. Perez Cervantes, and D. Weisbach. Trade and carbon taxes. *American Economic Review*, 100(2):465–69, 2010.
- European Commission. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions. [https://ec.europa.eu/commission/presscorner/detail/en/IP\\_21\\_3541](https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541), 2021. Online 14 July 2021; accessed 23 August 2021.
- C. Fischer and A. K. Fox. Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management*, 64(2):199–216, 2012.
- M. Fowlie and M. Reguant. Mitigating Emissions Leakage in Incomplete Carbon Markets. *Working Paper*, November 2020.
- Frontier Economics. Research on the Effects of a Carbon Price Floor: A Report for Energie-Nederland, 2018.
- R. Gerlagh and O. Kuik. Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis. *Energy Economics*, 45:381–388, 2014.
- M. Greaker, R. Golombek, and M. Hoel. Global impact of national climate policy in the nordic countries. *Nordic Economic Policy Review 2019*, pages 157–206, 2019.
- C. Hagem, M. Hoel, and T. Sterner. Refunding Emission Payments: Output-Based Versus Expenditure-Based Refunding. *Environmental and Resource Economics*, 77(3):641–667, 2020.
- M. Hoel. Global environmental problems: The effects of unilateral actions taken by one country. *Journal of Environmental Economics and Management*, 20:55–70, 1991.
- M. Hoel. Should a carbon tax be differentiated across sectors? *Journal of Public Economics*, 59(1):17–32, 1996.
- M. Hoel. Klimatpolitik och ledarskap-. *Rapport till Expertgruppen för miljöstudier 2012:3*, 2012.
- M. Jakob, R. Marschinski, and M. Hübler. Between a rock and a hard place: a trade-theory analysis of leakage under production-and consumption-based policies. *Environmental and Resource Economics*, 56(1):47–72, 2013.
- P. K. Kruse-Andersen and P. B. Sørensen. Energy taxes and cost-effective unilateral climate policy: Addressing carbon leakage. *CESifo Working Paper No. 7920*, 2019.
- P. K. Kruse-Andersen and P. B. Sørensen. Optimal Unilateral Climate Policy with Carbon Leakage at the Extensive and the Intensive Margin. 2021.

- O. Kuik and M. Hofkes. Border adjustment for European emissions trading: Competitiveness and carbon leakage. *Energy policy*, 38(4):1741–1748, 2010.
- E. Lanzi, J. Chateau, and R. Dellink. Alternative approaches for levelling carbon prices in a world with fragmented carbon markets. *Energy Economics*, 34:S240–S250, 2012.
- F. Misch and P. Wingender. Revisiting Carbon Leakage. *IMF Working Paper (WP/21/207)*, 2021.
- H. Naegele and A. Zaklan. Does the EU ETS cause carbon leakage in European manufacturing? *Journal of Environmental Economics and Management*, 93:125–147, 2019.
- OECD. The economics of climate change mitigation: policies and options for global action beyond 2012. *OECD Publishing*, 2009.
- G. Perino. New eu ets phase 4 rules temporarily puncture waterbed. *Nature Climate Change*, 8(4):262–264, 2018.
- G. Perino, R. A. Ritz, and A. Van Benthem. Overlapping climate policies. *NBER Working Paper no. 25643*, November 2020.
- R. Roson. Carbon leakage in a small open economy with capital mobility. 2001.
- T. Truong. GTAP-E: An energy-environmental version of the GTAP Model with emission trading: User’s Guide. 2007.
- T. P. Truong, C. Kemfert, and J.-M. Burniaux. GTAP-E: An energy-environmental version of the GTAP Model with emission trading. *DIW Discussion Papers*, 2007.
- UN Environment. Pledge Pipeline. Data download from: <https://www.unenvironment.org/explore-topics/climate-change/what-we-do/mitigation/pledge-pipeline>, 2018. Retrieved on 27 September 2018.
- F. Venmans, J. Ellis, and D. Nachtigall. Carbon pricing and competitiveness: are they at odds? *Climate Policy*, 20(9):1070–1091, 2020.

# 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 international climate policies**

<b>Region</b>	<b>Note</b>	<b>EU ETS member</b>	<b>Binding non-ETS constraint</b>	<b>Paris Agreement constraint</b>
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 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		No	No	Yes
23 ROEU	Rest of EU-27	Yes	No	No
24 Norway		Yes	No	Yes
25 Russia		No	No	No
26 Switzerland		No	No	Yes
27 Middle East and North Africa		No	No	Yes
28 Sub-Saharan Africa		No	No	Yes
29 RoEuropa	Rest of non-EU Europe	No	No	No
30 RoW	Small GTAP-regions (xtw)	No	No	Yes



## B Modelling EU ETS leakage

Our estimate of the intra-ETS sector leakage rate is based on the model from Beck and Kruse-Andersen (2020). The model consists of three parts: (1) a representative firm demanding emissions allowances, (2) an administrative system for emission allowances, and (3) an exogenous technological development reflecting that renewable energy competitors become relatively more competitive as renewable technologies mature. The representative firm represents all allowance demanding firms, and the administrative system ensures that all EU ETS rules are followed. The model is calibrated based on the pre-ETS emission trend as well as the market situation (price and emission level) in 2017. See Beck and Kruse-Andersen (2020) for details.

We impose a permanent reduction to allowance demand of 1.2 m. allowances from 2020, corresponding to around 10 pct. of the verified Danish ETS emissions in 2019 (based on the EU ETS data viewer). Nonetheless, it should be emphasized that the estimated leakage rate is not sensitive to the exact size of the shock.

The intra-ETS leakage rate at time  $T$ , denoted  $L_T^{ETS}$ , is computed as:

$$L_T^{ETS} = - \frac{\sum_{t=t'}^T \Delta e_t^{EU,ETS} - \Delta e_t^{DK,ETS}}{\sum_{t=t'}^T \Delta e_t^{DK,ETS}},$$

where  $t'$  is the first period in the model,  $\Delta e_t^{EU,ETS}$  is the absolute change in ETS emissions on the EU level in period  $t$ , and  $\Delta e_t^{DK,ETS}$  is the absolute change in Danish ETS emissions in period  $t$ .

The medium-run and long-run intra-ETS leakage rates are computed from the same shock. The only difference is the evaluation date  $T$  which is either 2030 or 2050.

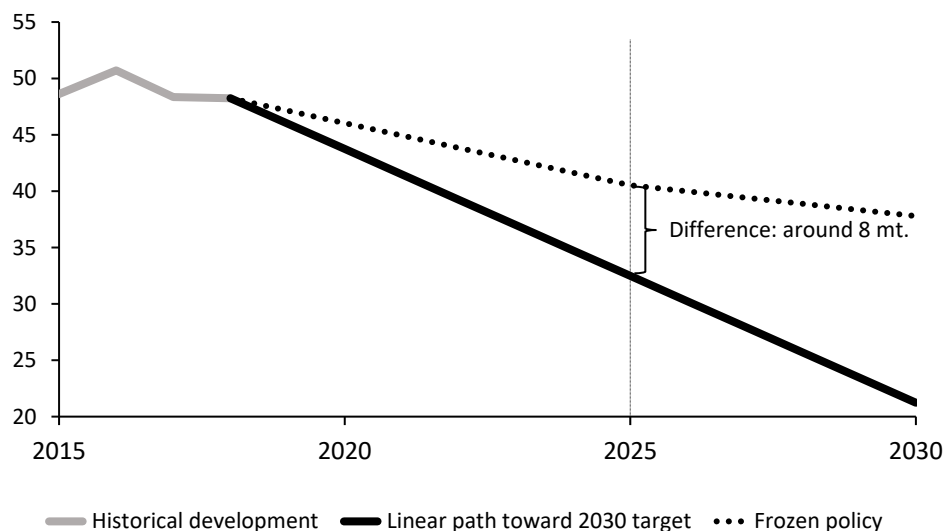
## C Danish emissions in 2025

This appendix explains why our starting point is a CO<sub>2</sub>e tax of 50 US-dollars. The Danish Climate Act of 2020 mandates that Danish carbon emissions must be reduced by 70 pct. in 2030 compared to 1990.

Figure 7 shows historical Danish emissions, a frozen policy projection of the emissions, and a linear emission path towards the 2030 target (all excluding LULUCF emissions). The frozen policy projection is far from the linear path, implying that Danish policymakers need to tighten the Danish climate policy to achieve the 2030 target.

Furthermore, assuming that Danish policymakers want to follow a roughly linear path towards the 2030 emission target, they need to cut projected emissions by around 8 mt. of CO<sub>2</sub>e in 2025. We achieve this emission reduction by imposing a 50 US-dollar CO<sub>2</sub>e tax in our model.

In April 2021, the Danish Energy Agency published a new emission projection which



**FIGURE 7: Danish emissions and the Danish 2030 emission target.**

*Source:* Danish Energy Agency (2020) and own calculations.

implies a smaller emission gap (Danish Energy Agency 2021). This is partly due to new political agreements. The policy considered in our study can be interpreted as an alternative that takes the economy all the way to the linear emission path.

## D Additional results

**TABLE 5: Sector-specific leakage rates and varying tax rates: central case with long-run EU ETS leakage**

Main Sector	Tax rate (US-dollars)		
	25	50	75
Agriculture	70.9	73.3	74.8
Energy-intensive industry	77.6	78.1	79.2
Electricity and heating	62.9	62.8	63.0
Transport	49.7	50.8	51.6
Trade and services	3.2	4.2	6.7
Other industries	17.7	20.9	21.4
Oil and gas extraction	54.9	53.1	51.8
Private consumption	20.1	20.5	20.1