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Carbon leakage in GreenREFORM

Global climate effects and leakage-adjusted regulation in a national economic model

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Documentation
25 May 2021

www.dreamgruppen.dk

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Preliminary draft - please do not cite
May 25, 2021

Abstract

Carbon leakage is at the front of the agenda for many policy makers. This poses a problem for national economic models, as they typically do not model foreign economies in detail, and as a result, cannot provide a reasonable estimate of any carbon leakage that arises as a consequence of national regulation. The purpose of this memo is threefold. First, we demonstrate the principles behind optimal regulation when policy makers have a domestic emission target and an aversion towards carbon leakage. We show how policy makers need to know how emissions abroad change when domestic net imports of different goods change. We call these key parameters leakage coefficients. Second, we develop an approach to estimating leakage coefficients. Third, we show that the approach we develop has broader applications: In fact, it can be used to estimate carbon leakage as a result of *any* policy that can be implemented in a national economic model. We demonstrate the approach using the large-scale national CGE-model of Denmark, GreenREFORM, in combination with simulations on the global GTAP-E model. We pay special attention to the issue of carbon leakage through the EU ETS system. A series of tests indicate that the method is well-suited to capture the leakage effects present in the global GTAP-E model. We do stress, however, that leakage effects are highly uncertain.

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[*] We thank Niels Christian Fredslund from the Secretariat of the Danish Economic Councils for many fruitful discussions on carbon leakage and simulation setups. We also thank The Danish Economic Councils for access to their modified GTAP-E model code. Any remaining errors are our own.

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Contents

1 Introduction

Policies to reduce greenhouse gas (GHG) emissions are often national or regional in scope. An example of a national policy is Denmark's goal to reduce emissions to 30% of 1990-emissions in 2030. Two examples of regional policies are EU's European Trading System (ETS), and binding reduction targets for member states in sectors not covered by the ETS. However, the effects of carbon emissions on climate change are global. This means that the impact of national policies on carbon emissions does not stop at the national border, and that the global effect of national policies is of interest. This poses a challenge for policy makers, since economic models used for these exercises are typically national in scope . As climate mitigation policies take center stage in the global effort to contain global warming, this issue becomes increasingly salient.

Global climate effects of national policies are also called carbon leakage. Carbon leakage can occur through several different channels, including :

1. **Relocation of economic activity:** As a response to domestic climate regulation, domestic producers may loose competetiveness compared to foreign competitor who face less strict regulation. This means that domestic producers may reduce production, and foreign producers may increase production. This combination induces leakage, as the domestic production reduction leads to a decrease in domestic emissions which is at least partially offset by increases in emissions abroad due to increased production.
2. **Changes in fossil fuel prices:** As a response to tighter climate regulation, fossil fuel demand falls. This puts a downward pressure on global fossil fuel prices, which leads to increased use. Thus, the global change in emissions may be smaller than the observed domestic reduction.
3. **Through carbon allowance markets:** When emissions are covered by a carbon allowance market where allowances can be traded and banked, and when the total amount of allowances are fixed, a reduction in emissions will not result in a reduction of total allowances available. This means that there may be zero effect on emissions in the long run, i.e., a carbon leakage of 100%.
4. **Political effects:** Tighter domestic regulation may induce policy makers in other countries to also tighten regulations. Such political effects abroad are e.g. used as motivation for setting an ambitious emission reduction goal in Denmark.

5. **Endogenous technological change:** Domestic regulation may induce additional domestic research and development into new technologies that can reduce emissions at a cheaper cost than what is currently available. To the extent that the new technologies can also be used abroad, it may reduce emissions abroad. This channel can therefore work to reduce leakage of domestic policies.

Carbon leakage effects are typically reported as a *leakage rate,* β, which measures the offsetting increase in foreign emissions (ΔGHG^{ROW}) as a share of the decrease in national emissions (ΔGHG^{Nat}) :

$$\beta = -\frac{\Delta GHG^{ROW}}{\Delta GHG^{Nat}} \tag{1}$$

In this memo, we outline a method to simulate global effects of national policies through channel 1-3 using a standard economic model with a national, rather than global, scope. The method is based on combining results from the national model with a set of simulations on a global economic model. The method is tractable, since the global model simulations need to be run only once. This means that - after the global model simulations have been carried out - the method works as a standard extension of the national model with no need to link to other models. There are three main contributions of this memo.

1. We provide a theoretical foundation for the information needed to implement optimal regulation when policy makers have a domestic emission target and an aversion towards carbon leakage. We name this the optimal leakage-adjusted reglation. A key input for this regulation turns out to be the emissions effects abroad associated with an increase in domestic net imports of different goods. We call these effects leakage coefficients.
2. We introduce and test a tractable method to estimating sector-specific leakage coefficients.
3. We argue that the method introduced is suitable to model the leakage effects of *any* climate regulation - not just the optimal leakage-adjusted regulation - using a national model.

This memo is organized as follows: In section 2, we introduce a theoretical framework which shows how the optimal leakage-adjusted policy can be estimated using information about changes in domestic imports and exports. The key take-away from this model is that in order to conduct optimal leakage-adjusted policy, information about sector-specific leakage coefficients is required. Section 2 is not required to understand what follows, and this section can be skipped by readers who are more interested in the practical application than theoretical considerations. We continue in section 3 by showing how the global trade model GTAP-E (Burniaux and Truong, 2002) can be used to estimate these leakage coefficients. We argue that the leakage coefficients have a broader application and can be used to estimate leakage effects of *any* national policy. In section 4, we show a practical application of our method, using the Danish large-scale environmental-economic national CGE model, GreenREFORM, in conjunction with leakage coefficients estimated on GTAP-E.[1] Section 5 concludes.

We illustrate the method in the Danish context, but we believe that the overall method - with suitable adjustments - is applicable to any country where a national economic model is available. That being said, we believe that the final results, namely leakage effects of national policies, are highly uncertain. Any model simulation comes with an unknown degree of model uncertainty; we believe this uncertainty is more likely to be squared than doubled when two models are linked. On top of this comes additional known imprecisions related to the practical application related to the GTAP-E database and model as well as simplifying assumptions on leakage through the ETS system. We believe that the method is still useful to give an idea about the magnitude of leakage effects, even though the point estimates should not be taken for granted.

2 Theoretical framework

This section introduces a simple model that illustrates two points. Firstly, it demonstrates the principles behind optimal regulation, when policy makers have a domestic emission target and an aversion towards carbon leakage. We show that the optimal allocation can be implemented using differentiated carbon and consumption taxes. This regulation differentiation increases with the degree of leakage aversion. Thus, it is possible to implement the optimal regulation without border carbon adjustments. This is an important point in our context, as an EU economy cannot introduce import tariffs or export subsidies within EU's single market.

Secondly, the model shows that in order to implement optimal regulation, policy makers need knowledge on the carbon leakage associated with international trade of all goods

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[1] The augmented version of GTAP-E is described in more detail in DØRS (2021a). The practical application of the "linked" version of the method was originally developed and used to estimate leakage effects in DØRS (2021b), and is included here as a way to check the validity of the "decoupled apprach".

including fossil fuels. Estimating this leakage is our main goal in the empirical section. We assume that the good-specific carbon leakage per unit of net imports is constant. This assumption is, however, not crucial for our deviation of optimal regulation. Yet, it simplifies our analytical expressions, and we show in our empirical section that the assumption is reasonable in a Danish context.

2.1 Structure

Consider a small open economy. There are N regular consumption goods in the economy indexed $i = 1, 2, ...N$. Consumers derive utility from the consumption of these N consumption goods as well as fossil fuels. In the following description of the economy, units are chosen such that one unit of fossil fuel consumption leads to one unit of (carbon) emissions.

We assume constant international prices, as the domestic economy is small and therefore has little impact on international prices. Our assumption eliminates terms-of-trade effects. One may argue that the terms-of-trade effects should be present even if they are small. On the other hand, it would not be legal - and probably not desirable either - for a small EU country to exploit such terms-of-trade effects: illegal due to the single market rules, and undesirable, as it may provoke costly retaliation. We therefore abstract from price effects here.

A representative consumer solves the problem:

$$\max_{\{c_i\}_{i=1}^N, E} \; u(c_1, ..., c_N, E) \quad \text{st.} \quad I = \sum_{i=1}^{N} c_i(p_i + t_i) + E(p_e + t_E), \tag{2}$$

where $u(\cdot)$ is a utility function that is strictly increasing and concave in all arguments, I is income, c_i measures consumption of good i, E measures the consumption of fossil fuels, p_i is the international exogenous price of consumption good i, and p_e is the international exogenous price of fossil fuels. Finally, t_i is a domestic consumption tax on good i, and t_E is a carbon tax imposed on households.

Domestic firms produce consumption goods using only fossil fuels as input. There is one firm producing each of the N consumption goods. The firms solve the problem:

$$\max_{e_i} \; f_i(e_i)p_i - e_i(p_e + \tau_i), \quad f_i'(e_i) > 0, \quad f_i''(e_i) < 0, \tag{3}$$

where $f_i(e_i)$ is the production of good i, e_i is the fossil fuel input, and τ_i is a sector-specific carbon tax.

For simplicity, there is no domestic production of fossil fuels, and thus, all fossil fuels are imported. Trade must balance, implying that the value of net imports equals zero:

$$\sum_{i=1}^{N} p_i m_i + p_e \left(\sum_{i=1}^{N} e_i + E \right) = 0, \quad m_i = c_i - f_i(e_i), \tag{4}$$

where m_i is net imports of good i.

The government keeps a balanced budget. The entire tax revenue is transferred to the representative consumer through a lump-sum transfer, T:

$$T = \sum_{i=1}^{N} \tau_i e_i + t_E E + \sum_{i=1}^{N} t_i c_i. \tag{5}$$

The income of the representative consumer is:

$$I = T + \sum_{i=1}^{N} \pi_i, \tag{6}$$

where profits from the production of good i, denoted π_i, is given by:

$$\pi_i = f_i(e_i) p_i - e_i (p_e + \tau_i). \tag{7}$$

The government has a (binding) domestic emission target. In particular, the government wants to reduce the economy's domestic emission level to $\bar{E}$, implying that:

$$\bar{E} = \sum_{i=1}^{N} e_i + E. \tag{8}$$

Finally, there are two types of carbon leakage: (1) carbon leakage from changes in trade patterns for regular consumption goods, and (2) carbon leakage through the fossil fuel market. The first channel reflects that an increase in net imports of good i implies that production and thereby emissions increases in the foreign economy to meet the increased demand. The fossil fuel channel reflects that an increased domestic demand for fossil fuels puts an upwards pressure on the international price, reducing the foreign demand. Although the price change is likely to be very small - and therefore not taken into account when we consider the domestic economy - it affects a very large market. The emission effect might therefore be important.

The amount of carbon leaking to the foreign economy when net imports of good i increases is given by:

$$\mathscr{L}_i = (m_i - m_{0,i})\, L_i, \quad L_i > 0, \tag{9}$$

where $m_{0,i}$ is the net imports of good i without regulation, and L_i is a constant leakage coefficient associated with imports. Specifically, L_i is the increase in foreign emissions caused by a unit increase in net imports of good i.

The amount of carbon leaking to the foreign economy when the domestic fossil fuel consumption decreases is:

$$\mathscr{L}_F = \left[\left(\sum_{i=1}^{N} e_{0,i} + E_0 \right) - \left(\sum_{i=1}^{N} e_i + E \right) \right] L_F, \quad L_F > 0, \tag{10}$$

where $e_{0,i}$ is fossil fuel consumption associated with domestic production of good i in absence of regulation, and E_0 is the representative consumer's fossil fuel consumption in the absence of regulation. The constant, L_F, measures the increase in foreign fossil fuel consumption caused by a unit decrease in domestic emissions due to carbon leakage through the fossil fuel market.

Estimating all the L_i and L_F parameters is our main focus in the empirical section. As noted above, our empirical results substantiates the restricted leakage functions applied here.

2.2 The market solution

The representative consumer maximizes utility subject to the budget constraint. The first-order conditions associated with this problem implies that:

$$\frac{u_i'(\cdot)}{u_E'(\cdot)} = \frac{p_i + t_i}{p_e + t_E} \quad \text{and} \quad \frac{u_i'(\cdot)}{u_j'(\cdot)} = \frac{p_i + t_i}{p_j + t_j}. \tag{11}$$

These expressions state the standard microeconomic results that the marginal rate of substitution between any two goods should equal their relative prices.

Each firm maximizes profits with respect to the emission level. The associated first-order condition implies that:

$$f_i'(e_i^*)p_i = (p_e + \tau_i) \tag{12}$$

where e_i^* is the optimal fossil fuel input of firm i. The expression states that the marginal profit associated with the fossil fuel input must equal the marginal cost of the fossil fuel input.

2.3 Optimal allocation

The government has the objective function:

$$V(c_1, ..., c_N, E, e_1, ..., e_N) = u(c_1, ..., c_N, E) - \kappa \left(\sum_{i=1}^{N} \mathscr{L}_i + \mathscr{L}_F \right), \quad \kappa \geq 0. \tag{13}$$

The government cares about the utility of the representative consumer. But the government also has a cost associated with carbon leakage. In particular, the unit cost of carbon leakage is κ.

A social planner maximizes the government's objective function with respect to $c_1, ..., c_N$, E, $e_1, ..., e_N$ subject to the balanced trade constraint and the domestic emission target. The Lagrangian associated with this problem is:

$$\begin{aligned} \mathbb{L} = {} & u(c_1, ..., c_N, E) - \kappa \left(\sum_{i=1}^{N} \mathscr{L}_i + \mathscr{L}_F \right) \\ & - \lambda \left(\sum_{i=1}^{N} p_i \left(c_i - f_i(e_i) \right) + p_e \left(\sum_{i=1}^{N} e_i + E \right) \right) + \eta \left(\bar{E} - \sum_{i=1}^{N} e_i - E \right), \end{aligned} \tag{14}$$

where λ is the shadow cost associated with the trade constraint, and η is the shadow price of domestic emissions.

The first-order conditions imply that:

$$u_i'(\cdot) = \kappa L_i + \lambda p_i \tag{i}$$

$$u_E'(\cdot) + \kappa L_F = \lambda p_e + \eta \tag{ii}$$

$$\kappa f_i'(e_i) L_i + f_i'(e_i) p_i \lambda + \kappa L_F = \lambda p_e + \eta. \tag{iii}$$

Equation (i)-(iii) together with the two constraints characterizes the social planner's allocation.

Equation (i) implies that in optimum the marginal utility gain from consuming good i must equal the marginal cost of doing so. The marginal cost of good i consumption is the associated balanced trade cost plus the cost of the associated carbon leakage.

The balanced trade cost can be explain the following way. Consuming one additional unit of the good i requires one additional unit of import or to forgo one unit of export. This has a cost since trade needs to balance.

The leakage cost comes from the fact that consuming one additional unit of good i increases net imports by one unit, resulting in L_i unit of carbon leakage. The unit price of leakage is κ, implying that the total leakage cost is κL_i.

According to equation (ii), the marginal benefit of increasing household fossil fuel consumption is the marginal utility gain plus the benefit from reduced leakage through the fossil fuel market. The marginal cost equals the marginal trade constraint cost plus the shadow price of domestic emissions.

Finally, equation (iii) states that the marginal gain from increasing the fossil fuel input for firm i must equal the marginal cost of doing so. The marginal benefit consists of three terms: (1) the marginal gain from reduced leakage through the trade channel, $\kappa f_i'(e_i)L_i$, (2) the marginal benefit of a more lax trade constraint due to higher exports or lower imports of good i, $f_i'(e_i)p_i\lambda$, and (3) the marginal benefit from reduced leakage through the international fossil fuel market channel. The marginal cost of increasing the fossil fuel input of firm i consists of two terms: (1) the cost of a more tight trade constraint due to a higher import of fossil fuels, λp_e, and (2) the cost of domestic emissions, η.

2.4 Optimal regulation

The optimal climate policy given the objective function of the government can be implemented by imposing differentiated consumption and carbon taxes. The following proposition states the optimal tax system.

Proposition 1. *The optimal allocation given objective function (13) can be implemented in the market economy by imposing the following tax system:*

$$\textit{Sector-specific carbon taxes:} \qquad \tau_i = \frac{\eta p_i - \kappa\left(L_F p_i + p_e L_i\right)}{\kappa L_i + \lambda p_i} \qquad \forall i$$

$$\textit{Household carbon tax:} t_E = (\lambda - 1)p_e + \eta - \kappa L_F$$

$$\textit{Consumption taxes:} t_i = \kappa L_i + (\lambda - 1)p_i \quad \forall i.$$

The optimal tax system imposes differentiated carbon taxes across all sectors, where more leakage-exposed industries (higher L_i) are, all other things equal, subject to a lower carbon tax . Meanwhile, goods produced by less leakage-exposed industries are, all other things equal, taxed more heavily.

It is worth noting that implementing the optimal tax system requires knowledge on sector-specific leakage coefficients, L_i, and leakage through the fossil fuel market.

3 Sector-specific leakage coefficients

The key challenge to implementing the optimal leakage-adjusted policy of the previous section is to estimate sector-specific leakage coefficients, L_i. To recap, L_i is the increase in foreign emissions caused by a unit increase in net imports of good i. Estimating leakage coefficients is outside the scope of national economic models, as they do not include a detailed model of foreign emissions. There is also an additional complication: leakage effects are general equilibrium outcomes. This means that the total leakage may not be equal to the sum of changes in net imports times the sector-specific leakage coefficients. Instead, the leakage coefficient of sector i may depend on, e.g., changes in imports and exports of sector j. Sector-specific leakage coefficients may also vary with the size of the change. In this section, we show how the global trade model GTAP-E can be used to:

1. Estimate sector-specific leakage coefficients, L_i
2. Investigate the validity of constant sector-specific leakage coefficients. In other words, we try to answer if it is reasonable to assume that leakage coefficients are constant.

The method that we develop has broad use applications. In fact, we show that the method can be used to estimate leakage effects of *any* national policy where the effects on exports and imports are known.

This section proceeds as follows. First, we describe the method used to estimate sector-specific leakage coefficients using the GTAP-E model (section 3.1). We then describe how this method - with a few modifications - can be used to estimate carbon leakage associated with *any* policy that can be modelled in a national economic model (section 3.2). In the final subsection, we show that general equilibrium effects are not driving leakage effects. (section 3.3) This lends credence to the assumption in the theoretical model of constant leakage coefficients. It also justifies using constant sector-specific leakage coefficients to simulate carbon leakage on any type of national policy.

3.1 Estimates of sector-specific leakage coefficients

We use a modified version of the global trade model GTAP-E to estimate sector-specific leakage coefficients. This modified version of GTAP-E was developed by The Danish Economic Councils to conduct analyses of carbon leakage in Denmark (DØRS, 2019; Beck et al., 2019; DØRS, 2021b,a). GTAP-E is a global trade model with a special focus on the modelling of energy use (See Burniaux and Truong, 2002, for a detailed description of the model). The key building block of GTAP-E are models of economies in different countries or regions. In each economy, different sectors produce outputs using inputs from other sectors as well as factors of production: capital, labor, land and natural resources. A representative consumer consumes a basket of goods. A government consumes a basket of goods and sets distortionary taxes and transfers. Special attention is paid to production and consumption of fossil fuels, and GHG emissions from fossil fuel use are modelled as proportional to the use of fossil fuels. The primary channel for interaction between economies is through international trade: all imports can be traced to an export from some other economy. Further, economies interact through a market for international transport of goods as well as through a global capital market. The modifications to the standard GTAP-E model include the following:

- Modelling of non-CO_2 greenhouse gases.
- Modeling of leakage through the ETS system.
- Binding restrictions on emissions in the EU in sectors not covered by the ETS.

A more detailed description of the modifications can be found in Beck et al. (2019) and DØRS (2021a). We use the same sectoral and regional aggregation of GTAP-E as (DØRS, 2021b). These aggregations can also be found in the appendix to this memo.

We consider a vector of changes in Danish imports, M, and exports, X, from different sectors in the economy, $i = \{1, ..I\}$, $\Delta q^{DK} = \{\Delta q^{DK}_{M,1}, \dots, \Delta q^{DK}_{M,I}, \Delta q^{DK}_{x,1}, \dots, \Delta q^{DK}_{x,I}\}$.[2] We exogenize exports from Denmark and imports to Denmark in GTAP-E. [3] This means that it is possible to estimate the effect on emissions outside Denmark when Danish

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[2] The theoretical model focused on leakage coefficients of net imports, but in practice, leakage coefficients for imports and imports need not be identical (with reversed signs), for instance, there is 1) less than perfect substitution between use of imports and domestically produced inputs; or 2) distortionary tariffs on either imports or exports. We therefore consider the leakage coefficients of changes in imports and exports seperately in this section.

[3] This is the same methodology used by DØRS (2021b) for estimating leakage. Danish imports and exports are exogonized through by imposing endogenous import and export tariffs. Additional changes are made to ensure that there are no no spillovers from changes in Denmark to the rest of the world through the market for international trade as well as through the international savings market.

imports and exports change, keeping everything else equal. This is done by shocking either exports from Denmark or imports to Denmark from a specific sector and see how emissions outside Denmark react. This distorts the Danish economy in GTAP-E substantially, but since we are only interested in the effects outside Denmark, this does not pose a problem for our purposes.

An increase in Danish imports of some good can be interpreted – everything else being equal – as an increase in the global demand that good. This demand increase will be met by an increase in foreign production. However, the increase in foreign production is likely to be smaller than the increased demand for Danish imports, since the demand increase puts upwards pressure on global prices, which will induce producers and consumers abroad to substitute away from the use of this product in foreign production and in foreign consumption. Conversely, an increase in Danish exports can be interpreted as an increase in global supply. However, the effect on total consumption abroad is likely to be smaller than the increase in Danish exports. This is because the increase in supply will put downwards pressure on global prices, which will decrease foreign production. On the demand side, foreign consumers and producers will substitute towards imports from Denmark and away from domesticcally produced products as well as imports from other countries.

A concrete example may clarify further: Suppose Denmark decides to increase taxes on fossil fuel use in the Danish industry. This will lead to higher prices for Danish manufacturers, who become less competetive compared to foreign competiters. As a consequence, Danish firms and consumers will reduce the use of Danish industry goods and exports will be reduced. In total, Danish industry production will be reduced, and Danish fossil fuel emissions will also fall. The reduction in domestic use will to some extent be met by an increased reliance on imports. The increase in Danish net imports can only be met by an increase in industry production abroad. This increase will lead to increased emissions abroad. How much does foreign production increase? This depends on the extent to which the increase in Danish demand is offset by a decrease in foreign demand through increased prices.

We also note that the effects on net imports are likely to differ depending on the instrument used to reduce Danish emissions. Consider, for instance, an alternative policy which subsidizes use of renewable energy in Danish industry such that the effects on Danish GHG emissions is equal to the tax increase policy. A subsidy to renewable energy use will likely lead to a lower reduction in the competetiveness of Danish industry. Therefore, there will be a smaller effect (or even a negative efect) on Danish net imports. As a consequence, the increase in foreign industry production, and therefore in foreign emissions, is smaller than under the tax policy. As a consquence, the leakage rate of the subsidy policy is smaller than the leakage rate of the tax policy.

A national model can estimate the effects of the tax on fossil fuel use on Danish industries as well as changes in imports and exports. However, a global model is required to inform about how global production and emissions respond to such changes. Using GTAP-E, changes in emissions outside Denmark, ΔGHG^{ROW}_{GTAP}, can be estimated as a function of changes to Danish imports and exports:

$$\Delta GHG^{ROW}_{GTAP} = \Delta GHG^{ROW}_{GTAP}(\Delta q^{DK}) \tag{15}$$

To estimate sector-specific leakage coefficients, we define the vector $\Delta q0^{DK}_{j,i}$. This is a vector of zeros except for the cell (j,i), where $j = \{m, x\}$ is the set of imports and exports and i is the sector. To be precise, define $\Delta q0^{DK}_{j,i}$ as:

$$\Delta q0^{DK}_{j,i} = (0, \ldots, 0, \Delta q^{DK}_{j,i}, 0, \ldots, 0) \tag{16}$$

The idea is to calculate sector-specific leakage coefficients as the change in foreign emissions as calculated by GTAP, per change in imports or exports:

$$L_{j,i} = \Delta GHG^{ROW}_{GTAP}(\Delta q0^{DK}_{j,i}) / \Delta q0^{DK}_{j,i} \tag{17}$$

This gives a constant leakage coefficients per unit of imports or exports. But there can be several reasons why leakage coefficients can not in general be assumed to be constant. We return to this issue in the next session. One salient issue is that leakage coefficients cannot be assumed to be constant over time. As a consequence, we follow DØRS (2021b) and make a projection of the GTAP-E database emissions and GDP to 2030. The projection is calibrated to external projections, cf. DØRS (2021a) for more details. This gives us a set of leakage coefficients for the base year of the GTAP-E model (2014) as well as a set of leakage coefficients for 2030.

We estimate leakage coefficients using (17) and using increases in sector-specific imports and exports of 1 billion Euros in 2014-prices as $\Delta q0^{DK}_{j,i}$'s. The resulting sector-specific leakage coefficients for imports and exports are illustrated in figure 1. There is substantial variation in both sign and size of the calculated leakage coefficients. Both make intuitive sense. For instance, we would expect additional exports of oil products to induce increased emissions abroad, because increased exports are driven by increased demand abroad for oil products as a result of a lower domestic export price. On the other hand, increased exports of electricity will displace foreign fossil fuel consumption, leading to a decrease in foreign emissions. This is reflected by a negative leakage coefficient for export of electricity. Agricultural products, most notably cattle, work in the same way as electricity, since, like electricty, there are substantial emissions embedded in cattle production.

The magnitudes of the estimated leakage coefficients can be qualified using back-of-the-envelope-style calculations: For example, we find that an additional export of DKK 1 million worth of oil products in 2014 result in an increase in foreign emissions of 176 tons CO_2e. If we assume that the increase in exports give rise to a 1:1 increase in foreign consumption, we can now calculate the implicit price of a liter of gasoline by using an emissions factor of 2.3 kg/l (a standard emissions factor for gasoline). When we do this, we get a price per liter of DKK 13.10.[4] This is a relatively high price, since the Danish gasoline price is in fact around 6 DKK/l, when consumption taxes are excluded.

However, it is likely that exports do not give rise to a 1:1 increase in foreign consumption, since there are offsetting effects on foreign production through downwards price pressure and a decrease in foreign demand, as described earlier. In fact, an increase in Danish exports of oil products is likely to lead to a smaller than 1:1 increase in foreign consumption of oil products. If, for instance, the *net* increase in fossil fuel energy use abroad is around 50% of the increase in oil products exports from Denmark, the implicit price is instead 6.65 DKK/l, which is much closer to the actual price.

We note that coal exports and imports seems to have very low leakage coefficients. This is at least partly caused by the choice of a high degree of substitution between domestic and foreign sources in the GTAP-E model (Armington import elasticity for coal is 2.8, cf. Burniaux and Truong (2002)). For most sectors, leakage coefficients for 2030 tend to be attenuated towards zero, compared to 2014 leakage coefficients. This reflects the reduction in emissions in production in the 2030 projection. There is a high degree of (negative) correlation between import and export leakage coefficients (correlation coefficient = -0.94). Since foreign emissions are driven by total foreign consumption, which is own production plus net imports, this is as expected. They need not be identical, however, if there is less than perfect substitution between use of imports and domestically produced inputs or if there are distortionary tariffs placed on either imports or exports.

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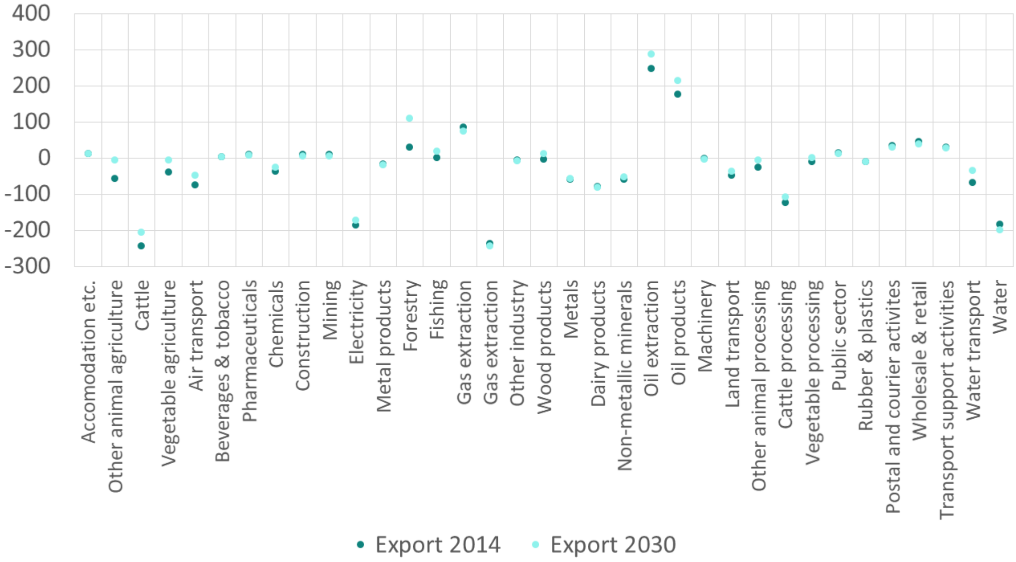
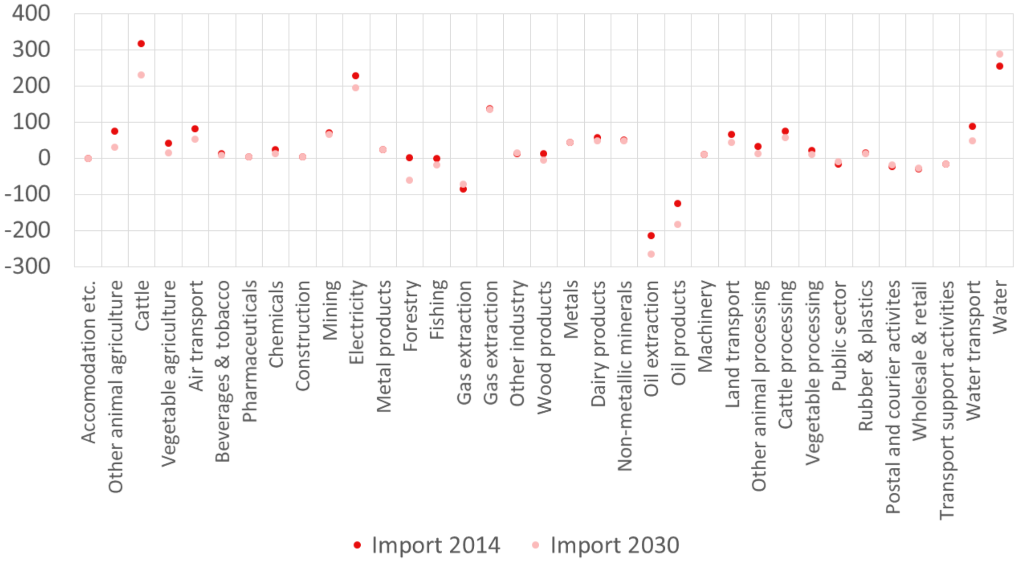
[4] $\frac{2.3\ kg/l}{0.176\ kg/DKK} = 13.10\ DKK/l$

Figure 1: Sector-specific leakage coefficients, tons CO_2e per million DKK



(a) Exports



(b) Imports

3.2 Estimation of carbon leakage for any policy: a decoupled approach

Using the sector-specific leakage coefficients, leakage of any policy can be estimated, as long as changes in domestic imports and exports, $\Delta q0_{j,i}^{DK}$, are known. These changes can be estimated using a national economic model. Consequently, leakage can be estimated as the sum of sector-specific leakage coefficients. In practice, we calculate:

$$\Delta GHG_{DC}^{ROW}(\Delta q^{DK}) = \sum_{j,i} \left[L_{j,i} * \Delta q0_{j,i}^{DK}\right] \tag{18}$$

A benefit of this approach is that, once leakage coefficients are estimated, there is no need to make additional simulations using GTAP-E. For this reason, we call this the *decoupled apprach*. The decoupled approach can be a reasonable approximation to the true leakage effects if general equilibrium effects that arise when changes in several types of imports and exports occur simoultanously are sufficiently small. This corresponds to the assumption of constant sector-specific leakage coefficients in the theoretical model of section 2. We test this assumptuion using the GTAP-E model in section 3.3.

If the national model on which $\Delta q0_{j,i}^{DK}$ are simulated also simulates changes in national emissions, ΔGHG^{DK}, the decoupled approach can be used to estimate the leakage rate (5) as a consequence of a national policy:

$$\beta^{DC} = -\frac{\Delta GHG_{DC}^{ROW}(\Delta q^{DK})}{\Delta GHG^{DK}} \tag{19}$$

3.2.1 Leakage through the ETS

The method of (18) takes account of two of the main channels of carbon leakage, namely relocation of economic activity and changes in fossil fuel prices as a response to national policies. However, it does not take account of carbon leakage through the ETS. This leakage channel can be substantial: In a standard allowance system with intertemporal banking, and a fixed supply of allowances, we would expect long-run leakage to be 100% within the covered sectors. The reason is this: When emissions reductions lead to a reduced use of allowances, these allowances will simply be used somewhere else, by someone else, perhaps at a later point in time. Since allowances can be banked, short-run allowance market leakage can be below 100%.

The ETS system, however, is not a standard allowance system. The ETS reform of 2018 introduced changes to how the so-called Market Stability Reserve works, which means that even long-run leakage can be below 100% (Beck and Kruse-Andersen, 2020; Perino and Willner, 2016). Every year, new ETS allowances are issued. When the stock of unused allowances reach some critical level, a share of newly issued allowances will not be issued but instead put into the Market Stability Reserve (MR). In some cases, these allowances will re-enter the market at a later time when the stock of unused allowances is lower. There is, however, a limit to how many allowances that can be placed in the MSR. If the MSR is above this critical limit, additional allowances placed in the MSR will be cancelled and never re-enter the market. This implies that the total amount of marketed allowances is in some cases (i.e., when the MSR is at its limit) endogenous to the allowance stock, and therefore to allowance demand. This, in turn implies, that to the extent that a reduction in demand for ETS allowances leads to allowance cancellations, the long-run leakage of the ETS system can be below 100%.

When the direct ETS leakage rate described above is below 100%, this implies that a reduction in emissions in sectors covered by the ETS in one country leads to a reduction in total emissions from sectors covered by the ETS. This translates to a reduction in demand for fossil fuels, which leads to lower fuel prices, which again leads to higher demand for fossil fuels outside the ETS system, i.e. in sectors and countries that are not covered by the ETS. This means that the total effect on emissions is likely to be smaller than the direct leakage through the ETS system. These observations lead to three questions, namely:

1. How large are direct leakage effects through the ETS?
2. How large are the offsetting effects of increases in non-ETS sectors and in countries not covered by the ETS?
3. How can these be modelled as part of the framework proposed here?

For question 1, we currently rely on the central estimate of DØRS (2021b) and assume a baseline direct leakage rate until 2030 of $L_{DK}^{ETS} = 20\%$.[5] However, this estimate may not be sufficient to capture the dynamics of leakage effects in a dynamic model such as GreenREFORM. We are currently working on this issue, which is also secribed in more detail at the end of this section.

For question 2, we estimate the offsetting effect, L_{EU}^{ETS}, using the GTAP-E model. This approach is described in more detail in section 3.3.3.

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[5] This variable can be changed when conducting simulations within GreenREFORM, as the GTAP-E simulations care only the change in ETS-covered emissions in the rest of EU (i.e., excluding Denmark), $\Delta ETS^{nDK} = L_{DK}^{ETS} * \Delta ETS^{DK}$. This is described in more detail in section (4)

For question 3, we follow the choices made in DØRS (2019) and DØRS (2021b) and exogenize emissions assumed to be covered by the ETS in GTAP-E outside Denmark. This requires an additional extension to the GTAP-E model, where total emissions in sectors and regions covered by the ETS are exogenized by endogenizing a uniform tax (which can be negative) on these emissions. The appendix contains a mapping of which sectors in GTAP-E that are considered to be part of the ETS system for the current analysis. In this way, emissions covered by ETS can be shocked to mimic the leakage effect through the ETS. An example may clarify: consider a Danish climate policy which reduces emissions in Danish sectors covered by the ETS by ΔETS^{DK} tons. Using the estimate of the direct leakage rate of the ETS, we know the change in ETS-covered emissions in EU outside Denmark to be $\Delta ETS^{DK} * L_{DK}^{ETS}$ tons. This can be transferred to the GTAP-E model as a shock.

Using the linked approach, changes in emissions outside Denmark, ΔGHG_{GTAP}^{ROW}, can be estimated using GTAP-E as a function of changes to Danish imports and exports as well as changes in ETS-covered emissions outside Denmark. GTAP-E takes care of the offsetting effects of question 2, so no further adjustment is needed. We can augment (15) to reflect the extension of the linked apprach with changes in Danish ETS-covered emissions:

$$\Delta GHG_{GTAP}^{ROW} = \Delta GHG_{GTAP}^{ROW}(\Delta q^{DK}, \Delta ETS^{DK} * L_{DK}^{ETS}) \tag{20}$$

Using the decoupled approach, we add an extra term to the calculation of leakage of (18) to account for leakage through the ETS system. Here, we need to include the offsetting effect directly:

$$\Delta GHG_{DC}^{ROW}(\Delta q^{DK}) = \sum_{j,i} \left[L_{j,i} * \Delta q0_{j,i}^{DK} \right] - (1 - L_{EU}^{ETS}) * (L_{DK}^{ETS} * \Delta ETS^{DK}) \tag{21}$$

ETS leakage dynamics and the ETS leakage rate Given the previous discussion on the effects of the MSR, it may seem obvious to employ a leakage rate of 0% when the MSR is full and a reduction in allowance demand leads to cancellations, and a leakage rate of 100% when the MSR is no longer full. However, since agents are forward looking and allowances may be banked, the dynamics are more complex. This can be illustrated by comparing the leakage rates of emissions that all place before the MSR is no longer binding, which is assumed to happen in 2039 (DØRS, 2019; Beck and Kruse-Andersen, 2020). These leakage rates depend crucially on the demand profile for ETS allowances that economic agents expect for the entire life span of the ETS system.

As a result, a temporary reduction in Danish ETS allowance demand leads to a lower leakage rate than a permanent reduction. This is because allowance users optimize over the entire life span of the ETS system: If allowance demand is only temporarily suppressed, allowance holders will save additional allowances today in order to be able to sell them at a higher price later, when allowance demand is no longer suppressed (DØRS, 2019; Beck and Kruse-Andersen, 2020). However, the increase in savings today increases cancellations through the MSR. This reduces the leakage rate.

The 20% leakage rate of DØRS (2021b) is calculated based on a reduction in Danish ETS allowance demand for the ten-year period of 2021 to 2030. This means that the leakage rate is best suited for temporary shocks, and that the leakage rate of a permanent shock, such as a permanent tax on greenhouse gas emissions, can be higher. Some illustrative simulations on the ETS model used by both DØRS and Beck and Kruse-Andersen (2020) show this. For this illustration, the effects of a permanent reduction to the ETS demand are simulated. The permanent shock is announced in 2017 and takes place form 2020 and onwards. Figure 2 shows the resulting leakage rate for different years, starting in 2030. The leakage rate for year t is calculated as the cumulated change in total allowance use up until and including year t, divided by the cumulated change in allowance demand up until and including year t, i.e., the leakage rate in year t is calculated as:

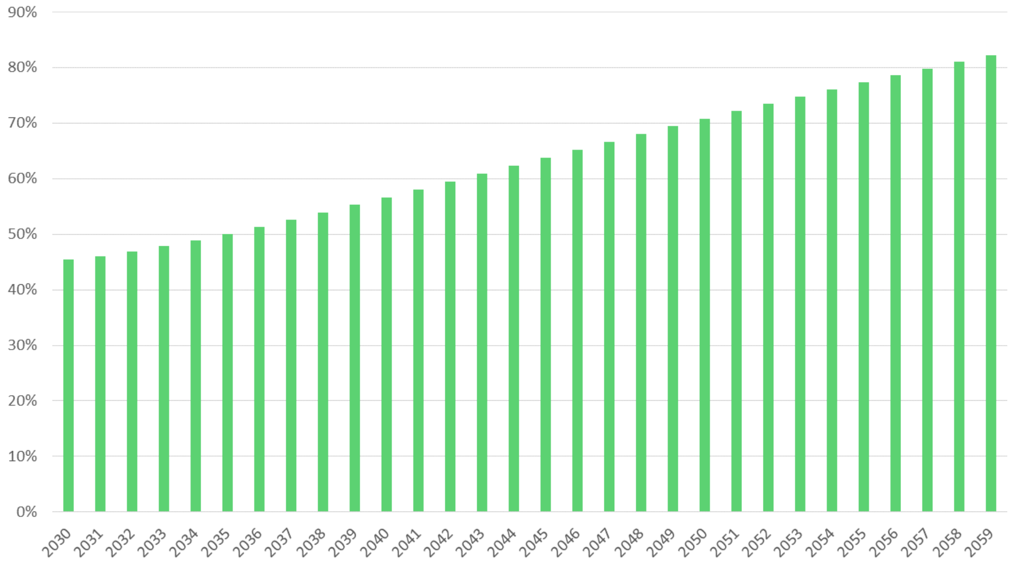
$$L_{DK,T}^{ETS} = \frac{\sum_t^T \Delta GHG_{EU,t}^{ETS} - \Delta GHG_{DK,t}^{ETS}}{\sum_t^T \Delta GHG_{DK,t}^{ETS}} \tag{22}$$

Notably, the leakage is above 40% in 2030 even though the MSR is still binding. The leakage rate rises as the time horizon for evaluating the change increases.

Another way to describe the dynamics is that a reduction in Danish ETS allowance demand in year t induces changes in allowance demand in all future years. Likewise, if a change in allowance demand in year $t+1$ is announced in year t, it will affect allowance savings already in year t. In order to estimate yearly changes in foreign greenhouse gas emissions, these dynamics are crucial.

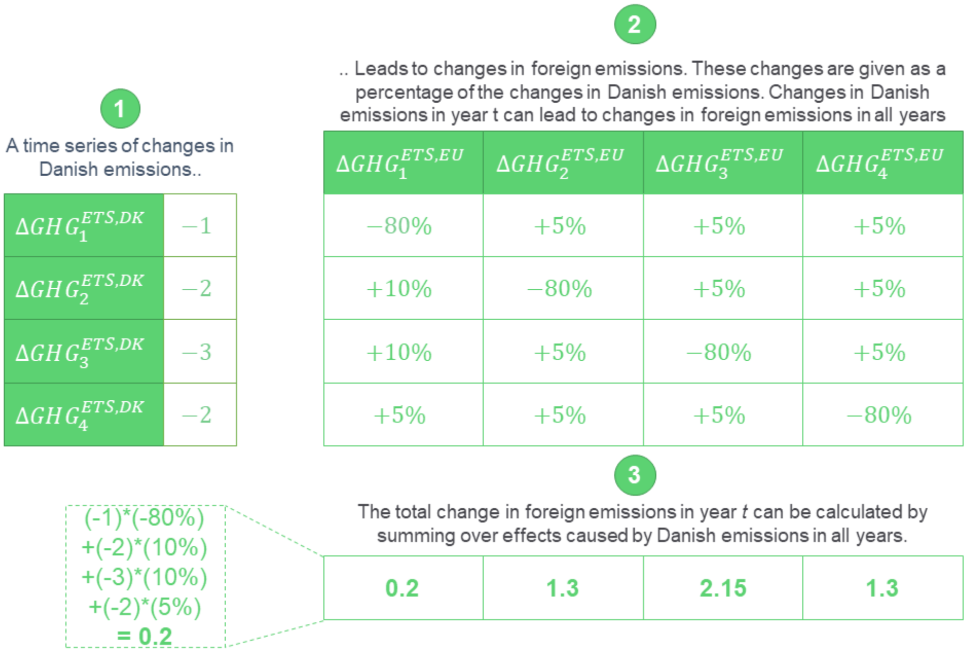
GreenREFORM can calculate effects of both temporary and permanent shocks. In fact, it is unlikely that a given shock in GreenREFORM will have a permanent and constant effect on Danish ETS emissions, as changes in emissions are likely to change from year to year due to general equilibrium effects in the model. How to capture these dynamics is an area of current research. One promising option is to decompose a time series of changes

Figure 2: The ETS leakage rate of a permanent reduciton in allowance demand, evaluated in different years



Source: Own simulations on the model of Beck and Kruse-Andersen (2020).
Note: The leakage rate for year t is calculated as the cumulated change in total allowance use up until and including year t, divided by the cumulated change in allowance demand up until and including year t.

Figure 3: Decompsing the dynamics of ETS leakage



A time series of changes in Danish emissions..

$\Delta GHG_1^{ETS,DK}$	-1
$\Delta GHG_2^{ETS,DK}$	-2
$\Delta GHG_3^{ETS,DK}$	-3
$\Delta GHG_4^{ETS,DK}$	-2

.. Leads to changes in foreign emissions. These changes are given as a percentage of the changes in Danish emissions. Changes in Danish emissions in year t can lead to changes in foreign emissions in all years

$\Delta GHG_1^{ETS,EU}$	$\Delta GHG_2^{ETS,EU}$	$\Delta GHG_3^{ETS,EU}$	$\Delta GHG_4^{ETS,EU}$
-80%	$+5\%$	$+5\%$	$+5\%$
$+10\%$	-80%	$+5\%$	$+5\%$
$+10\%$	$+5\%$	-80%	$+5\%$
$+5\%$	$+5\%$	$+5\%$	-80%

The total change in foreign emissions in year *t* can be calculated by summing over effects caused by Danish emissions in all years.

0.2	**1.3**	**2.15**	**1.3**

(-1)*(-80%)
+(-2)*(10%)
+(-3)*(10%)
+(-2)*(5%)
= 0.2

in ETS emissions to yearly shocks and consider their effects on emissions seperately. This approach is illustrated in figure 3.

3.3 Are sector-specific leakage coefficients constant?

In this section, we conduct a series of tests to investigate the constancy of leakage coefficients. If leakage coefficients are approximately constant, i.e., general equilibrium effects are not driving leakage results, it is reasonable to use constant leakage coefficients to estimate the effect of national policies as described in section 3.2.[6] Further, the assumption of constant leakage coefficients of the theoretical model in section 2 is justified.

We test this assumpion by comparing results of the decoupled approach with GTAP-E simulations model that take account of the potential non-constancy of leakage coefficients. The idea is the following: changes in imports and exports as a consequence of a national policy are simulated in a national model. These changes are collected in the vector Δq^{DK}. The effect in GTAP-E of these changes can be found by running a simulation in GTAP-E

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[6] The alternative to the decoupled approach is to run a GTAP-E simulation on the simultaneous changes in all trade flows, as done in DØRS (2021b).

where these changes in imports and exports are fed into the model as a shock (alongside changes in domestic ETS allowance use). This gives rise to a "linked" estimate of leakage:

$$\Delta GHG^{ROW}_{LINKED} = \Delta GHG^{ROW}_{GTAP}(\Delta q^{DK}, \Delta ETS^{DK}) \tag{23}$$

The linked estimate does not assume that leakage coefficients are constant. Instead, the estimate is a general equilibrium outcome where all changes are analyzed at the same time. We note that the linked estimate of leakage effects is the exact method used to estimate leakage effects in DØRS (2021b).

Alternatively, the estimated leakage coefficients can be used to estimate leakage using the decoupled approach of (21), repeated here for convenience:

$$\Delta GHG^{ROW}_{DC}(\Delta q^{DK}) = \sum_{j,i} \left[L_{j,i} * \Delta q0^{DK}_{j,i} \right] - (1 - L^{ETS}_{EU}) * (L^{ETS}_{DK} * \Delta ETS^{DK})$$

where $\Delta q0^{DK}_{j,i}$ is a vector of zeros except for the element (j,i), where it is equal to the corresponding cell of Δq^{DK}.

We proceed to test the decoupled approach by comparing $\Delta GHG^{ROW}_{LINKED}$ and ΔGHG^{ROW}_{DC} for a series of different types of shocks. If differences are small, not much is lost from using the decoupled approach, compared to the linked approach. The overall conclusion is that the decoupled method performs quite well. While results are not identical, the decoupled method, are generally of the same absolute magnitude. We therefore believe that the decoupled results are sufficient to inform about the magnitude of leakage. At the same time, the assumption of constant leakage coefficients of the theoretical model is to some extent justified. While the method does introduce some uncertainty, we believe that it is smaller than the the fundemental model uncertainty related to carbon leakage results.

In the end, we can only run a finite number of tests; however, we believe that the results of the tests are good enough that the method can be used for an arbitrary shock without the need to run additional simulations in GTAP-E. In the following, we show results of a battery of tests of the decoupled method, namely:

1. **Sector interaction effects:** We test whether the decoupled approach can account for effects in general equilibrium when several trade flows are changed at the same time. We conclude that sector general equilibrium effects, while they do exist, are not so strong as to make leakage effects calculated using the decoupled approach void of information on the magnitude of leakage effects.

2. **Scale effects:** The decoupled method employs a constant factor on foreign emissions per change in Danish sector-specific imports and exports. This means that leakage effects are linear as a function of the change in trade flows. However, the effect size may depend on the size of the distortion introduced into the foreign economy. We investigate whether these effects appear to be critical in GTAP-E simulations. We also investigate whether the direction of change in imports and exports matter. We conclude that scale effects do not appear to be of critical importance.

3. **ETS leakage:** We test whether the decoupled method can adequately account for the effects of leakage through the ETS system. We conclude that the decoupled method appears to capture the correct magnitudes of emissions changes of general equilibrium outcomes.

3.3.1 Sector interaction effects

We conduct two basic tests of the decoupled method.

Increasingly complex shocks We run a series of 70 simulations using the linked approach, where each shock builds upon the last. The first shock changes the exports of Danish vegetables, the second shock adds a change in exports of Danish cattle and so on. The final simulation changes both imports and exports of all 35 GTAP-E sectors (35*2 = 70 simulations). The results of the first shock will be identical to the results using the decoupled method, since only a single sector is shocked.[7] The shock consists of increases in exports and imports to each sector by 100 million Euros. A priori, interaction effects will be increasingly important as the shock complexity increases.

Figure 4 shows results of the 70 simulations. As expected, the difference between the linked and decoupled methods, increase as shock complexity increases. There is a high degree of correlation in the direction and the magnitude of the linked and decoupled methods. Are the differences between the two methods small or large? One way to interpret these differences is to frame the difference in terms of the errors introduced when calculating leakage rates.

The leakage rate, β, is defined as:

$$\beta = -\frac{\Delta GHG_{ROW}}{\Delta GHG_{DK}} \tag{24}$$

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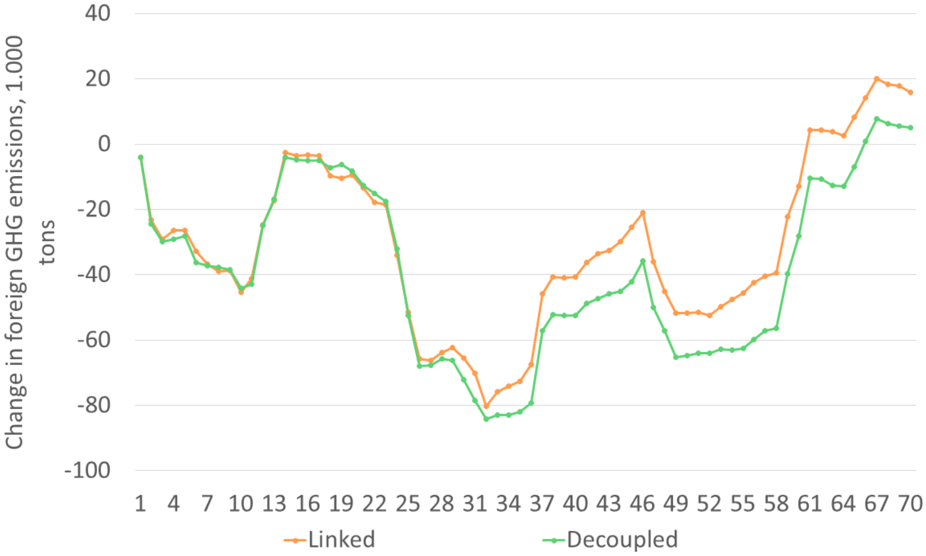
[7] This holds in the absence of scale effects which are discussed later in this section.

Figure 4: Increasingly complex shocks



Note: The figure shows changes in foreign GHG emissions from a series of increasingly complex shocks. The x-axis refers to how many combinations of sectors and imports & exports that are shocked.

The decoupled method introduces an error, here interpreted as an error rate on the true emissions:

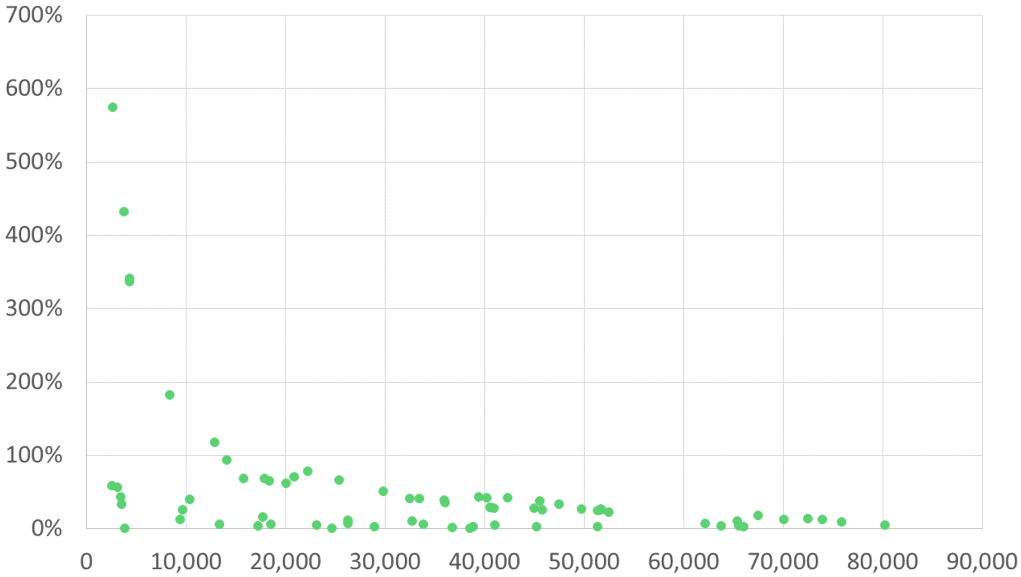
$$\beta_{DC} = -\frac{\Delta GHG_{ROW} * (1 + \epsilon_{DC})}{\Delta GHG_{DK}} \tag{25}$$

The effect on the leakage rate is therefore:

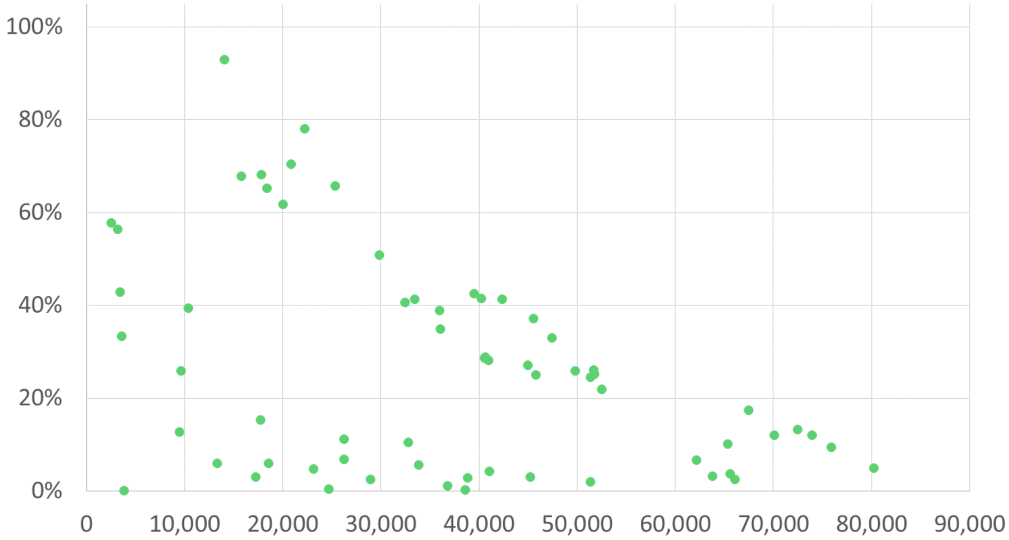
$$\beta_{DC} - \beta = -\frac{\Delta GHG_{ROW} * \epsilon_{DC}}{\Delta GHG_{DK}} = \beta * \epsilon_{DC} \tag{26}$$

If, for instance, the error rate is 25% and the leakage rate is 20% (the central estimate of DØRS (2021b)), the leakage-rate error introduced by the decoupled method is 3 percentage points. Figure 5 plots ϵ_{DC} and ΔGHG_{ROW} for the 70 shocks. Some error rates are quite large, but this is only the case when changes in foreign emissions are small. For the shocks that induce larger changes in foreign emissions, error rates are smaller. The average difference between the two methods is 7.700 tons CO_2e, which translates to 25% of the average change in emissions using the linked method This implies that the method does relatively well when changes in foreign emissions are large. This is reassuring, as it is exactly in these cases that precise estimates of leakage rates are most important.

Figure 5: Errors and shock sizes



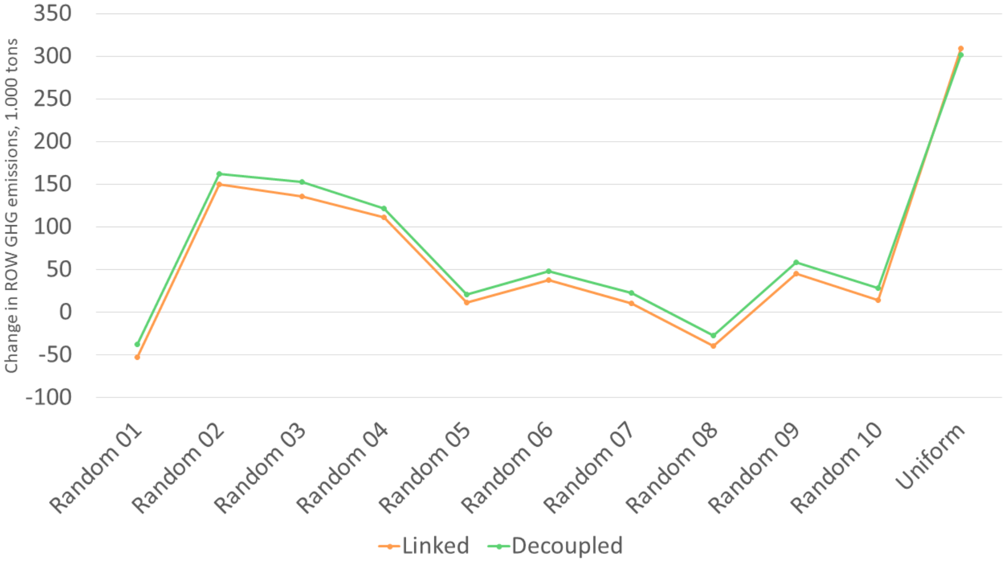
(a) All 70 simulations



(b) Simulations with error rates below 100%

A series of complex shocks We run a series of 11 simulations that each include changes to imports and exports of all 35 GTAP-E sectors. The first 10 consist of randomly

Figure 6: A series of complex shocks



generated simulations. For each simulation, we draw 70 increases in imports and exports from a uniform distribution of between 0 and 50 million Euros. The final simulation is the GTAP-E shock of DØRS (2021b) when investigating the impact of a uniform CO2-tax on the Danish economy. This final shock also includes a changes in ETS emissions. The series of 11 shocks mimic the complexity of a real application of the decoupled approach to estimating leakage as a consequence of a national policy.

The results are illustrated in figure 6. The effects of the decoupled approach are generally of a similar magnitude to the effects of the linked approach. The average error introduced is 10.900 tons CO_2e, or 16% of the average change using the linked approach. This lends credence to using the decoupled approach for estimating leakage.

3.3.2 Scale effects

We run three sets of tests for scale effects:

Sector-specific shocks of different sizes In order to investigate the impact of shock sizes, we run 3 simulations where we increase exports or imports from/to a single sector by 10, 50 and 100 million Euros. We run 3 simulations for each of the 35 sectors and for imports and exports seperately, for a total of 3*35*2=210 simulations. We proceed

Table 1: Scale parameters (β's), N=70

Mean	1.11
10%	0.69
25%	0.92
50%	1.02
75%	1.18
90%	1.38

to investigate the importance of shock sizes by fitting functions of the following form to each of the 35*2=70 sector-import/export combinations, here indexed by i:

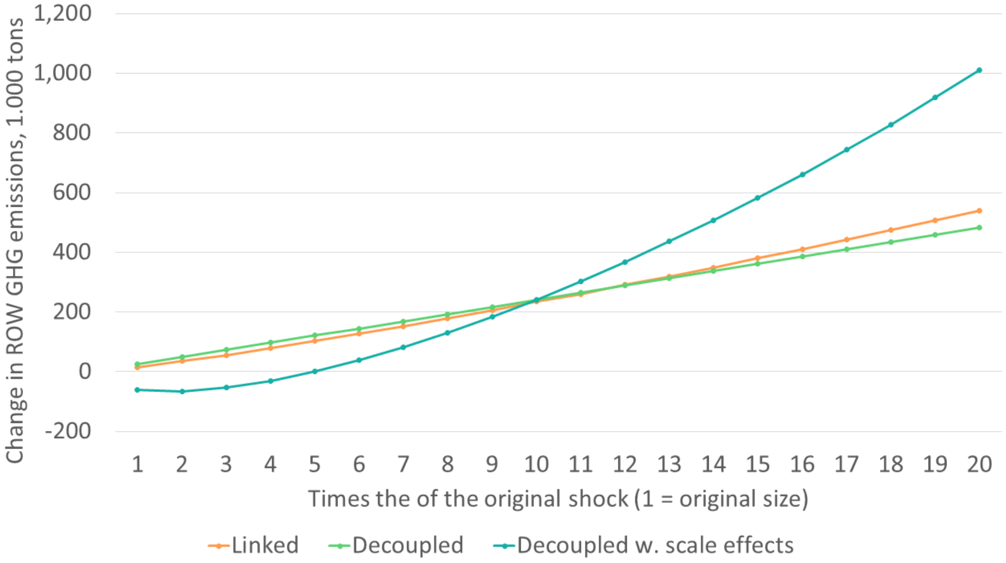
$$\Delta GHG_i^{ROW} = L_i * s^{\beta_i},\ s = \{10, 50, 100\} \tag{27}$$

$\beta = 1$ implies that shock effects are linear. Table 1 reports the results of the fitted β parameters. Most β's are close to 1, with a few outliers.

A complex shock at different scales We also check whether leakage exhibit scale effects. We do this by running a single shock – the most complex shock of figure 4 – in 20 versions, where we scale the original shock by factors of {0.1,0.2..,2}. The results of the shocks, along with the predicted results using constant factors, are illustrated in figure 7. The shock does exhibit some scale effects – fitting equation (1) on the 20 versions gives a β value of 1.18. However, the predicted results using constant factors does a fairly decent job of getting the magnitudes right over the examined range of shocks. The modest scale effects are likely to be at least partly caused by the fact that Denmark is a small economy. Therefore, even effects that are large for Denmark are likely to be small, as a share of production in Denmark's trading partners. Therefore, the foreign distortions are also relatively small. We also attempt a prediction using the sector-specific $\beta's$ reported in table 1, but it is evident from figure 7 that this gives a worse fit in this particular case.

Given that scale effects seem to be modest and that the sector-specific β's did not improve the prediction in a complex shock, we do not introduce an explicit modelling of scale effects in the decoupled method. This may introduce some additional uncertainty for very large shocks, but we believe this is, on balance, preferable to introducing an unknown degree of uncertainty on shocks of all sizes.

Figure 7: Scale effects in a complex shock



Negative vs positive shocks The leakage coefficients illustrated in Figure 1, are calculated using shocks to GTAP-E that model *increases* in exports or imports. A priori, effects should be of similar sizes if leakage coefficients are calculated using *decreases* in exports or imports instead. Nevertheless, we test this by running all shocks as decreases in imports or exports instead. Results are reported in figure 8. A few shocks are not possible to conduct using decreases instead of increases (because there may not be an existing trade flow to decrease). For the shocks where we can make the comparison, sector-specific leakage coefficients are very similar and almost identical for most sectors. We therefore conclude that using increases in imports or exports as the sole basis for calculating leakage coefficients is reasonable.

3.3.3 Modelling of ETS leakage

To isolate the effect of ETS leakage, we run a series of simple import and export shocks to the GTAP-E system with and without an additional effect through the ETS system.

Before we do so, we need to estimate the offsetting effect of increases in non-ETS emissions when demand for fossil fuels in sectors covered by the ETS system falls, i.e., $L_{EU}^{ETS} = L_{DK}^{ETS} * \Delta ETS^{DK}$ of equation (21). We estimate this by running a series of shocks in GTAP-E where we shock the total emissions of ETS-covered emissions (ex-

Figure 8: Estimated leakage coefficients on increases and decreases in imports and exports

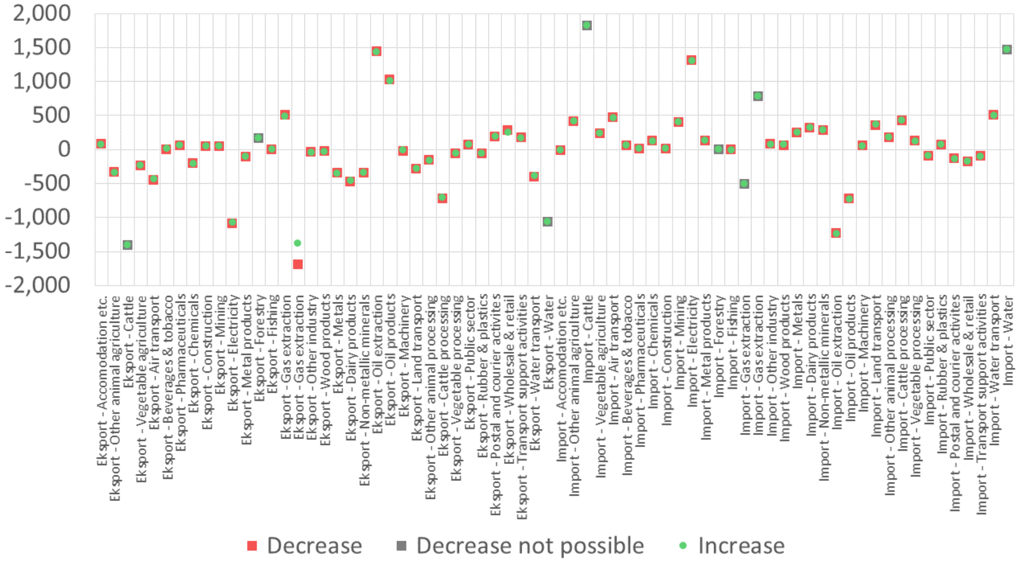


Table 2: Estimates of L_{EU}^{ETS}

ΔETS^{nDK}, 1.000 tons CO_2e	L_{EU}^{ETS}
10	0.09
100	0.13
1.000	0.17
Average:	**0.13**

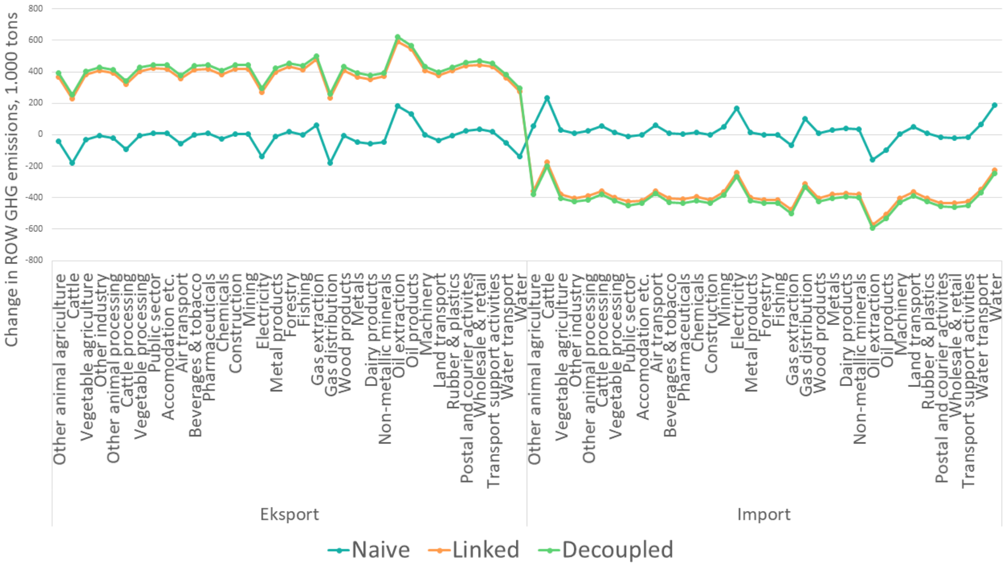
cluding Denmark), ΔETS^{nDK}, and record the total fall in emissions outside Denmark, ΔGHG^{nDK}. We then calculate:

$$L_{EU}^{ETS} = \frac{\Delta GHG^{nDK}}{\Delta ETS^{nDK}} \tag{28}$$

Table 2 shows estimated offsetting leakage rates for three different magnitudes of changes in total ETS-covered emissions. There is a tendency for offsetting leakage to increase as changes in ETS-covered emissions increase. For the analyses conducted here, we assume that the offsetting leakage is equal to the average of the three shocks, i.e., $L_{EU}^{ETS} = 0.13$.

We complete the analysis by conducting a series of 70 simulations where we change both exports from or imports to Denmark in a single sector and total ETS emissions outside

Figure 9: Effects of ETS leakage



Denmark. We then use (21) to predict effects using the decoupled method.[8] Increases in exports are accompanied by an increase in ETS emissions outside Denmark of 0.5 million tons; increases in imports are accompanied by a decrease in ETS emissions of the same size. These are large changes in ETS emissions, compared to the direct effect through sector leakage, and it is therefore likely to be a conservative estimate of the general equilibrium effect of including changes in ETS emissions. Results are illustrated in figure 9.

The decoupled method does a good job at replicating the simulations. The average deviation from the simulations is 6%. Using (26), this implies that the error in leakage rate estimates for a true leakage rate of 20% is around 1.2 percentage points.

4 Leakage effects in GreenREFORM

In this section, we document how leakage calculation is implemented in practice in GreenREFORM. We also illustrate the leakage effects from a uniform tax on Danish greenhouse gas emissions. Attempting to implement the leakage-adjusted tax system of section 2 is a focus area for future work.

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[8] In practice, we increase imports or exports by 100 million euros.

4.1 Implementation in GreenREFORM

In order to implement the decoupled approach in GreenREFORM, the leakage coefficients must be mapped from GTAP-Esectors to GreenREFORM sectors. A mapping between the sectors of GTAP-E and GreenREFORM can be found in appendix table (6). Sectors may map 1:1, or one GTAP-E sector may cover several GreenREFORM sectors. In these cases, the same GTAP-E leakage coefficient is applied to each GreenREFORM sector, ie. for $i^{GR} \in i$:

$$L_{j,i^{GR}} = L_{j,i|i^{GR} \in i} \tag{29}$$

, where i is GTAP-E sectors and i^{GR} is GreenREFORM sectors. In other cases, several GTAP-E sectors may map into one GreenREFORM sector. In this case, a weighted average of leakage coefficients is calculated, using the value of imports or exports, $q_{j,i}^{DK}$, as weights. ie., for $i \subset i^{GR}$:

$$L_{j,i^{GR}} = \frac{\sum_{i \in i^{GR}} L_{j,i} \cdot q_{j,i}^{DK}}{\sum_{i \in i^{GR}} q_{j,i}^{DK}} \tag{30}$$

Leakage coefficients have been estimated in GTAP-E for year 2014 and 2030. Coefficients in the model are linearly interpolated for years between 2014 and 2030. After 2030, coefficients are, in lack of better information, assumed to be constant. A policy shock in the GreenREFORM model results in a change in rest-of-world emissions stemming from individual sectors. From this we can calculate sector-specific leakage effects. These effects should be interpreted as follows: The sector-specific leakage effect for some sector i is the total effect on emissions abroad (i.e., in all sectors and regions) caused by a change in imports, exports and ETS usage in the Danish sector i. Sector-specific leakage is given by:

$$\Delta GHG_{i^{GR}}^{ROW} = L_{j,i^{GR}} \cdot \Delta q0_{j,i^{GR}}^{DK} - (1 - L_{EU}^{ETS}) \cdot (L_{DK}^{ETS} \cdot \Delta ETS_{i^{GR}}^{DK}) \tag{31}$$

Where $\Delta q0_{j,i^{GR}}^{DK}$is the change in imports and exports and $\Delta ETS_{i^{GR}}^{DK}$ is the change in ETS quota usage resulting from the policy shock (relative to the baseline model scenario). Following (21), the total leakage effect is the sum of sector-specific leakage effects:

$$\Delta GHG_{TOT}^{ROW} = \sum_{i^{GR}} \Delta GHG_{i^{GR}}^{ROW} \tag{32}$$

Likewise, sector-specific and total leakage rates can be calculated as:

$$\alpha_{i^{GR}} = -\frac{\Delta GHG_{i^{GR}}^{ROW}}{\Delta GHG_{i^{GR}}^{DK}} \tag{33}$$

and

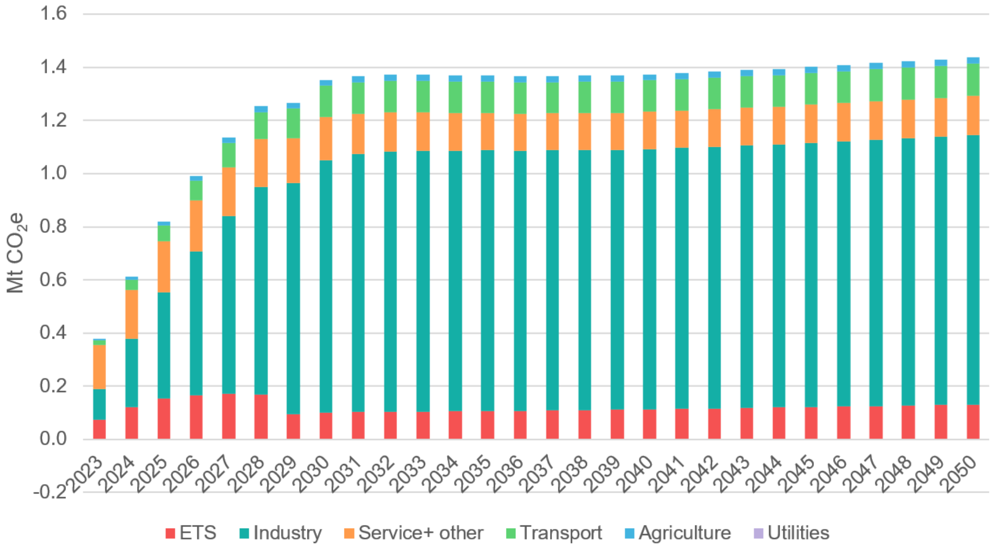
$$\alpha_{TOT} = -\frac{\Delta GHG_{TOT}^{ROW}}{\Delta GHG_{TOT}^{DK}} \tag{34}$$

4.2 Results

In this section, we present preliminiary results from imposing a uniform CO_2e-tax. Figure 10 shows the leakage effects imposing a 1250 kr. tax on CO_2e, which is phased in linearly from 2023 to 2030. The model version also includes the GreenREFORM agricultural module, which has a seperate and more detailed production function than other sectors in the model. The GreenREFORM model system also includes development of detailed modules for the waste, utilities and transport sectors. These modules are not included in the model version used for the results presented here; rather, the waste, utilites and transport sectors are modelled as standard CGE sectors . Future domestic emissions are calibrated to the Danish Energy Agency's 2020 emission projections (The Danish Energy Agency, 2020).

The leakage effects from a given sector can be seperated into two channels (as shown in equation 31). Firstly, leakage is driven by changes in imports and exports from a given sector, which is determined by leakage coefficients, $L_{j,i^{GR}}$. Secondly, leakage comes from changes in sectors' usage of ETS quotas. In figure 10, the first effect is shown for individual categories of sectors, while the effects through the ETS channel is shown summed accross all sectors.

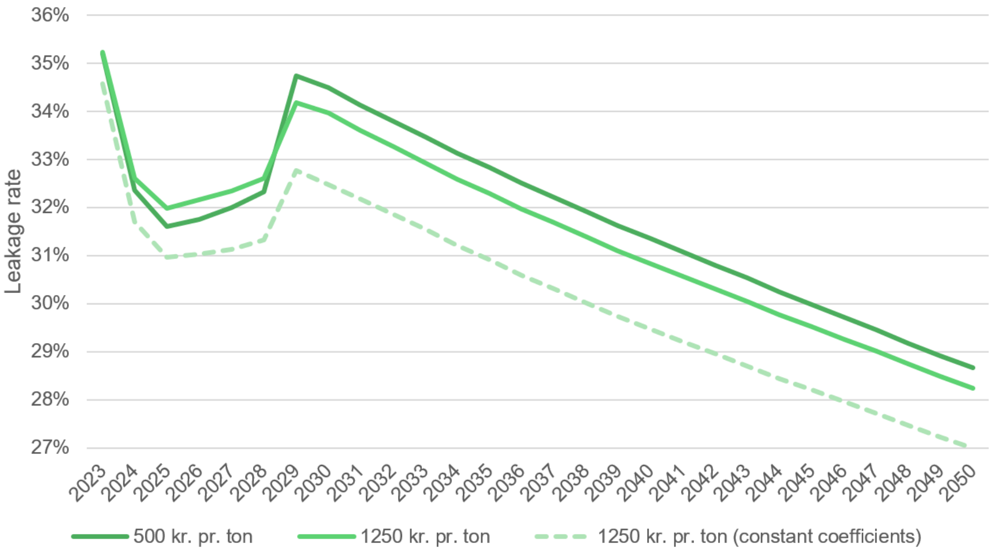
Figure 10: Leakage by sector, 1250 kroner CO_2e tax



The figure shows that the majority of leakage comes from changes in imports and exports, mainly from industrial sectors, service sectors and transport sectors. In the current model version, the quantity of agricultural land available is exogenous. This means that a carbon tax has limited effects on the cost of production in agricultural sectors, since land prices account for most of the adjustment. Hence, the leakage effects from agriculture are modest, despite relatively high leakage coefficients in these sectors. An endogenous supply of agricultural land is currently under development.

Figure 11 shows the total leakage rate from imposing a uniform tax on CO_2e of 500 and 1250 Danish kroner.

Figure 11: Leakage rates for a 500 kroner and 1250 kroner CO_2e tax



DØRS (2021b) estimate the leakage rate of a somewhat similar uniform tax on CO_2e to be around 21%. The leakage rate is somewhat higher in this illustrative example. We believe this is primarily caused by differences in the underlying models. Notably, DØRS (2021b) includes a wider range of technological possibilites to reduce emissions than the version of GreenREFORM used for these calculations do. The technologies reduce the costs of cutting emissions, which reduces the loss in competitiveness of Danish firms. This leads to lower leakage rates. The final version of GreenREFORM will also include technological reduction possibilites.

As discussed in section 3.2.1, the estimate for leakage through the ETS is likely to be upwards adjusted in future calculations. This will increase the overall leakager rate.

The results show that the leakage rates decline in the first years of the tax implementation. This is because changes in imports and exports occur more quickly than changes in domestic emissions, which drives up leakage effects in the first years. Thereafter leakage rates increases in years 2025-2029. This is mainly driven by an increase in leakage from industrial sectors. These sectors adapt more slowly to the tax change. This is because they are more capital intensive and changes in capital stocks are subject to convex installation costs. However, industrial sectors tend to have relatively high leakage coefficients. After the tax is fully phased in, the leakage rates slowly decline again. This is because domestic emissions continue to decline after 2030, while leakage coefficients are assumed to remain be constant after 2030.

When fully phased in, the leakage rate is lower for a 500 kroner tax than for a 1250 kroner tax. This is because leakage from industrial sectors accounts for a larger proportion of total leakage, when the tax rate is set at a higher level. Also, the leakage coefficients estimated for year 2030 contribute to higher leakage in total than the coefficients estimated for year 2014. Thus, if the leakage coefficients estimated for year 2014 are held constant, leakage rates are lower (as shown in figure 11).

5 Conclusion

The conclusion from a series of tests is that the decoupled apprach to estimating leakage effects of national policies appears to be working well in the sense that not much is lost from using constant leakage coefficients compared to a more direct link with the GTAP-E model. Although the method in this sense gives reasonable estimates of leakage effects, we do stress that the resulting estimates of leakage are no better than the models employed. The method of calculating leakage using the GTAP-E model in itself results in fairly uncertain estimates of leakage. There are several reasons for this. One reason is that the GTAP-E model does not model all aspects of emissions well. For instance, GTAP-E does not explicitly model renewable energy sources. DØRS (2021a) note additional points of concern, including an important point regarding the employed modelling of leakage through the ETS system. The modeling implies that leakage to the rest of the EU in sectors covered by the ETS can *only* take place through the ETS system. An example can clarify this issue : If a factory closes in Denmark and rebuilds its facilites in Germany, this would result in 100% leakage. However, in the modified version of GTAP-E, the direct ETS leakage rate is exogenously imposed (and set to 20% as a default). This means that we may end up *underestimating* the magnitude of leakage in the ETS system.

Other model issues include:

- **No modelling of foreign LULUCF emissions.** The GTAP-E model does not include emissions from LULUCF emissions. This means that if Danish policies give rise to increases or decreases in LULUCF emissions abroad, these changes will not be reflected in the estimated leakage rates. One salient example where this may be relevant is that a reduction in the production of Danish cattle and pigs may reduce the cropland area abroad required for growing feed for these animals. This can reduce LULUCF emissions abroad. In this example, the leakage rate may be overestimated. Further, the reduction in Danish production will be at least partially offset by increases in cattle and pigs production elsewhere in the world in order to meet global demand. It seems likely that many sectors only induce negligible changes in foreign LULUCF emissions. However, for some sectors, in particular agriculture and food processing industries, changes in LULUCF emissions may not be negligible.

- **Each sector consists of heterogenous subsectors and firms.** This is an issue shared to some extent by all macroeconomic models, and it also applies to GTAP-E as well as GreenREFORM. In some cases, the lack of within-sector heterogeneity may bias results. One example is if a highly CO2-intensive Danish sector (e.g., production of cement) is mapped to a broader and, on average, less CO2-intensive sector in GTAP-E (e.g., all production of non-metallic minerals). This will bias leakage effects, since the model will in this case implicitly assume that the reduction in cement production will be offset by production of non-metallic minerals abroad. In these cases, it may be relevant to adjust leakage coefficients of specific sectors to better match their foreign counterparts.

- **Explicit sector regulation:** The cornerstone of GTAP-E is relatively simple, regional CGE-models. These models are connected with each other through, among other things, global trade and savings. The simple, regional CGE-models model all kinds of production using standard production functions. This means that there is no explicit modelling of sector-specific regulation. In some cases, this type of regulation may be important for leakage effects. One example is that the EU sets targets on the average emission coefficient of cars produced in the EU. When these targets are binding, leakage through changes in the composition of Danish car ownership may be very high. If the emission coefficient target is binding, car producers meet the target by subsidizing the sale of low- and zero emission vehicles by charging a higher price for their high-emission vehicles. Say, for instance, that Denmark subsidizes the purchase of electric vehicles. This leads to an increased demand for electric vehicles at all prices. Car manufacturers can now reduce the subsidy to low- and zero emission vehicles and still meet their binding target. The offsets the decrease in emissions from Danish cars by an increased sale of high-emissions vehicles in other EU countries.

To conclude, the leakage coefficients reported in this memo can be thought of as a set of “default” values. For concrete analyses, it may be relevant to adjust these coefficients to take account of e.g., LULUCF emissions abroad, sector heterogeneity and important sector regulation measures abroad.

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Appendix: GTAP-E aggregation and mapping to GreenREFORM

We use the same aggregation and sector mappings as DØRS (2021b). Sectors in the employed GTAP-E aggregation are detailed in table 3. Regions in the GTAP-E aggregation are shown in table 4. Sectors of GreenREFORM are detailed in table 5. The mapping between GTAP-E sectors and GreenREFORM sectors is shown in table 6

Table 3: GTAP-E aggregation

Aggregated sector	**GTAP-E sectors**	**ETS sector**	**Non-ETS sector**
Vegetable agriculture	pdr,wht,gro,v_f,osd,c_b,pfb,ocr		x
Cattle	ctl,rmk		x
Other animal agriculture	oap,wol		x
Forestry	frs		x
Fishing	fsh		x
Oil extraction	oil	x	
Gas extraction	gas	x	
Mining	coa,oxt	x	
Cattle processing	cmt	x	
Other animal processing	omt,vol	x	
Vegetable processing	pcr,sgr,ofd	x	
Dairy products	mil	x	
Beverages & tobacco	b_t	x	
Other industry	tex, wap, lea, ppp, ele, eeq, mvh, otn, omf		x
Wood products	lum		x
Oil products	p_c	x	
Chemicals	chm	x	
Pharmaceuticals	bph		x
Rubber & plastics	rpp	x	
Non-metallic minerals	nmm	x	
Metals	i_s, nfm	x	
Metal products	fmp		x
Machinery	ome		x
Electricity	ely	x	
Gas distribution	gdt		x
Water	wtr	x	
Construction	cns		x
Wholesale & retail	trd		x
Land transport	otp		x
Water transport*	wtp		
Air transport	atp	x	
Transport support activities	whs		x
Postal and courier activites	cmn, ofi, ins, rsa, obs, ros, dwe		x
Accomodation etc.	afs		x
Public sector	osg, edu, hht		x

The table shows sectors of the employed GTAP-E aggregation. Some sectors are assumed to be part of EU-ETS (in the EU, cf. table 4), and emissions from these sectors in the EU are exogenized as described in section 3.3.3. Other sectors have binding emissions targets (when part of the EU, cf. table 4), and total emissions for these sectors as a whole are also exogenized. * : Water transport emissions are not regulated through ETS nor through binding non-ETS restrictions in the EU (cf. table 4).

Table 4: Regions of GTAP-E

Region	Part of ETS?	Binding non-ETS restrictions?
North America	-	-
Latin America	-	-
Denmark	-	-
EU excl. Denmark	YES	YES
Europe excl. EU	-	-
Africa	-	-
Middle East	-	-
Eurasia	-	-
China	-	-
South-East Asia	-	-
Rest of World	-	-

Table 5: Sectors of GreenREFORM

GreenREFORM code	Name (Danish)
2000	Forestry
3000	Fishing
0600a	Extration of oil
10120	Manufacture of food products, beverages and tobacco
13150	Textiles and leather products
16000	Manufacture of wood and wood products
19000	Oil refinery etc.
20000	Manufacture of chemicals
21000	Pharmaceuticals
23000	Manufacture of other non-metallic mineral products
25000	Manufacture of fabricated metal products
35001	Production and distribution of electricity
35002	Manufacture and distribution of gas
36000	Water collection, purification and supply
41430	Construction
45000	Wholesale and retail trade and repair of motor vehicles and motorcycles
46000	Wholesale
47000	Retail sale
52000	Support activities for transportation
53000	Postal and courier activities
55560	Accommodation and food service activities
64000	Financial service activities, except insurance and pension funding
68203	Renting of residential buildings
71000	Architectural and engineering activities
1010	Conventional plant production
1011	Organic plant production
1020	Horticulture
1031	Conventional cattle (incl. milk production)
1032	Organic cattle (incl. milk production
1051	Conventional pigs
1052	Organic pigs
1061	Conventional poultry
1062	Organic poultry
1070	Fur animals
1080	Agricultural contractor
37000	Kloak- og rensningsanlø¦g
38391	Indsamling af affald
38392	Behandling og bortskaffelse
38393	Forbrø¦nding af affald
38394	Genbrug
38395	Rensning af jord og grundvand mv.
49011	Passagertransport med regional- eller fjerntog
49012	Godstransport med tog
49022	S-togstrafik/ lokaltog (og metro)
49024	Buskørsel, nø¦r
49025	Buskørsel, fjern
49031	Vejgodstransport og flytteforretninger
49032	Rørtransport
50001	Passagertransport (sø-, kyst- og transport ad indre vandveje)
50002	Godstransport (sø-, kyst- og transport ad indre vandveje)
51001	Passagertransport med fly
51002	Godstransport med fly
off	Offentlig sektor

Table 6: Mapping between GTAP-E aggregation and GreenREFORM sectors

GTAP code	Langt navn	GreenREFORM sectors
1-8	Vegetable agriculture	1010, 1011, 1020
9, 11	Cattle	1031, 1032
10, 12	Other animal agriculture	1051, 1052, 1061, 1062, 1070
13	Forestry	2000
14	Fishing	3000
16	Oil extraction	0600a
17	Gas extraction	0600a
15	Mining	
19	Cattle processing	10120
20	Other animal processing	10120
23-25	Vegetable processing	10120
22	Dairy products	10120
26	Beverages & tobacco	10120
27-29, 31, 40, 41, 43-45	Other industry	13150
30	Wood products	16000
32	Oil products	19000
33	Chemicals	20000
34	Pharmaceuticals	21000
35	Rubber & plastics	25000
36	Non-metallic minerals	23000
37-38	Metals	25000
39	Metal products	25000
42	Machinery	13150
46	Electricity	35001
47	Gas distribution	35002
48	Water	36000, 37000, 38391, 38392, 38393, 38394
49	Construction	41430
50	Wholesale & retail	45000, 46000, 47000
52	Land transport	49011, 49012, 49022, 49024, 49025, 49031, 49032
53	Water transport	50001, 50002
54	Air transport	51001, 51002
55	Transport support activities	52000
56-61, 65	Postal and courier activites	53000, 55560 71000, 64000
51	Accomodation etc.	55560
62, 63, 64	Public sector	off