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# Potential Carbon Leakage under the Paris Agreement

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## Abstract

Carbon leakage is the effect of emissions transferring to certain countries due to others having a stricter climate policy. This phenomenon is shown to have undercut the effectiveness of the Kyoto Protocol. Considering the increasingly globalised nature of the world economy, carbon leakage may have an even greater potential under the Paris Agreement some fifteen years later. Although a more global approach to combatting climate change, the Paris Agreement is susceptible to leakage because of its lack of policy harmonization and enforcement mechanisms. Here we perform the first quantitative analysis of the potential for carbon leakage under Paris, using the GTAP-E general equilibrium model of the world economy with energy and carbon emissions to analyse leakage effects under six scenarios. Two of these scenarios analyse regions implementing climate policy in isolation, two greater participation, but still not harmonized, global Paris Agreement policy, and a further two analyse the effect of a US withdrawal from the agreement. Both cases are considered with and without the US withdrawal. Our analysis demonstrates that there is potential for significant carbon leakage effects, in line with the rates produced from studies on the Kyoto Protocol. Depending on model elasticities, we find medium carbon leakage in the range of 1-9% (with a central estimate of 3-4%) under co-ordinated Paris Agreement policy across countries, compared to high leakage of 8-31% when countries operate in isolation. However, scenarios where the US withdraws from the agreement result in roughly doubling of leakage rates, in the range of 3-16% (central estimate 7%), which demonstrates the vulnerability of the Paris Agreement in its current form. To limit leakage effects greater policy co-ordination to achieve consistent implicit carbon prices is needed across countries.

## 1. Introduction

Climate change is a problem on a global scale and thus requires global co-operation for effective solutions. The first multi-national agreement to combat climate change was the Kyoto Protocol, which was signed in 1997 and came into effect only in 2005 after the threshold number of ratifications and covered emissions was met. It required most industrialised nations to reduce their greenhouse gas emissions relative to 1990 levels. However, there are conflicting opinions on how successful it was at achieving significant emission reductions (Almer and Winkler 2017, Maamoun 2019). One limitation of the Protocol was the exclusion of developing countries, including big emitters such as China, which therefore had no restraint on growing their emissions. Indeed, sharp increases in emissions occurred in countries such as China during the two Kyoto commitment periods, ending in 2020.

One particular systemic issue that affected the Kyoto Protocol was carbon leakage. This occurs when emissions rise in one country as a result of strict climate change policies in another. Emissions are then merely transferred from one country to another through changes in trade patterns and relocation of industries. Estimates of the magnitude of carbon leakage from the Kyoto Protocol, expressed as a percentage of the emission reductions in the abating country, range from around 10% (Palstev 2001) to as high as 130% (Babiker 2005). Despite the potential significance of carbon leakage, it is rarely factored into countries' climate policies.

The successor to the Kyoto Protocol, the Paris Agreement was adopted in 2015. Unlike the former, the latter includes almost all countries, and could therefore be seen as the first truly global agreement on climate change. Nevertheless, studies have shown that the initial Paris Agreement pledges result in greatly varying carbon prices among parties (Aldy et al. 2016, Fujimori et al. 2016). This lack of policy harmonisation across countries will mean that opportunities for carbon leakage persist. Due to the Paris NDCs having no binding enforcement mechanism, carbon leakage pressure may result in countries failing to meet their pledges.

In the very globalised economy that has developed over the past few decades, a change in domestic policy can have far-reaching effects. Exports as a percentage of global GDP have risen from 23% in 1997, when the Kyoto Protocol was signed to 30% in 2018 (World Bank 2020). This suggests that carbon leakage could be an even greater problem under Paris, as there is clearly a lot of potential for trade flows to shift and companies to relocate to countries that are more competitive due to less stringent climate policy.

Here we analyse the potential effectiveness of the Paris Agreement at reducing emissions on the global scale by assessing the possible channels and levels of carbon leakage. We do this by building on a previous study (King and van den Bergh 2019) that categorises the pledges of individual countries based on their potential ambition and effectiveness. This is accomplished through normalising the pledges to indicate the actual change in emissions relative to a recent base year, which makes them directly comparable.

Next, we use the GTAP-E computable general equilibrium model of the world economy to analyse the potential leakage under several scenarios consistent with the normalised pledges. This approach has been used by previous studies to estimate levels of carbon leakage, particularly under the Kyoto Protocol. Computable general equilibrium (CGE) models are a popular tool for analysing national climate change mitigation policy in the context of global social-economic and policy issues, as they are well suited to analyse the impact of policy-induced price changes on emissions (Babatunde et al. 2017). CGE models take real world data to build a multi-sector model of the global economy in a state of general equilibrium. A policy shock, such as a carbon tax or emissions quota affecting implicit carbon prices, is then applied to one of more of the regions. This generates a new equilibrium state based on the global impact of that shock, by adjusting prices and quantities. In the context of this study, a CGE model is a useful tool as it can model changes in supply of and demand for commodities, both domestically and through trade, from the policies or policy targets at national levels. Hence, we are able to analyse the effect on emissions in a non-abating region as a result of the climate policy shock in the abating region. As general equilibrium models are imperfect approximations of the global economy, dependent on the underlying parameters, we also perform a sensitivity analysis of some key parameters.

This is the first study that we are aware of that applies this methodology to the Paris Agreement. Our analysis demonstrates that there is potential for significant carbon leakage effects, in line with the rates produced from studies on the Kyoto Protocol. As much can be learned from studies of the Kyoto Protocol, we will start by examining assessments of its carbon leakage.

## 2. Carbon leakage under the Kyoto Protocol

### 2.1. Background

The Kyoto Protocol marked the first legally binding limits on greenhouse gas emissions for industrialised countries, designated as Annex I countries. These countries accounted for around 55% of total greenhouse gas emissions in 1990 (Breidenich et al. 1998). It was the general view that the main responsibility for tackling climate change belonged to these countries as they had through their historical development become by far the largest greenhouse gas emitters. Imposing comparable greenhouse gas emission targets for developing countries was considered as a serious risk for their economic development. Legally binding emission targets were set for the first commitment period of 2008-2012 for the Annex I counties. The parties were unable to agree a uniform target, so individual targets were set, with the average commitment at 5% below 1990 levels. An enforcement mechanism was also established. If a country did not comply with their targets over the first commitment period, they would have to make up the difference in the second commitment period, plus an additional 30%.

The Kyoto Protocol however ran into several difficulties. Firstly, although it was signed by the United States in 1998, it was never ratified by the Senate and thus never became legally binding. The George W. Bush administration subsequently announced in 2001 that it would not implement the Kyoto Protocol. Canada also decided to withdraw from the Protocol effective from December 2012. Despite these issues, the remaining countries surpassed their average commitment by 2.4GtCO$_2$e per year (Shishlov et al. 2016). Nine of the 36 countries that fully participated in the commitment period failed to meet their individual targets and had to resort to flexibility mechanisms. However, this was more than made up for by the countries that overachieved their targets. This principally came from the countries of the former Soviet Union. Due to the rapid collapse of their economies, emissions fell dramatically compared to their base year, which was generally 1990. Nevertheless, ignoring this effect (estimated at 2.2GtCO$_2$e per year), the Protocol slightly overachieved its targets. However, this would not have been realised if the United States and Canada had hypothetically participated over both commitment periods.

The effect on emissions at the global scale is more complicated. From 1998 to 2015 global emissions rose 30% from 38.4 GtCO$_2$e to 49.8 GtCO$_2$e, according to data from the PRIMAP database (Gütschow et al. 2018). These emission increases were not evenly distributed across countries as the Annex I countries reduced their emissions by 6% while the non-Annex I countries saw a 61% increase in emissions. This shows that the Kyoto Protocol was ineffective at reducing emissions at the global scale. One factor involved in this trend of emissions rising in non-Annex I countries while falling in Annex I countries is carbon leakage.

## 2.2. Channels of Carbon Leakage

The mechanisms through which carbon leakage operates are changes in patterns in the trade of products and relocation of energy- or carbon-intensive industries to other countries. The relative stringency of climate policies among countries is therefore important. In the context of the Kyoto Protocol, there was a more extreme case of policy differences between a group of abating countries (Annex I) and non-abating countries, with effectively absence of climate policy in the latter. The Kyoto Protocol therefore had clear potential for carbon leakage to encourage growth in non-Annex I emissions as a result of the emission reductions in Annex I countries. A common measurement of carbon leakage is the ratio of the increase in emissions in non-abating countries to the reduced emissions in abating countries. Our analysis focusses on this definition of 'strong' carbon leakage, where emission transfers are a direct result of climate mitigation policy. Emission transfers that are independent of climate policy are instead defined as 'weak' carbon leakage (Peters & Hertwich, 2007). A hypothetical carbon leakage rate of 100% would imply that all emission reductions leak away causing the climate policy in the abating country to be completely ineffective at reducing emissions globally.

According to Görlach (2018), carbon leakage occurs through three main channels:

(i) Operational leakage

Operational leakage occurs when climate policies increase the costs of production in carbon-intensive industries in a country. This results in a decline in exports of the good from the country, and in increase in imports from countries with less strict climate policies (Alexeeva-Talebi et al. 2012, Dröge et al. 2009, Marcu et al. 2013). There is in effect a change in the global trade flows of the carbon-intensive goods from countries with strict to less strict climate policies.

(ii) Investment leakage

Investment leakage is a longer-term effect than production leakage. Companies will start up production plants or invest more in countries with less stringent climate change policies as it is relatively more attractive to do so (Marcu et al. 2013). In effect, over time there will a relocation or 'capital flight' of carbon-intensive industries to the countries with less stringent climate policies. How quickly this will happen will depend on the particular industry and the size of the investment required to move the infrastructure to a different country.

(iii) Leakage through resource markets

The third type of carbon leakage occurs due to interaction of resource markets, particularly fossil fuel markets. If one country with a large enough share of the fossil fuel market introduces policies that reduce demand for fossil fuels, the result will be a reduction in the price of those fossil fuels. This will provide an incentive for other countries to consume more fossil fuels due to lower costs – the effect of which can be substantial (Böhringer et al. 2010).

One method of assessing the extent of carbon leakage under a climate change policy is through a computable general equilibrium (CGE) model, which uses economic data to estimate how an economy might react to policy changes. This typically divides the global economy into different regions and sectors and runs policy scenarios to see the effect on the economic sectors in each region and change in trade flows between them. Models of this type are particularly useful for assessing carbon leakage, as their central mechanisms evolve around relative costs and prices and how these are affected by national climate policies.

Peters et al. (2011) used the Global Trade Analysis Project (GTAP) database CGE model to analyse emission transfers via international trade from 1990 to 2008. They found that emissions from the production of traded goods increased from 20% of global emissions in 1990 to 26% in 2008, illustrating the importance of monitoring emission transfers in international trade. Other studies have attempted to directly assess the leakage rate under the Kyoto Protocol using a similar approach. Paltsev (2001) calculated this rate to be between 5% and 15%, depending upon assumptions in the GTAP-EG model, specifically the fossil fuel supply elasticity and the Armington elasticity of substitution between domestic and imported goods. Other models have produced similar ranges: 8% to 20% (Bernstein et al. 1999) and 2% to 21% (Burniaux and Martins 2000). However, another study found much higher levels of leakage, up to 130%, when fully modelling relocation effects (Babiker 2005). Although these studies were ex ante analyses of the potential for carbon leakage, they suggest that carbon leakage had the potential to be a non-trivial issue in reducing the effectiveness of the Kyoto Protocol.

## 3. Paris Agreement

### 3.1. Background and comparison with the Kyoto Protocol

On 12 December 2015, during the 21st Conference of Parties (COP21), the Paris Agreement was adopted by 196 states parties within the United Nations Framework Convention on Climate Change (UNFCCC). It became fully effective on 4 November 2016 after it was ratified by countries accounting for over 55% of global emissions. The primary goal of the agreement is “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (UNFCCC 2015). This was arguably the first truly global agreement on mitigating climate change, as unlike Kyoto there is no distinction made between developed and developing countries, and covers almost all global emissions. There is, however, still a principle of “common but differentiated responsibility and respective capabilities”, which may put greater expectations on developed countries to reduce their emissions. As of May 2020, eight parties had still not ratified the agreement, including the significant emitters Iran and Turkey.

The Paris Agreement takes a ‘bottom-up approach’ to reducing emissions, through countries making voluntary commitments in the form of Nationally Determined Contributions (NDCs). This contrasts with the Kyoto Protocol’s ‘top-down approach’ of setting the emission reduction targets of 5% below 1990 levels during the first commitment period. The NDCs are subject to regular review and updated every five years, with the first round of NDCs typically setting emission targets until 2030. Unlike Kyoto, the commitments are not legally binding and there is no direct enforcement mechanism. The agreement instead relies on a system of ‘pledge and review’ to hold countries to accountable for their promises (Jacquet and Jamieson 2016). The initial round of NDC commitments has already come under strong criticism for being insufficient at meeting the overall goals of the agreement, with studies suggesting they would result in a temperature rise of 2.6-3.1°C (Rogelj et al. 2016, Höhne et al 2017, Schleussner et al. 2016). There has also been criticism that countries may fail to meet the pledges they have made, with all major industrialised currently falling short of their targets (Victor et al. 2017). There is currently an ‘implementation gap’ of countries failing to meet their pledges of 7.7GtC$0_2$e (Roelfsema et al. 2020). On top of this, the US withdrawal from the Paris Agreement under

Trump showed potential to further undermine its efficacy (Zhang et al. 2017). While Biden has indicated re-entry, his political majority in Congress (notably the Senate) is fragile and may turn into a minority during his term. This underpins the critical role which the USA plays in safeguarding the climate, and for this reason we devote specific attention to scenarios with and without it.

### 3.2. Potential for carbon leakage

The potential for carbon leakage in the Kyoto Protocol was clear. Countries were divided into abating and non-abating countries, making emission transfers across the borders very likely. In the Paris Agreement process, 165 Intended Nationally Determined Contributions (INDCs) were submitted, covering 192 countries, as the EU submitted a joint INDC for its 28 member countries. Many countries submitted both unconditional and conditional commitments. The conditional pledges are more ambitious than the unconditional pledges, but dependent on certain external stipulations, such as the access to international finance. The majority of the INDCs have now been converted to NDCs by the countries formally joining the Paris Agreement by submitting an instrument of ratification, acceptance, approval or accession. The INDCs cover 96.4% of global emissions (World Resources Institute 2019), and include major emitters such as China and India, which did not have emission targets in the Kyoto Protocol. Being inclusive of almost all nations, carbon leakage conceivably seems less of an issue under Paris than with Kyoto. However, there are several challenges which give high potential for carbon leakage under Paris.

Firstly, absent of any direct enforcement mechanism, countries are not legally bound to meet the emission targets set out in their NDCs. Other goals, such as economic growth and development, may have greater priority for some countries than reducing carbon emissions. Currently, only six of the G20 members are on track to meet their unconditional targets (den Elzen et al. 2019), which highlights how under the absence of strong enforcement, the emission goals are not yet a primary focus of major economies. Through the carbon leakage mechanisms, there may be opportunities for economic growth in carbon-intensive production, particularly in developing countries if others do successfully reduce emissions. Some countries may go for carbon-intensive growth regardless of their promises, as there is very little in the way of punishment for not meeting targets. If an important emitter decides to withdraw from the agreement, as the US did before subsequently re-joining, countries may be more reluctant to meet their targets at the detriment of economic growth opportunities. If the US had not reversed its decision to withdraw from the Agreement, it would likely have become a country where carbon leakage flows to.

Secondly, the NDC targets presented by countries varied considerably, with some countries producing much weaker targets than others. In an earlier study we grouped the pledges into four categories (King and van den Bergh 2019):

i) Absolute emission reduction targets relative to a historic base year,
ii) ‘Business as usual’ (BAU) reduction targets,
iii) Emission intensity per GDP reductions,
iv) Projects absent of GHG-emission targets

Of these, category ii, iii and iv pledges are more susceptible to carbon leakage. Category ii pledges were mainly submitted by developing countries, where some level of abatement takes place compared to no policies. Already these pledges predominantly convert into substantial growth in emissions by 2030. As these countries are already foreseeing growth in emissions, their policies will be weak, and it will be fairly easy to realise a little more growth in emissions.

Category iii pledges include the big emitters China and India, and in total cover 32% of global emissions, are also susceptible to leakage. As there is no fixed target on emissions, even if the GDP intensity target is met, emissions have the potential to rise further if GDP growth is at a greater rate than projected. There is little evidence that reducing carbon emissions is given priority in the current focus of China's economic planning, as also indicated by its energy policy still strongly favouring fossil fuels over renewables (Gosens and Jotzo 2020). Carbon leakage may actually stimulate further growth in GDP through increased exports and investment, which will be difficult to resist by these countries.

Category iv pledges, submitted by 45 countries, covering 7% of global emissions, are arguably the most susceptible to leakage. These countries did not present an explicit emission target, but instead listed intentions for various projects such as investment in renewable electricity. As they are not stating an emission target, there is little to prevent unrestrained growth in emissions through leakage, and they are not easily held accountable under the system of pledge and review.

Lastly, only 28% of all unconditional NDC pledges, resulted in emission reductions by 2030 relative to 2015 levels. The marginal abatement costs between countries also vary by two orders of magnitude (Aldy et al. 2016). This is significant as the relative strength of policies is an important factor in the carbon leakage mechanisms, as long as absolute emissions are not fixed by any climate policy. Although Paris was able to overcome one of the key weaknesses in the Kyoto Protocol by including almost all nations, the relative differences in policy strength amongst countries and lack of enforcement mechanisms mean carbon leakage is still likely. Hereon we quantitatively analyse this potential for carbon leakage under various scenarios using the GTAP-E general equilibrium model.

## 4. Methodology

### 4.1 Scenarios

To create a range of scenarios to analyse the potential for carbon leakage we take the previous study by King and van den Bergh (2019), which normalised the NDCs for all countries to show expected emission changes by 2030, as a starting point. It calculated countries' emission changes for both the conditional and unconditional pledges relative to 2015 emission levels. For the purpose of this analysis, we assume that all the conditions will be met, and thus use the expected emission changes of the conditional pledges. Our scenarios therefore represent a somewhat optimistic interpretation of the pledges, as there is little evidence yet that they will all be met. We re-perform the normalisation to change the base year to 2014, to be consistent with the data year we use for our analysis in the GTAP-E model. The use of a 2014 base year is not ideal, as it predates the date of the NDC submissions. However, it is used to be consistent with the GTAP version 10 database, which has 2014 as its most recent year of data. It should therefore be kept in mind when interpreting the results that due to the limitations of the database, the analysis is estimating effects if the policies had been applied to a historical snapshot of the economy. The results are supplied in Online Appendix 1.

Countries can be divided into two groups; a ‘leakage from’ region that is using serious climate policy to reduce emissions, and a ‘leakage to’ region, with weaker policies, in which will see a rise in emissions as a result of those policies in the first group. Effectively we are assuming that all countries in the ‘leakage to’ group have a zero-carbon price. This is consistent with the study by Fujimori et al. (2016) where these countries have carbon prices below zero. Aldy et al. (2016) however, find non-zero, but relatively small carbon prices, notably an average of $17 per tonne $CO_2$ for China. The ‘leakage from’ carbon prices will be computed by the GTAP-E model. When interpreting the results, it is important to consider the relative difference in carbon prices to determine if the approach may be over or under estimating leakage levels. To account for how much the Paris Agreement reduces leakage potential through being a collective agreement, we also include two scenarios of regions implementing climate policy in isolation to the rest of the World. Using this framework, we have developed the following six scenarios:

*Scenario 1: Net abating countries (NAB)*

In the previous study by King and van den Bergh (2019), 74 of the 168 conditional pledges result in net emission reductions by 2030. The remaining countries have climate change policies that are inadequate at producing a net abatement of emissions. These countries are therefore more likely to be susceptible to inwards emission transfers as they are already willing to accept growth in emissions. We therefore divide the countries into two regions: abating and non-abating countries. Both the abating and non-abating regions comprise of a mixture of the four different NDC categories, so the NDC category itself is not directly relevant in defining the regions under this scenario. The ‘leakage from’ region for this scenario instead consists of the net abaters in our normalisation provided in Online Appendix 1. This produces a ‘leakage from’ region that accounts for 37.7% of global emission in 2014.

*Scenario 2: Net abating countries minus the US (NAB-US)*

In this scenario we explore the potential impact on carbon leakage rates of a US withdrawal from the Paris Agreement, still not unlikely given the fragile majority of the Democrats in the Senate. The US therefore moves from the abating to the non-abating region while all other countries remain the same. This reduces the share of global 2014 emissions for the ‘leakage from’ region to 24.2%.

*Scenario 3: Category i abating countries (CIAB)*

In this scenario we take a stricter variation of the NAB by assuming that only category i countries in King and van den Bergh (2019), targeting a net reduction in emissions by 2030, will be in the ‘leakage from’ group. All category ii, iii and iv countries, and those category i countries such as Russia which are not targeting a net reduction in emissions, will therefore be susceptible to receiving carbon leakage. In effect, the ‘leakage from group’ is very similar to the Kyoto Annex i countries, with the notable inclusion of Brazil and Kazakhstan, but exclusion of Russia and Ukraine. This adapted category i accounted for 31.6% of global emissions in 2014.

*Scenario 4: Category i abating countries minus the US (CIAB-US)*

As with scenarios NAB-US, in this scenario we explore the impact of a US withdrawal from the Paris Agreement. The US is moved to the ‘leakage to’ category in this scenario to explore the impact of the US withdrawing from the Paris Agreement. This reduces the emissions in the ‘leakage from’ group to 18% of global emissions in 2014.

*Scenario 5: EU only abating (EUAB)*

The previous scenarios look to analyse the effect of the Paris Agreement as a global, cohesive agreement. To assess the benefit of this collective action, we also want to analyse the carbon leakage effects of regions acting independently. This could also be interpreted as a situation where these regions have much more stringent policy than the rest of the World. Given its high ambition level and size, in this scenario we consider the case of only the European Union reducing emissions, which accounted for 7.9% of emissions in 2014.

*Scenario 6: Japan only abating (JAPAB)*

Here, we take an even more extreme example of the EUAB scenario above, with a single country attempting climate policy independently. Japan was chosen in particular due to its NDC pledge being the most ambitious single country in terms of net abatement of emissions, excluding the US. The NDC results in a 343MtC02e reduction in emissions from 2014 to 2030.

### 4.2 Calculation of abatement rates

The level of abatement of carbon emissions for each scenario is calculated by comparing the NDC pledges to a base year of 2014, following the same methodology in King and van den Bergh (2019). This abatement rate is derived using a separate method for each of the four NDC categories. The dataset used for historical greenhouse gas emissions is The PRIMAP database (Gütschow *et al* 2018). Category i abatement levels are calculated by projecting the emissions to 2030, and re-normalising the percentage reduction to a consistent base year of 2014. For category ii pledges we take the projected 2030 emissions, calculated from the reduction against the 2030 BAU submissions, and then compute the percentage change relative to actual 2014 emission levels. Category iii abatement rates are combined with OECD (2018) long-term GDP forecasts to calculate the expected 2030 emissions. As Category iv submissions had no defined level of 2014 emissions in their NDCs for 2030, emissions are assessed by extrapolating the trends of emissions between 2005 and 2014. This involves applying an exponential smoothing method, which forecasts time series data with greater weight given to most recent data. Libya, Nicaragua and Syria did not submit NDCs, so the same methodology as category iv is applied to the these countries.

The anticipated abatement rates, or increase in emissions, relative to 2014 levels for all countries are detailed in Online Appendix 1. As previously mentioned, we assume that all conditions of the NDCs are fulfilled and thus use the conditional NDC targets rather than the unconditional targets. In the cases that Land Use Land Use Change and Forestry (LULUCF) were excluded from the NDCs, the projected emissions associated with these were added using the exponential smoothing method

To run the analysis through the GTAP software, we need to aggregate individual countries into broader regions. In order to use the GTAP model to assess the carbon leakage it requires as an input the specific abatement rate for the 'leakage from' region. To calculate this, we divide a weighted average of the 2030 NDC emissions by a weighted average of the 2014 emissions. This is illustrated in Equation 1:

$$A_r = \frac{\sum_{i=1}^{n} w_i^{NDC} s_i^{NDC}}{\sum_{i=1}^{n} w_i^{t} s_i^{t}} \qquad (1)$$

Where $A_r$ = abatement rate of region *r, w*$_i$ = emissions of country *i, and s*$_i$ = share of emissions of country *i* in region *r* under the projections *NDC* (King and van den Bergh 2019) and at base year *t* (2014 in our analysis).

Using these abatement rates for the 'leakage from' regions as an input, the GTAP-E model will calculate the emissions for the 'leakage to' regions. In other words, these emission levels are endogenous variables in the model.

Table 1 presents the calculated overall abatement rates for the 'leakage from' region under the four scenarios. The abatement rates range from 13.6% in scenario EUAB to 25.4% in scenario JAPAB. The differences in rates between scenarios are due to there being different combinations of countries forming the 'leakage from' region. The abatement rates are significantly lower in scenarios NAB-US and CIAB-US, compared to scenarios NAB and CIAB, as the US has a high abatement rate and a large weight in the share of emissions. The rate for the CIAB scenario is smaller than that for NAB, as it is a more selective set of countries, namely those that are amongst the most ambitious ones in terms of percentage reduction in emissions.

**Table 1:** Abatement rates for the four scenarios

| Scenario | 'Leakage from' region | | | | |
|---|---|---|---|---|---|
| | 2014 emissions ($GTCO_2e$) | % global 2014 emissions | Conditional NDC 2030 emissions ($GTCO_2e$) | Potential abatement by 2030 ($GTCO_2e$) | Abatement rate |
| **NAB** | 18.2 | 37.7% | 14.0 | 4.2 | 22.8% |
| **NAB-US** | 11.5 | 24.2% | 9.6 | 2.0 | 17.0% |
| **CIAB** | 15.6 | 31.6% | 11.9 | 3.7 | 23.9% |
| **CIAB-US** | 8.9 | 18.0% | 7.4 | 1.5 | 17.3% |
| **EUAB** | 3.9 | 7.9% | 3.4 | 0.5 | 13.6% |
| **JAPAB** | 1.4 | 2.6% | 1.0 | 0.3 | 25.4% |

### 4.3 GTAP-E Model

The four scenarios outlined in Section 4.1 are analysed using the GTAP-E CGE model, which is a multi-region, multi-sector model of the global economy using the latest GTAP 10 database depicting the global economy in 2014. The GTAP-E model is a modified version of the standard GTAP model, to incorporate inter-fuel and energy-capital substitution in production, carbon emissions from the combustion of fossil fuels, carbon taxation and emissions trading (Truong & Burniaux 2007). This provides a more complete representation of energy-environmental-economy linkages than the standard GTAP model. Although the GTAP-E model allows for emission trading between countries, we decided to deactivate this mechanism, as the Paris Agreement does not specify any emission trading instruments in its current form. The EU Emission Trading Scheme is the only active multi-national greenhouse gas emission trading system, but since the EU is treated as a single unit in our analysis, we are unable to model intra-region trading[1].

The GTAP-E model modifies the standard GTAP production structure to incorporate a capital-energy composite, which comprises 'electricity' and 'non-electricity' groups. The 'non-electricity' group covers Coal, Gas, Oil and Petroleum Products. On the consumption side, the GTAP model assumes a separation of government and private consumption. For both types of consumption, energy commodities are separated from non-energy commodities, to allow for different substitution elasticities within, and between, the two sub-groups. Goods are aggregated into eight sectors: agriculture, coal, oil, gas, oil products, electricity, energy intensive industries and other industry and services. Online Appendix 2 provides the disaggregation of these sectors.

The model is adapted to group countries into two regions; namely the 'leakage from' and 'leakage to' region. The composition of countries in each region for the four scenarios was

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[1] As of 1 January 2020 the Emission Trading Scheme also incudes Switzerland, but this is not included in the analysis as Switzerland is not treated as an individual region. The impact would anyway not be large enough to significantly influence the results.

already explained in Section 4.1. To analyse the scenarios, the model is run with a percentage reduction shock to $CO_2$ emissions equivalent to the abatement in Table 1.

### 4.4. Regions

The GTAP 10 database which is used in the analysis divides the data into 141 regions. Of these, 121 are individual countries comprising 98% of global GDP, with the other countries falling into a further 20 aggregate regions. For this analysis we use the eight countries/regions with 2014 emissions above 1Gt$CO_2$e (China, USA, EU, India, Indonesia, Russia, Brazil and Japan) as individual regions, with two more regions aggregating the remaining ‘leakage from’ and ‘leakage to’ countries. Table 2 shows the regional aggregation within each of the four scenarios.

**Table 2: Regional aggregation of six scenarios**

| Scenario | ‘Leakage from’ regions | ‘Leakage to’ regions |
|---|---|---|
| NAB | USA, EU, Brazil, Japan, ‘Other Abaters’ | China, India, Indonesia, Russia, ‘Other Non-Abaters’* |
| NAB-US | EU, Brazil, Japan, ‘Other Abaters’ | China, USA, India, Indonesia, Russia, ‘Other Non-Abaters’* |
| CIAB | USA, EU, Brazil, Japan, ‘Other Category i Abaters’ | China, India, Indonesia, Russia, ‘Other non-Abaters’* |
| CIAB-US | EU, Brazil, Japan, ‘Other Category i Abaters’ | China, USA, India, Indonesia, Russia, ‘Other Non-Abaters’* |
| EUAB | EU | China, USA, India, Indonesia, Russia, Brazil, Japan, ‘Other Non-Abaters’* |
| JAPAB | Japan | China, USA, EU, India, Indonesia, Russia, Brazil ‘Other non-Abaters’* |

*Note:* * The ‘Other Non-Abater’ group consists of different countries depending on the scenario

One complication when making this aggregation is that some of the 20 aggregate regions in the GTAP 10 database contain countries that split across the ‘leakage from’ and ‘leakage to’ regions for the purposes of our analysis. For example, the “South Central Africa” region comprises of Angola (in the ‘abater’ category) and Democratic Republic of the Congo (in the ‘non-abater’ category). In these cases, we calculate the total 2014 emissions which fall into each category, and then allocate the aggregate region to which category has the greater emissions. For example, the “South Central Africa” region is allocated to our “Other Non-Abaters” region as the emissions of Democratic Republic of Congo (241 Mt$CO_2$e) were greater than Angola’s (52 Mt$CO_2$e). Although this reallocation of countries is not desirable, it is a way of working around the limitations of the database. This should have an insignificant impact on the results since the countries reallocated in scenario NAB, for example, amount to less than 1% of 2014 global emissions. The breakdown of all regional allocations for the NAB and CIAB scenarios is detailed in Online Appendices 3 and 4.

### 4.5. Scenario shocks

Using equation 1 in Section 4.2, we first calculate the abatement rates for the regions in the different scenarios. This is a weighted average of the abatement rates for countries as shown in Online Appendix 1. We then take these abatement rates for the 'leakage from' regions and run them as a scenario shock through the GTAP-E model for the six scenarios, as specified in Table 3. The GTAP-E model then generates a new equilibrium of the world economy including energy substitution effects. Each of the abating regions will have an individual carbon price corresponding to the level of abatement they are trying to achieve. Along with this, the GTAP model generates the $CO_2$ emissions for the 'leakage to' regions.

**Table 3: Scenario shocks in GTAP**

| **Region** | **% reduction in emissions from 2014** | | | | | |
|---|---|---|---|---|---|---|
| | **NAB** | **NAB-US** | **CIAB** | **CIAB-US** | **EUAB** | **JAPAB** |
| US | 32.8 | 0 | 32.8 | 0 | 0 | 0 |
| EU | 13.6 | 13.6 | 13.6 | 13.6 | 13.6 | 0 |
| Brazil | 8.3 | 8.3 | 8.3 | 8.3 | 0 | 0 |
| Japan | 25.4 | 25.4 | 25.4 | 25.4 | 0 | 25.4 |
| Other abaters | 19.9 | 19.9 | 24.2 | 24.2 | N/A | N/A |
| China | 0 | 0 | 0 | 0 | 0 | 0 |
| India | 0 | 0 | 0 | 0 | 0 | 0 |
| Russia | 0 | 0 | 0 | 0 | 0 | 0 |
| Indonesia | 0 | 0 | 0 | 0 | 0 | 0 |
| Other non-abaters | 0 | 0 | 0 | 0 | 0 | 0 |

### 4.6 Sensitivity analysis

General equilibrium models are imperfect approximations of the global economy, among others, as the results are dependent on the parameters underlying the models. It is therefore important to perform a sensitivity analysis around key parameters to see how my they influence the results. Paltsev (2001) found that the Armington elasticity, which specifies the degree of substitution in demand between countries, was an important factor in determining the level of leakage from the Kyoto Protocol. Leakage rates ranged between 6.9% and 15.4% depending on the Armington elasticities used. The Armington elasticity is a key parameter in trade economics analysis, however its size remains an area of much debate (Feenstra et al. 2018, McDaniel et al. 2003).

There are also other elasticities in the GTAP-E which are likely to significantly influence the results. Online Appendix 5, taken from Burniaux and Troung (2002), shows the GTAP-E Production function and Capital-Energy composite structure, which is what differentiates it from the standard GTAP model. There are four important elasticities of substitution in the structure; between capital and energy, between electricity and non-electricity energy, between coal and non-coal energy, and between gas, oil and petroleum products. In view of this, we perform a sensitivity analysis of the results by adjusting both elasticities of substitution and the Armington elasticities to establish a range of leakage rates. This produces three sets of results with default, low and high GTAP-E parameter values; involving reducing the default parameters by 50% and increasing them by 100%. Full details about the parameter values used for distinct sectors are available in Online Appendix 6.

## 5. Results

The model output using default parameters for scenarios NAB and NAB-US is provided in Online Appendix 7, for scenarios CIAB and CIAB-US in Online Appendix 8, and for scenarios EUAB and JAPAB in Online Appendix 9. From these we have been able to calculate the carbon leakage rate, which is the total emission increase in the 'leakage to' regions divided by the total emission reduction in the 'leakage from' regions. These are shown in Figure 1. In Table 4 we also provide the changes in emissions for each region under the six scenarios, using the default parameters. It should be noted that the emission increases given in Online Appendices 7, 8 and 9 do not represent the total expected increase in emissions as a result of the NDC pledges, but merely the potential carbon leakage effect. These increases are in addition to any increases in emissions already expected from the NDC, and hence would provide an additional challenge to staying within the 2°C above those commonly identified (Rogelj et al. 2016).

In all our scenarios, carbon leakage effects are observed, and follow patterns that we might expect. Scenarios EUAB and JAPAB, where we are analysing isolated climate policy, have high leakage rates of 13.6% and 17.0% respectively. The higher leakage rate of the JAPAB scenario is expected as it is one country in isolation rather than a region of countries as with the EU. We see a much lower rate of leakage with the co-ordinated Paris Agreement scenarios of NAB and CIAB, 3.8% and 3.1% respectively. These levels are comparable to the lower range of values analysed in previous studies of the Kyoto Protocol. The lower leakage rate of the CIAB scenario is perhaps counter-intuitive given the smaller number of countries in the 'leakage to' region compared to NAB, but may reflect the differences in geographic location and economic development between the scenarios. However, the leakage rates between CIAB and NAB are broadly similar. The main difference between the two scenarios concerns the less developed countries that are planning emission reductions but are instead allocated to the ‘leakage to’ region. This suggests that the more developed, primarily Annex I countries, are still the most influential when it comes to potential for leakage.

However, we see quite a dramatic effect on leakage rates as a result of a US withdrawal from its Paris Agreement obligations. In these scenarios the rate of leakage roughly doubles; to 6.61% in Scenario NAB-US and 7.62% in Scenario CIA-US. This clearly illustrates the importance that a major player in the global economy and source of greenhouse gas emissions, such as the US, can have on the effectiveness of climate policy in other countries.

The range in leakage rates in Figure 1 illustrates the results of the sensitivity analysis for the rates of climate leakage. It indicates that the rates of leakage are very sensitive to changes in the Armington and substitution elasticities. The rates of leakage roughly half using all “low” parameters simultaneously and roughly double using the “high” parameters simultaneously. The expected rate of leakage most likely falls within this range generated. However, as the magnitude of these elasticity parameters is debatable, there is quite a degree of uncertainty as to the extent of leakage we may see in the real-life implementation of the Paris Agreement.

**Table 4: Emission change per region with default parameters**

| **GTAP Region** | **Change in emissions ($MtCO_2$)** | | | | | |
|---|---|---|---|---|---|---|
| | **NAB** | **NAB-US** | **CIAB** | **CIAB-US** | **JAPAB** | **EUAB** |
| **US** | -1,695 | 2 | -1,695 | 1 | 5 | 7 |
| **EU** | -450 | -450 | -450 | -450 | 7 | -450 |
| **Brazil** | -37 | -37 | -37 | -37 | 1 | 1 |
| **Japan** | -263 | -263 | -263 | -263 | -263 | 3 |
| **Other Abaters** | -540 | -540 | -340 | -340 | N/A | N/A |
| **China** | 24 | 18 | 21 | 14 | 4 | 6 |
| **India** | 11 | 8 | 9 | 7 | 3 | 3 |
| **Russia** | 11 | 9 | 10 | 8 | 2 | 5 |
| **Indonesia** | 5 | 4 | 5 | 4 | 2 | 1 |
| **Other non-abaters** | 61 | 44 | 41 | 49 | 14 | 23 |
| **Global change** | -2,872 | -1,204 | -2,699 | -1,007 | -207 | -367 |

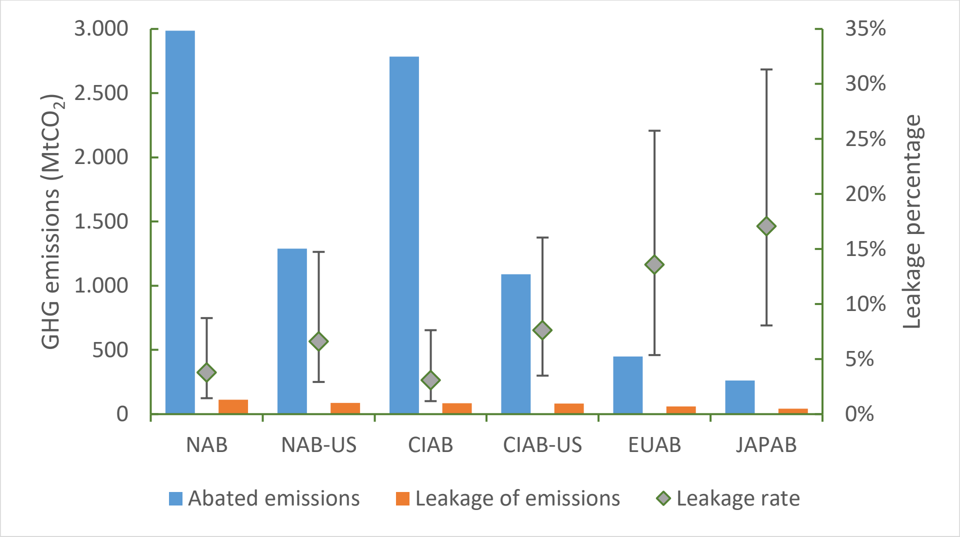

**Figure 1. Scenario leakage rates.** The range on the leakage rate values shows the distribution of results from the sensitivity analysis. The bars with leakage of emissions pertain to default parameters.

## 6. Discussion

Table 5 illustrates how the carbon leakage channels of changes in trade flows and relocation of industry appear as a result of our analysis of scenario NAB. We generally see trade moving from the abating countries to the non-abating, particularly for the US, with a $6bn reduction in their trade balance. However, Russia and India have a negative change in their trade balances due to reduced exports of fossil fuels. There is also a significant relocation of energy-intensive industry such as metal and chemical manufacture (explained fully in Online Appendix 2), from the abating to non-abating countries. For example, Japan's output from these industries reduces by 8.3% while Russia's increase by 4.6%. There is also a relocation of other industries and services, but at much lower rate than the energy-intensive industry.

**Table 5: Change in trade, industry output and carbon prices for scenario NAB**

| Region | Trade balance 2014 | Change in trade balance | % change in industry output | | Nominal carbon price |
|---|---|---|---|---|---|
| | (million USD) | (million USD) | Energy-intensive industry | Other industry and services | (USD per tonne of $CO_2$) |
| US | -10,220 | -5,986 | -0.60 | -0.22 | 60.2 |
| EU | 87,567 | +406 | -1.20 | -0.24 | 52.5 |
| Brazil | -11,090 | -485 | -0.80 | -0.19 | 41.5 |
| Japan | 28,421 | -164 | -8.32 | -0.86 | 141.8 |
| Other abaters | -23,240 | +681 | -1.77 | 0.07 | 45.3 |
| China | -26,848 | +4,326 | 0.69 | -0.05 | 0 |
| India | 2,099 | -814 | 1.50 | 0.06 | 0 |
| Russia | -14,634 | -975 | 4.60 | 0.11 | 0 |
| Indonesia | -11,405 | +128 | 1.93 | 0.19 | 0 |
| Other non-abaters | -20,651 | +2,884 | 2.88 | 0.17 | 0 |

Our analysis demonstrates that there is potential for significant carbon leakage effects, in line with the rates produced from studies on the Kyoto Protocol. This highlights several failures of the Paris Agreement that could likely lead it to be even less effective than envisioned. Firstly, we see the problem arising from a lack of enforcement mechanisms. Only six of the G20 members (den Elzen et al. 2019) are currently on track to meet their NDC pledge, and will face little in the way of repercussion if they fail to do so. Even if all countries do successfully implement the required policies to meet their goals, our analysis suggests that between 1.4% and 16.0% of abatement could be lost to leakage. However, the current sentiment towards protectionism and rise in trade restrictions, particularly in the form of non-tariff barriers, may make a low-Armington elasticity scenario more likely (Kinzius et al. 2019).

The scenarios we ran where the US withdraws from the Paris Agreement demonstrate the vulnerability of current framework. Under these scenarios, the rate of leakage roughly doubled as the US took advantage of the economic opportunities arising from policies in the abating countries. The non-compliance of such a significant party as the US could also cause other countries to relax their commitment to their NDC targets, particularly if they see the US outcompeting them economically as a result of the carbon policies.

Another way of looking at the challenge of carbon leakage is by examining the nominal carbon price produced by the model simulation in GTAP, which are shown in Table 5 for scenario NAB. These represent nominal carbon tax rates that the model computes as being equivalent to the emission reductions we inserted as a shock. Note that if global emissions were limited, such as by the cap in a global carbon market, then the resulting carbon price would be uniform globally. Since this is not the case in GTAP, we calculate prices for each country (block) which then reflect stringency of emissions reduction. There are notable differences between regions, ranging from \$41.5 per tonne of $CO_2$ in Brazil to \$141.8 in Japan, with the non-abating countries having zero carbon price. It could be argued that having no carbon price in the 'leakage' means the model is overestimating the level of leakage. However, a zero carbon price for the INDCs of these countries is in line with the study by Fujimori et al. (2016) and just below those in Aldy et al. (2016) where the average carbon price of China is $17 per tCO2e, and Russia and India are below $5 per tCO2e. Moreover, what mattes for a general equilibrium calculation is relative prices or price differences, not absolute prices. Incidentally the carbon prices for the 'leakage from' countries are generally significantly below those in Aldy et al. (2016), which has an EU carbon price over 100$ per tCO2e. It is therefore equally arguable that our analysis is underestimating levels of carbon leakage. This is undoubtedly an area that requires further analysis, however our results here open up the conversation that carbon leakage may continue to persist under the Paris regime.

As with any tax, a difference between countries will create economic opportunities in the lower tax regime and make their goods more internationally competitive. This highlights another failure of the Paris Agreement. Although it was able to get almost all countries onboard, it failed to get them to move towards a global carbon price, i.e. consistent among all countries. This would effectively limit carbon leakage effects and other systemic issues, which undercut policy effectiveness (Baranzini et al. 2017).

## 7. Conclusion

The Paris Agreement was undoubtedly a step in the right direction regarding global efforts to limit the extent of climate change. It improved on the Kyoto Protocol by getting almost all nations into an agreement on reducing or curbing emissions. However, it has some inherit weaknesses which ultimately challenge its effectiveness. Other studies have already shown that current pledges are insufficient to stay within the range of 1.5°C to 2°C average temperature rise, and need a significant increase in future ambition to achieve this. Asymmetries have been created through the freedom given to countries to design pledges in the format and to the level of their choosing. On top of this there are no enforcement mechanisms to make countries stick to their pledges. And arguably the most important deficiency is that the Paris agreement was unable to coordinate policies. Carbon leakage pressure may therefore become a factor in countries failing to meet their Paris pledges.

To analyse the degree to which not having fully co-ordinated policies could produce carbon leakage in the Paris Agreement, we used the GTAP-E general equilibrium model to assess the impact of climate policy on the global economy. Six scenarios were analysed: two baseline scenarios of regions implementing policy in isolation (JAPAB and EUAB), two scenarios representing collective but unharmonized Paris Agreement policies (NAB and CIAB), and two further scenarios showing the impact of the US withdrawal from the Agreement (NAB-US and CIAB-US). A sensitivity analysis was performed on key parameters to produce a range of potential leakage rates for each scenario.

The results of our analysis were very sensitive to the adjustments in parameters, creating a wide range of results for the rate of leakage. Our baseline scenarios of regions implementing policy in isolation produced high levels of leakage. For the JAPAB scenario the leakage was between 8.1% to 31.3% (16.1% with default parameters). The NAB and CIAB scenarios produced significantly lower levels of leakage between 1.4% and 8.7% (respectively 3.8% and 3.1% with default parameters), showing the benefit of some degree of global policy co-ordination. However, leakage still remains a potential issue, and a US withdrawal from the agreement would roughly double its rate to between 2.9% and 16.0% depending on parameters used. This would be a doubly-bad scenario as we would suffer from both missing out on the planned emission reductions of the US, and increased levels of leakage.

Our conclusions support a call to revisit aspects of the Paris Agreement to produce more greater policy coordination and enforcement, notably through a global carbon price, if we want to increase the chance of controlling climate change. In addition, one may think of anti-leakage policies, such as border carbon tariffs, but only as a short-term solution to stimulate a process towards harmonization in the longer run (Al Khourdajie and Finus 2020, Fischer et al. 2012, Fowlie 2009). However, our analysis supports the continued focus on such policies as being important post-Paris, since leakage is still a relevant concern. Having a globally co-ordinated climate policy rather than mere national targets has the potential to significantly reduce rates of carbon leakage.

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## Declarations

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### Conflicts of interest/Competing interests

No conflicts of interest

### Availability of data and material

Availability of data and material

### Code availability

Not applicable