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The economic and environmental benefits from international co-ordination on carbon pricing: Insights from economic modelling studies

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The economic and environmental benefits from international co-ordination on carbon pricing: Insights from economic modelling studies

Environment Working Paper No. 173

By Daniel Nachtigall and Jane Ellis *(1)*

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Abstract

This paper assesses quantitative estimates based on economic modelling studies of the economic and environmental benefits from different forms of international co-ordination on carbon pricing. Forms of international co-ordination include: harmonising carbon prices (e.g. through linking carbon markets), extending the coverage of pricing schemes, phasing out fossil fuel subsidies, developing international sectoral agreements, and establishing co-ordination mechanisms to mitigate carbon leakage. All forms of international co-operation on carbon pricing can deliver benefits, both economic (e.g. lower mitigation costs) and/or environmental (e.g. reducing GHG emissions and carbon leakage). Benefits tend to be higher with broader participation of countries, broader coverage of emissions and sectors and more ambitious policy goals. Most, but not all, countries gain economic benefits from international co-operation, and these benefits vary significantly across countries and regions. Complementary measures outside co-operation on carbon pricing (e.g. technology transfers) could ensure that co-operation provides economic benefits for all countries.

Keywords: International Co-operation, Climate change mitigation, Harmonising carbon prices, Fossil fuel subsidy reforms, Border carbon adjustment, Sectoral agreements, Climate-economy-modelling

JEL Codes: F18, H23, Q54, Q56, Q58

Résumé

Le présent document analyse des estimations quantitatives fondées sur des études menées pour modéliser les avantages économiques et environnementaux de différentes formes de coordination internationale en matière de tarification du carbone. Ces pratiques concertées sont notamment les suivantes : l'harmonisation des prix du carbone (par exemple, à travers le couplage des marchés), l'extension du champ d'application des dispositifs de tarification, l'élimination progressive des subventions aux combustibles fossiles, l'élaboration d'accords sectoriels internationaux et la mise en place de mécanismes de coordination visant à limiter les délocalisations de carbone. Toutes les formes de coopération internationale en matière de tarification du carbone peuvent générer des retombées tant économiques (par exemple, réduction des coûts d'atténuation) qu'environnementales (par exemple, diminution des émissions de gaz à effet de serre et des délocalisations de carbone). En règle générale, les avantages se font d'autant plus sentir que les pays sont nombreux à participer, qu'il y a davantage de types d'émissions et de secteurs pris en compte et que les objectifs des politiques sont ambitieux. La plupart des pays tirent des gains économiques de la coopération internationale, mais pas tous, et ces gains varient considérablement d'un pays ou d'une région à l'autre. Pour que la coopération internationale en matière de tarification du carbone puisse profiter économiquement à tous les pays, il peut être judicieux de l'accompagner d'autres mesures (par exemple, les transferts de technologies).

Mots-clés: coopération internationale, atténuation du changement climatique, harmonisation des prix du carbone, réformes des subventions aux combustibles fossiles, ajustement carbone aux frontières, accords sectoriels, modélisation climatique et économique

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Executive summary

This paper assesses quantitative estimates of the economic and environmental benefits from different forms of international co-ordination on carbon pricing based on reviewing available economic modelling studies. Better awareness and understanding of these benefits could encourage governments to increase their ambition on climate action, and thus facilitate collective efforts to meet the goals of the Paris Agreement. Quantifying the benefits of international co-ordination on pricing of greenhouse gas (GHG) emissions, including carbon dioxide (CO_2) and the distribution of these benefits across country groupings can help policy makers make better-informed decisions about the implications and potential forms of international co-ordination.

Forms of international co-ordination include: harmonising carbon prices (e.g. through linking carbon markets), extending the coverage of pricing schemes, phasing out fossil fuel subsidies, developing international sectoral agreements, and establishing co-ordination mechanisms to mitigate carbon leakage. In practice, implementing co-ordination mechanisms would require high levels of trust between the participating jurisdictions, and could involve political, practical or legal challenges, which may impede co-ordination. These issues are out of the scope of this current analysis.

All forms of international co-operation on carbon pricing can deliver benefits, both economic (e.g. lower mitigation costs) and environmental (e.g. reducing GHG emissions and carbon leakage). Benefits tend to be higher with broader participation of countries, broader coverage of emissions and sectors and more ambitious policy goals (e.g. with emission reduction targets that align with the temperature goals of the Paris Agreement).

The economic benefits of international co-operation vary across countries and regions. For most countries, co-operation would result in lower mitigation costs (for international carbon markets) or reduced energy prices (for multilateral fossil fuel subsidy (FFS) removal). Some forms of co-operation would be unambiguously beneficial for all co-operating countries (e.g. extending the coverage of pricing schemes towards non-CO_2 GHGs, linkages between countries with relatively similar mitigation ambition and abatement costs). Other forms of co-operation (e.g. multilateral FFS removal, international carbon markets) would not necessarily generate direct economic benefits for all countries, posing challenges to regional or global co-operation mechanisms. If indirect benefits (e.g. better health due to reduced air pollution) are accounted for, however, all countries benefit from co-operation.

Complementary measures to international co-operation could also ensure that co-operation provides economic benefits for all countries. However, establishing how to do this in practice may be politically challenging. Possible measures include redistributing the economic savings from co-operation across countries (e.g. via direct monetary transfers or technology transfers) or using a mix of international co-ordination mechanisms simultaneously. Alternatively, reinvesting the economic gains from co-operation into raised climate ambition would reduce long-term climate risks for all countries.

Harmonising carbon prices both globally and regionally can deliver substantial economic benefits. Country-specific shadow carbon prices (i.e. prices necessary to meet specific mitigation targets) vary substantially across countries and regions, highlighting large potential for cost savings from harmonising carbon prices. Using carbon markets to help countries meet the mitigation goals in their initial Nationally Determined Contributions (NDCs) with a uniform global carbon price has the potential to reduce global mitigation costs by between 58 and 63% compared to countries meeting these targets unilaterally. The absolute global gains are higher for more ambitious mitigation targets. Gains from sub-global emissions trading (e.g. through linking carbon markets) also brings benefits, albeit to a lower extent than global co-operation. While most developed countries/regions (e.g. Japan,

EU, USA) would gain direct economic benefits from global or regional emissions trading, emerging economies (notably China) would not always benefit directly compared to unilateral achievement of mitigation targets even after accounting for the revenues from selling allowances. China would face a rise in domestic carbon prices under linked markets, which could negatively affect its international competitiveness *vis-à-vis* more developed and less carbon-intense economies. Accounting for indirect benefits (e.g. health benefits, reduced climate damages) or complementing carbon markets (e.g. through financial or technology transfers) could make international emissions trading beneficial for all countries.

Harmonising carbon prices through international emissions trading between developed and developing countries could be designed to have a progressive impact on the income distribution in both groups of countries. Emissions trading would lead to reduced carbon prices in developed countries and to increased carbon prices in developing countries. As carbon pricing without specific revenue recycling schemes tends to be regressive in developed countries but is potentially progressive in developing countries, emissions trading could be progressive in both country groups. However, the actual impact will vary depending on the design of any revenue recycling schemes.

Extending the coverage (sectors and/or gases) of carbon pricing schemes would deliver economic and environmental benefits, enabling countries to tap diverse sources of low-cost abatement options. International co-operation on reducing emissions in the power sector is generally estimated to have the largest potential for saving mitigation costs. Extending the coverage of carbon pricing beyond the power sector (e.g. to transport or industry) would further reduce aggregate mitigation costs, albeit to a lower extent. Extending the coverage of pricing schemes to non-CO_2 GHGs could lead to average cost savings of up to 50% compared to scenarios covering only CO_2 emissions. However, results are sensitive to the properties of GHGs, notably the atmospheric lifetime. Sectoral agreements could potentially reduce sector-specific GHG emissions, reduce mitigation costs and competitiveness concerns, though the evidence is scarce.

A global phase out of fossil fuel subsidies (FFS) would reduce global CO_2 emissions compared to a business-as-usual (BAU) scenario, but may increase CO_2 emissions in some countries. Global FFS removal by 2030 would reduce net global CO_2 emissions by 1-4% by 2030 compared to BAU. Phasing out FFS would increase domestic energy prices, reducing energy demand and emissions in the reforming countries. However, lower domestic demand would dampen global energy prices, leading to increasing energy demand and emissions abroad (carbon leakage). Compared to BAU, multilateral FFS reforms would bring direct economic benefits to most countries (including those who have not reformed), notably energy-importing countries. However, multilateral FFS would not be beneficial for some energy-exporting economies due to the decreased value of exports as a result of lower global energy prices.

Co-ordination mechanisms to mitigate carbon leakage (e.g. in form of a climate coalition or carbon club) would reduce the risk of carbon leakage associated with carbon price differentials across regions. Increasing the size of the carbon pricing coalition, extending the coverage of carbon pricing to more GHGs as well as harmonising the carbon price within the coalition would reduce carbon leakage. In the absence of broad multilateral agreements or co-ordinated efforts to reduce leakage, specific policy instruments, including border carbon adjustments (BCA), carbon tax exemptions, or allocation of free allowances could reduce the risk of carbon leakage. Among those, BCA would be most effective. Yet, no instrument would be able to eliminate leakage entirely. BCA could bring economic benefits for coalition countries, but would transfer part of the cost of the mitigation effort to non-coalition countries whose exports essentially become taxed. Given the distributional implications, BCA could, in theory, provide incentives for non-coalition countries to join a climate coalition, but BCA's potential for doing so would be limited.

1 Introduction

Global climate action needs to increase substantially to limit global warming 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[1]). Limiting global temperature increase to 1.5°C rather than 2°C would involve higher economic costs, requiring early and strong climate action, but would bring substantial global benefits, including decreased damages and more adaption time for vulnerable ecosystems such as coral reefs (IPCC, 2018[2]). Yet, the aggregate emission reductions associated with countries' first unconditional Nationally Determined Contributions (NDCs[1]) are insufficient to meet even the 'well-below 2°C' target – and indeed would imply only a 66% chance to limit warming to 3.2°C by the end of the century (UNEP, 2019[3]).

Carbon pricing, through emissions trading schemes (ETS) or taxes, is a key element of an economically-efficient climate strategy. Pricing carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions incentivises private and public actors to reduce emissions cost-effectively while spurring innovation into zero-carbon technologies.[2] Carbon pricing has also important synergies with broader well-being goals, enhancing public health through lower levels of air pollution while generating revenues that allow for increase in public investments or reducing distortionary taxes (OECD, 2019[4]) (OECD, 2019[5]). Yet, carbon pricing alone is not sufficient to trigger the scale and speed of the economic transformations needed to reach the temperature goals of the Paris Agreement, but need to be accompanied by complementary measures (innovation, urban planning, investment in public transport infrastructure) (Tvinnereim and Mehling, 2018[6]). These complementary measures can reduce potential negative impacts of carbon pricing and increase carbon pricing's elasticity of demand, making carbon pricing more acceptable, feasible and effective (OECD, 2019[4]).

The extent of carbon pricing is increasing - however, progress remains slow. While the number of national and sub-national carbon pricing schemes has increased from 16 to 56 between 2009 and 2019 (World Bank Group, 2019[7]), 46% of energy-related CO_2 emissions in OECD and G20 countries do not face a carbon price (OECD, 2018[8]). Indeed, 88% of emissions in the same countries are priced below EUR 30 per ton of CO_2 – a low-end estimate for carbon prices necessary by 2020 to be in line with meeting the goals of the Paris Agreement (OECD, 2018[8]).

International co-operation on climate mitigation, including but not limited to carbon pricing, can enhance global ambition on climate mitigation as it brings mutual benefits to the countries involved. These benefits include direct economic benefits (e.g. lower mitigation costs, reduced competitiveness concerns), environmental benefits (e.g. reduced emissions of GHG and local air pollutants) and political benefits (e.g. signalling commitment to climate mitigation to domestic and foreign stakeholders) (Nachtigall, 2019[9]). Combining these benefits – for example reinvesting some of the savings in mitigation costs into additional mitigation or energy efficiency measures - could enhance global mitigation ambition, bringing countries' mitigation targets closer to the emission levels needed in order to meet the temperature goals in the Paris Agreement. Policy makers need to have a good understanding of the extent of the benefits from carbon pricing, as well as the distribution of these

[1] All mention of NDCs in this paper refer to countries' first NDCs.

[2] In this document, the term carbon pricing refers to put a price on CO_2 and other GHG emissions.

benefits (both within and between countries) in order to make better-informed decisions about the forms of international co-operation on carbon pricing.

This paper synthesises existing estimates of the economic and environmental benefits of different forms of international co-operation based on 59 economic papers of the economic modelling literature from the last 10 years or so (Table 1.1). The paper discusses each of these forms in turn. This literature uses economic modelling techniques, including integrated assessment models (IAMs) and computable general equilibrium (CGE) models to quantify the socio-economic and/or environmental effects of climate policies. Some of the studies covered in this report were published up to 10 years ago, meaning that mitigation targets (e.g. Kyoto, Copenhagen) or level of carbon prices (e.g. permit prices for EU ETS in phase II) are outdated. Despite this, most of the qualitative results of these studies are still relevant for current policy implications. For the sake of brevity, this paper only focusses on the quantitative results of these studies, without discussing the challenges that each of the proposed types of co-ordination could face. These challenges can be political (e.g. domestic barriers to carbon pricing and fossil fuel subsidy reforms; international burden sharing rules), practical (e.g. measuring emissions for different sectors) or legal (e.g. compatibility with international trade laws). These challenges may impede implementation of carbon pricing and are not further discussed here.

Table 1.1. Studies included in this paper: Number of studies and publication year of latest study

Section	Name	Number of studies	Publication year of latest study
2	Benefits of harmonising carbon prices	31	2019
2.1	Global co-operation	9	2019
2.2	Regional co-operation	13	2019
2.3	Distributional aspects	9	2020
3	Extending coverage of carbon pricing schemes	10	2020
3.1	Extending sectoral coverage	8	2020
3.2	Extending GHGs	2	2012
4	FFS reform	6	2018
5	International sectoral agreements	3	2018
6	International co-ordination on mitigating carbon leakage	9 (+25)[i]	2018
6.1	Environmental effects	6 (+25)[i]	2018
6.2	Economic effects	6 (+25)[i]	2018
6.3	Strategic incentives to join climate coalitions	3	2015
	Total	**59 (+25)[i]**	**2020**

Note: The (+25) refers to one meta study that summarises 25 previous studies.
Source: Authors.

The results reported in the literature do not capture all benefits associated with international co-operation, and thus need to be interpreted with caution. Some models (notably IAMs) assess the benefits associated with reduced long-term climate damages, but may not capture the full range of benefits, including a reduced risk (and cost) of health impacts, and of extreme events. If international co-operation leads to raised climate ambition through international action, this would reduce longer-term damages from climate impacts. Capturing the future benefits from raising ambition is less straightforward to quantify than estimating current, direct mitigation costs. It is also not straightforward to capture broader well-being benefits (e.g. reduced air pollution) that can be enabled through co-operation in carbon pricing. Similarly, the extent to which international co-operation can facilitate the implementation or the strengthening of carbon pricing in other jurisdictions is typically beyond the scope of the papers discussed here. Finally, while most models quantify the direct economic benefits, they do not fully capture long-term economic dynamics related to technological change. These dynamics are most pertinent in international emissions trading, which brings direct economic gains from trade for developed and emerging economies, but may also result in relatively low international carbon prices.

Low carbon prices in developed countries, however, may deter economic transformation and investments in innovation that would enable deep decarbonisation to reach net-zero emissions by mid-century.

Results for the same (climate) policy in the same country can vary significantly across studies, so the numbers from studies need to be treated carefully. For example, the shadow carbon price (i.e. the carbon price necessary to reach specific mitigation target) for Japan's NDC is estimated to vary between USD 6 and 378/tCO_2e depending on the study (Section 2.1). Reasons for this divergence are related to different assumptions on inputs and key model parameters (see Box 1.1 and 6.3.Annex A) for more information on how economic models work). While there is large uncertainty on exact model results (e.g. shadow carbon prices, savings in mitigation costs), the merit of using multiple economic models is that they deliver a range of possible outcomes for similar policy questions.

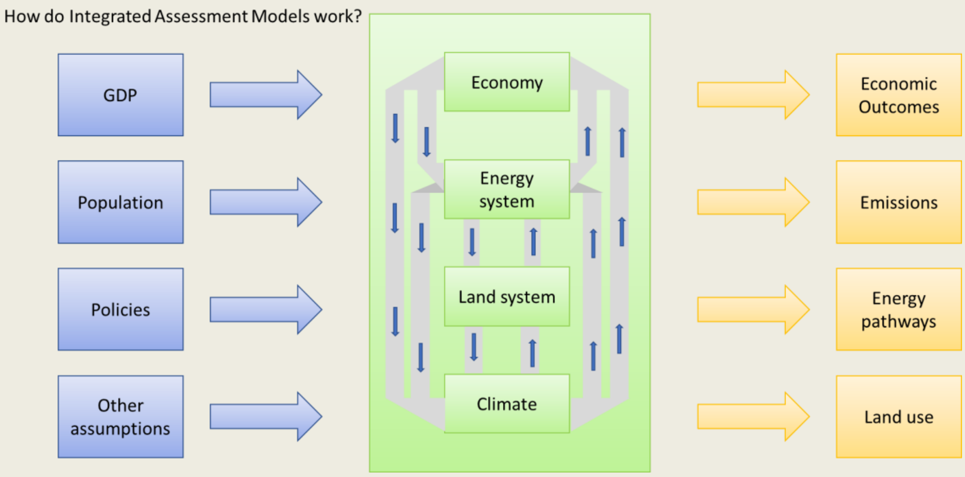
The overarching insights can be summarised as follows:

1. All forms of international co-operation can deliver benefits. The benefits from co-operation include direct economic benefits (e.g. lower mitigation costs) and/or environmental benefits (e.g. reducing GHG emissions and carbon leakage). Benefits tend to be higher with broader participation of countries, broader coverage of GHG emissions and sectors and more ambitious policy goals (e.g. updating reduction targets so that NDCs align with limiting global warming to well below 2°C). Direct economic benefits can be substantial. For example, meeting countries' first NDCs (which run to 2025 or 2030) through a global carbon market could save mitigation costs in the best case by up to 63% relative to national carbon pricing only, translating into annual cost savings of up to USD 259 billion by 2030.
2. The direct economic benefits of international co-operation are unlikely to be shared equally across countries and regions. Some forms of co-operation would be unambiguously beneficial for all participating countries, including extending the coverage of pricing schemes towards non-CO_2 GHGs and linkages between countries with similar mitigation ambition and abatement costs (though gains from trade would be small in the latter case). For other forms of co-operation, most countries would gain direct economic benefits from international co-operation whereas a few energy-exporting countries or few emerging economies would not always benefit directly compared to unilateral climate action. Yet, indirect benefits, including better health or reduced longer-term climate damages are typically not included in the economic benefits. In addition, the effect of international co-ordination on individual actors (e.g. households, firms) within a country can be significantly different from the aggregate average effect.
3. Redistributing the economic gains from co-operation across countries could ensure that co-operation leads to direct economic benefits for all countries. Indeed, direct economic benefits from international co-operation are of sufficient magnitude to enable all countries to benefit from co-operation. However, this would require international transfers (beyond the financial flows associated with international carbon markets), such as direct monetary transfers or technology transfers. If such transfers are not politically feasible, a combination of different forms of co-ordination mechanisms could also bring direct economic gains to all co-operating countries. Alternatively, the economic gains from co-operation could be reinvested in additional mitigation activities, which would reduce long-term climate risks and would therefore reduce potential future damage costs for all countries, including those that may not initially benefit directly.

Box 1.1. Structure, metrics and caveats of economic models

Researchers use economic models (e.g. Computable General Equilibrium Models - CGE or Integrated Assessment Models - IAMs) to assess the effects of climate policy and international co-operation ex-ante (see 6.3.Annex A for more information on models). Economic models are a representation of the (in this case global) economy, covering households and firms in different sectors (usually 2 to 15, but also up to 60) and different world regions (usually 5 to 20) that are connected through international markets (trade, capital). The time horizon ranges from 2030 or 2050 (CGEs) to as long as 2100 and beyond (mostly IAMs). Economic models require a number of input parameters and assumptions that determine the outputs as a result of the interplay of different systems (Figure 1.1).

Figure 1.1. Conceptual representation of an IAM



Source: Authors based on (CarbonBrief, 2018[10]).

Studies in this survey make use of multiple metrics of the (economic) effects of climate policies. All metrics are usually reported against a business-as-usual (BAU) scenario without (additional) climate policies. While the climate policy's effect on emissions is straightforward and reported as reduced CO_2 or GHG emissions, different mitigation cost metrics exist (Paltsev and Capros, 2013[11]).

- Shadow carbon price represents the marginal cost of an extra unit of emission reduction. Hence, this metric can be interpreted as mitigation effort, but not as the total cost of a policy.
- Loss in gross domestic product (GDP) represents the macroeconomic costs.
- Loss in welfare usually measures the amount of additional income needed for consumers to compensate for the consumption losses from a policy.

Two major channels can explain differences in the results from economic models across studies (Springer, 2003[12]). First, researchers may use different input parameters for BAU projections, including GDP, population, technological progress, etc. Second, results are usually sensitive to the choice of the model (e.g. IAM or CGE) and specific model parameters such as production or trade elasticities. Hence, sound research needs to transparently display the assumptions regarding the input and model parameters while checking the robustness of the results for alternative parameter choices.

Source: Authors.

2 Benefits of harmonising carbon prices

International co-operation in meeting individual countries' emissions reduction targets can reduce the aggregate costs of meeting national and international climate mitigation targets, and thus potentially enhance ambition of co-operating countries. This is because there is a large variation in abatement costs across sectors and countries. Flexibility in the location of mitigation efforts allows for increased mitigation in countries with low abatement cost and reduced mitigation in countries with high abatement cost. A uniform global carbon price would, in theory, ensure that the resulting emission reductions are reached at lowest global economic cost. Sub-global harmonisation of carbon prices would only achieve some of the economic benefits for co-ordinating countries as price difference across regions would persist. This section reviews the literature on economic and environmental benefits of global (Section 2.1) co-operation, including, but not limited to the goals of the Paris Agreement, and the benefits of regional co-operation through linking carbon markets (Section 2.2).

International climate agreements have explicitly enshrined mechanisms to foster international co-operation. The Kyoto Agreement in 1997 offered opportunities for incorporating flexibility mechanisms like international emissions trading, clean development mechanism and joint implementation to reach participating countries' abatement targets. More recently, Article 6 of the Paris Agreement foresees cross-country trade of internationally transferred mitigation outcomes (ITMOs) that countries can account against their NDCs. Yet, Parties have not yet agreed on the Rulebook for Article 6. In addition, some economies (e.g. the European Union) have indicated in their NDCs that they are aiming to fulfil their reduction obligation domestically, raising questions about the future demand for ITMOs from developed countries. Other countries, however, are pioneering the role of trading ITMOs under the Paris Agreement. For example, in October 2020, Switzerland and Peru concluded the first agreement to offset Swiss CO_2 emissions in climate projects in Peru (The Federal Council of Switzerland, 2020[13]).

The economics literature has assessed the environmental and economic benefits of internationally harmonised carbon prices for more than 20 years. In theory, full harmonisation of carbon prices across regions can be implemented through uniform (national) carbon taxes, a global ETS or full linking of national ETS (Baranzini et al., 2017[14]).[3] Yet, the distributional consequences of these instruments vary significantly. While uniform national carbon taxes would, in theory, ensure an economically efficient solution, they would shift the major part of mitigation costs to developing countries whose abatement potential is large. Compared to carbon markets, national carbon taxes would not redistribute financial flows across countries so that developing countries may lack the financial resources for ambitious carbon price levels. In theory, direct monetary transfers from developed to developing countries could mitigate this problem, but are likely to face domestic opposition. In addition, the amount of monetary transfers may be difficult to quantify. In contrast, a global ETS or linking national ETS would automatically involve financial flows from countries with high abatement costs to reach their targets to

[3] Some mechanisms would lead to a partial harmonisation of carbon prices, including international offset trading, limited linking of carbon markets or differential national carbon prices, e.g. depending on countries' GDP.

those with low abatement costs as the former would need to buy emissions allowances from the latter at the uniform (global or sub-global) carbon price.

Assessing the economic and environmental benefits from harmonised carbon prices requires a comparison between achieving a specific target (e.g. as laid out in an NDC) unilaterally and achieving the same target jointly. The aggregate cost of reaching both national and international emission reduction targets depends on four drivers (Peterson and Weitzel, 2015[15]):

- The stringency of emission targets relative to BAU. The more stringent the emissions reduction target the higher the (implicit) carbon price that is necessary to deliver the reductions.
- The country-specific abatement costs. This depends on the cost of switching away from GHG-intensive production and consumption patterns, determined by factors, including current capital stock, sectoral composition of economies, current and expected future technology costs, and resource availability.
- National and international feedback effects of domestic and international climate policy through changes in relative prices of fossil energy, affecting energy markets and input prices with implications on (inter)national value chains and production and consumption of other goods.
- The level of international co-operation, as this can harmonise abatement costs across different sources and locations, and – for some countries – can also generate income from permit trading if there are international carbon markets.

Generally speaking, the aggregate economic gains from harmonising carbon pricing between a group of countries (either globally or sub-globally) are higher if there are large differences in carbon prices for these individual countries under unilateral action. In contrast, if the (marginal) abatement costs across co-operating countries are similar, gains from co-operation would be smaller. Standard economic theory predicts that carbon trading would lead to economic benefits to all co-operating partners, as permit selling countries would be compensated for additional abatement which permit buying countries would not need to carry out. Yet, the gains from trade are typically larger for countries with high abatement costs (Alexeeva and Anger, 2016[16]).

However, carbon trading can have even negative economic effects for some of the participating model-regions when accounting for terms-of-trade effects (Marschinski, Flachsland and Jakob, 2012[17]). Terms-of-trade effects would reduce the welfare of permit-exporting countries, i.e. countries with low abatement costs (including several developing countries). The terms-of-trade effect implies that low abatement cost countries would usually have a competitive advantage *vis-à-vis* high cost (and high carbon price) countries under unilateral achievement of mitigation targets. This advantage would disappear if carbon prices are harmonised across regions (Marschinski, Flachsland and Jakob, 2012[17]). While CGE models would be capable to account for the terms-of-trade effect, IAM models would usually not.

Several caveats need to be kept in mind when comparing different modelling studies and their results, in addition to those outlined in Box 1.1 on assumptions on input and key modelling parameters:

1. Assumptions on mitigation targets. First, many of the older studies, notably on sub-national linking, analyse contemporaneous mitigation targets (e.g. Copenhagen pledges, Kyoto pledges) which are already outdated. Clearly, studies covered in this literature review have neither analysed more recent pledges (e.g. countries' net-zero targets) nor evaluated the impact of Covid-19 on achieving mitigation targets. Second, and specifically on NDCs, researchers need to translate different formats and time horizons of mitigation pledges into one country-specific absolute reduction target that serves as input for subsequent analysis. Assessing national mitigation targets is straightforward when pledges are based on absolute emission reductions. However, quantifying mitigation pledges is less clear-cut for NDCs that are expressed in other terms, e.g. emissions intensity or emission reductions relative to pre-specified baseline

emissions. In addition, some countries' first NDCs have defined 2025 as the target year whereas others have pledges to be fulfilled by 2030.

2. Assumptions on burden-sharing: Translating the agreed international goals related to limiting global warming below 1.5 or 2°C relative to pre-industrial levels into national emission reduction targets is even more challenging in the absence of a globally-agreed burden sharing agreement. The burden-sharing rule determines country-specific long-term mitigation targets and, thus, countries' mitigation costs and economic benefits from co-operation. Researchers typically analyse a number of burden sharing rules to determine the stringency of the national mitigation target for limiting global warming to 2 or 1.5 °C or scale up current NDCs. Burden sharing rules may be based on e.g. cumulative emissions, GDP, population, baseline emissions or a combination thereof (Fujimori et al., 2016[18]).
3. Results presented in Sections 2.1 and 2.2 focus on aggregate results for a particular country or region; the impact for individual actors (e.g. households, firms) within a country or region can be significantly different from the aggregate average and is further explored in Section 2.3. For example, carbon trading would not always lead to direct economic benefits to all countries, but would likely bring economic benefits to firms engaged in carbon trading.

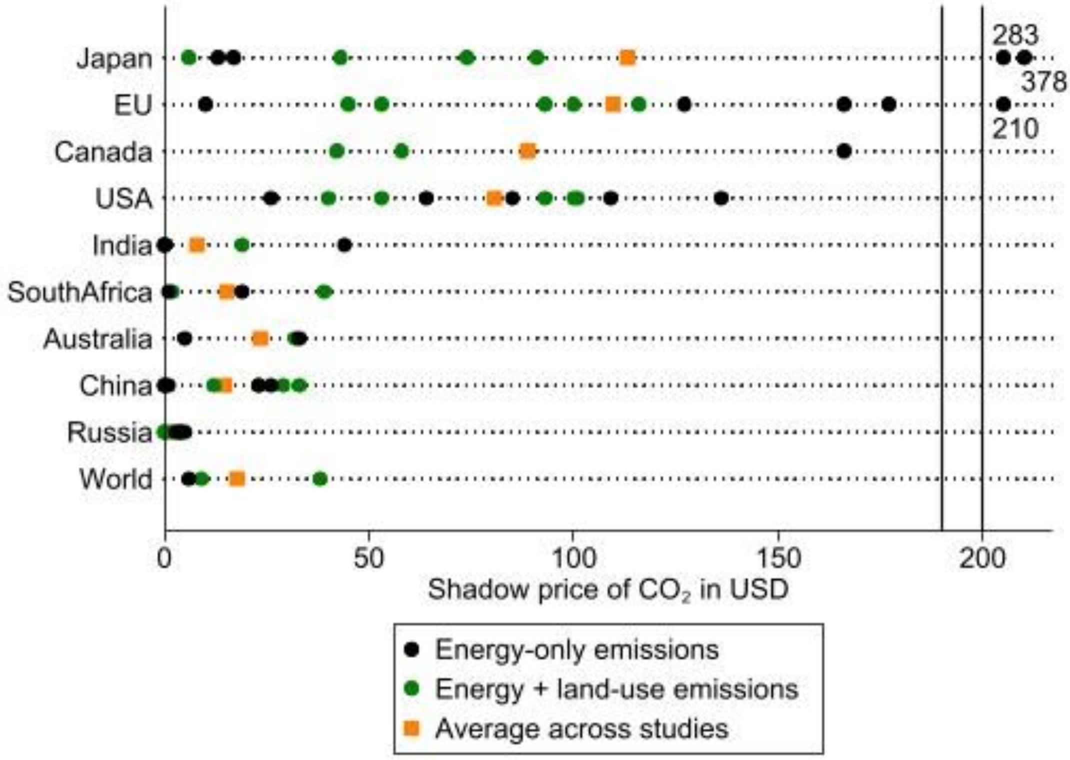
2.1. Global harmonisation of carbon prices

There is significant intra-regional variation in estimated shadow carbon prices, i.e. the carbon prices needed to achieve NDCs unilaterally (Figure 2.1). Based on six different studies (some of them analysing more than one economic model), Figure 2.1 shows the region-specific shadow carbon prices from multiple studies along with the average shadow carbon price across studies, if the region is covered in at least three different models. The highest variation within a region is reported for Japan, where estimated shadow carbon prices needed to achieve its NDC unilaterally vary between 6 and 378 USD/t CO_2e. The reason for this huge variation is rooted in the choice of models, input parameters and model parameters (Aldy et al., 2016[19]), (Box 1.1).

Intra-region variation of shadow carbon prices tend to be lower in emerging countries (e.g. India, China, South Africa), probably because the targets are less stringent but also indicating that assumptions about the large potential of low-cost abatement options in these countries are similar across studies. For many countries (e.g. Japan, EU, US, Canada), the higher estimates are calculated by models that only include emission reductions from energy-related CO_2 emissions. As land-use emission reductions can be low-cost, but are excluded from these calculations, this increases the estimated cost of reaching a specific mitigation target. The large variation of shadow carbon prices across studies is also a reminder to prioritise focussing on the range of potential outcomes across studies while treating the numbers (e.g. shadow prices) of single studies with caution.

The substantial difference in shadow carbon prices across regions highlights the large potential gains from international co-operation in reducing emissions. Regional shadow carbon prices for the NDCs tend to be highest in advanced economies (e.g. US, EU, Japan, Canada) and lowest in emerging economies (e.g. Russia, India, China and South Africa). In some regions (e.g. Russia), model results suggest shadow carbon prices to be zero, implying that those regions would reach their NDC targets under BAU. Low shadow carbon prices could reflect either limited ambition of mitigation targets or large potential of low-cost abatement options or a combination of both. For China and India, relatively low shadow carbon prices can also be attributed to the fact that the pledges in their first NDC are emission intensity targets, which can translate into less stringent reductions relative to BAU since more emissions are allowed if the economy grows (Aldy et al., 2016[19]).

Figure 2.1. Shadow carbon price to achieve the NDC targets by region for different models

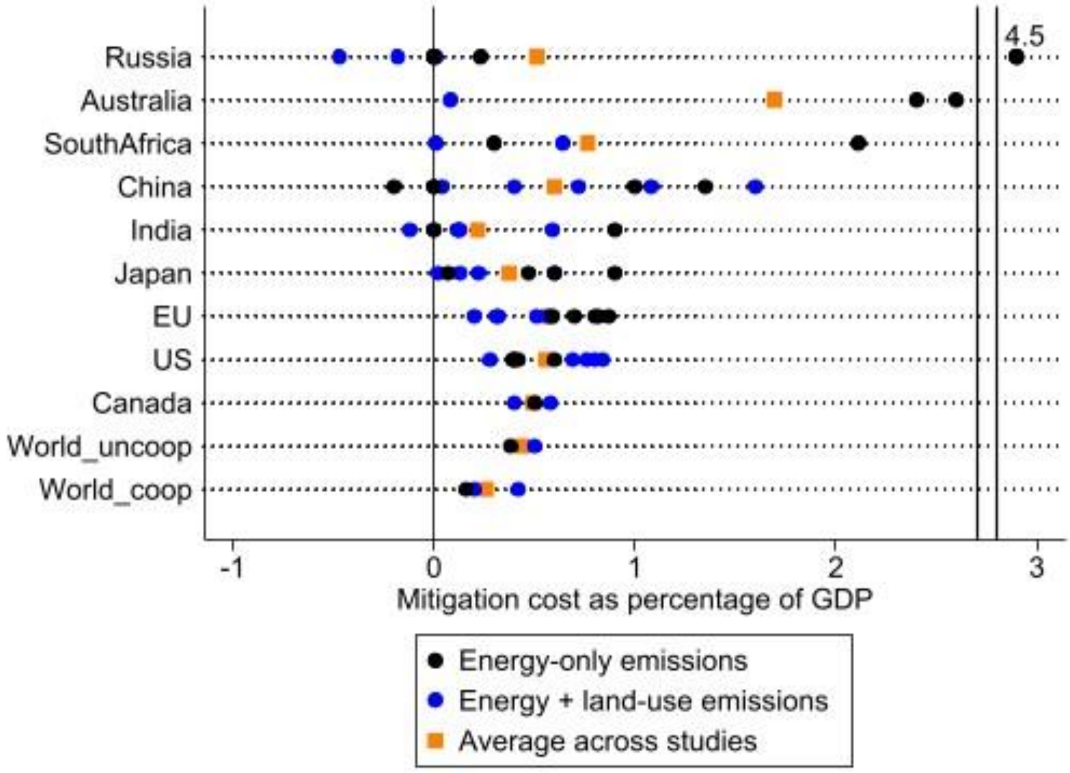


Note: Some models do not cover all regions, but merge these regions into larger blocs. (Aldy et al., 2016[19]) report the average results between 2025-2030. For the US, (Aldy et al., 2016[19]) report results for 2025 to reach the (I) NDC, equivalent to the target year for the US commitment.
Source: (Akimoto, Sano and Tehrani, 2017[20]); (Aldy et al., 2016[19]); (Aldy, Pizer and Akimoto, 2016[21]); (Dai, Zhang and Wang, 2017[22]); (Fujimori et al., 2016[18]); (Liu et al., 2019[23]) ; (Vandyck et al., 2016[24]).

If NDCs were achieved jointly (e.g. through a global carbon market), the global shadow carbon price would be between USD 6 and USD 38 per tCO_2e (see 'World' in Figure 2.1). These figures are based on three studies ((Akimoto, Sano and Tehrani, 2017[20]), (Fujimori et al., 2016[18]) (IETA, 2019[25])). As with regional shadow carbon prices, also the global shadow carbon price depends on sectoral and emissions coverage, notably on coverage of GHG emissions from land-use. If those emissions are included, the global carbon price would drop from USD 38/tCO_2e to USD 8/tCO_2e (IETA, 2019[25]). The relatively low shadow carbon price under global co-operation could indicate limited ambition of NDCs or the large potential of low-cost abatement measures in emerging economies, notably China and India.

Compared to variation in shadow carbon prices, there is less inter and intra-regional variation of mitigation costs expressed in terms of percentage loss in GDP relative to GDP under BAU (i.e. no policy scenario) (Figure 2.2.). While shadow carbon prices indicate the marginal cost of an extra unit of emission reduction, percentage loss in GDP includes the total policy cost, depending on number and costs of total emissions reduced (Box 1.1). As before, economic models that include emissions from land-use tend to show lower mitigation costs. Some models estimate a net gain in GDP (i.e. negative mitigation costs) for some regions (e.g. India, China and Russia). This can be attributed to a competitive advantage for export-oriented carbon-intensive industries, resulting from relatively low shadow carbon prices in those countries and rather high prices in competing regions (Figure 2.2). Yet, most models predict for most regions positive mitigation costs, on average between 0 and 1% loss of GDP.[4] The average global mitigation costs for reaching the NDCs unilaterally is 0.5% of GDP, based on the three studies mentioned above (see 'World_uncoop').

Figure 2.2. Mitigation cost as percentage loss in GDP for reaching NDC targets relative to BAU



Note: World_uncoop refers to the global costs of unilaterally achieving the NDCs. World_coop refers to collectively achieving NDCs. Some models do not cover all regions, but merge these regions into larger blocs. (Aldy et al., 2016[19]) report the average results between 2025-2030. For the US, (Aldy et al., 2016[19]) report results for 2025 to reach the (I)NDC, equivalent to the target year for the US commitment.
Source: (Akimoto, Sano and Tehrani, 2017[20]); (Aldy et al., 2016[19]); (Aldy, Pizer and Akimoto, 2016[21]); (Dai, Zhang and Wang, 2017[22]); (Fujimori et al., 2016[18]); (Liu et al., 2019[23]) ; (Vandyck et al., 2016[24]).

Global harmonisation of carbon prices could bring substantial savings of global mitigation costs (Table 2.1). Global co-operation could reduce global mitigation costs relative to unilateral NDC achievement in the best-case by 58%, 60% or 63% (Akimoto, Sano and Tehrani, 2017[20]), (Fujimori et al., 2016[18]), (IETA, 2019[25]) respectively. For example, global mitigation costs under a uniform global carbon price would decrease from 0.38% to 0.16% of GDP compared to unilateral achievement of NDCs

[4] In addition to shadow carbon prices and percentage reduction in GDP, Liu et al. (2019) report a third metric of mitigation costs namely the percentage loss in welfare (consumer surplus minus government revenues) compared to the base year. Interestingly, the US would experience an increase in welfare of 0.4% with regionally differentiated shadow carbon prices even though it would lose in terms of GDP. A similar trend is seen in China, India, and Japan which would increase welfare relative to BAU by 0.8%, 0.2% and 0.1% respectively in 2030. In contrast to the GDP metric, welfare also accounts for the effects of price changes, so that they are theoretically a better measure than GDP (Box 1.1). Especially for energy importing regions like the USA, China, India and Japan, this can make a difference. It also shows that different cost metrics can lead to contradicting qualitative results.

(Akimoto, Sano and Tehrani, 2017[20]). This would translate into significant annual cost savings, estimated variously at USD 259 billion (Akimoto, Sano and Tehrani, 2017[20]), USD 220 billion[5] (Fujimori et al., 2016[18]) and USD 249 billion (IETA, 2019[25]) in 2030.[6] If mitigation from land-use were included in global markets, aggregate savings could be as high as USD 320 billion in 2030 (IETA, 2019[25]).

Table 2.1. Aggregate economic gains from jointly achieving the NDCs

Study	Saving in mitigation costs in % compared to BAU	Annual savings in 2030 in bill USD	Sectors covered	Model used
(Fujimori et al., 2016[18])	60	220	Energy, industry and LULUCF	AIM (CGE)
(Akimoto, Sano and Tehrani, 2017[20])	58	259	Energy and industry	DNE21+ (IAM)
(IETA, 2019[25])	63	249	Energy and industry	GCAM (IAM)
(IETA, 2019[25])	NA	320	Energy, industry and LULUCF	GCAM (IAM)

Note: (Fujimori et al., 2016[18]) expresses savings from emissions trading in terms of welfare and not GDP.
Source: Authors.

The direct economic gains from global harmonisation of carbon prices are not shared equally across countries. Not all studies break down the global gains from trading by region (Akimoto, Sano and Tehrani, 2017[20]). Most countries or regions would benefit directly from international emissions trading with a uniform global carbon price to the extent that country-specific mitigation costs (in terms of loss in GDP) are lower in the co-ordinated scenario than in the unilateral scenario. The gains are largest for countries with rather high abatement costs (e.g. Japan, USA, EU), and for fossil-fuel exporting countries (e.g. Russia and Middle East and North Africa) as those countries tend to benefit most from a lower global carbon price ((Fujimori et al., 2016[18]) (IETA, 2019[25])).

Not all countries would gain direct economic benefits from global harmonisation of carbon prices even after accounting for the revenue from selling carbon permits. While (IETA, 2019[25]) finds that all countries and regions would benefit from carbon trading, though to a different extent, (Fujimori et al., 2016[18]) shows that not all countries are benefiting directly from emissions trading. This holds true for permit-selling countries (e.g. China and India) which may incur higher cost despite the revenues from selling permits. The reason is the terms-of-trade effect as explained above. Both China and India would have a comparative advantage under unilateral NDC achievement where domestic shadow carbon prices would be lower than in developed economies (e.g. EU and US). Yet, a global carbon market would raise their domestic carbon prices, negatively affecting the international competitiveness of their relatively emissions-intense industry vis-à-vis more developed and less emissions-intensive economies (Fujimori et al., 2016[18]). This effect can outweigh the initial gains from selling emissions permits, culminating in higher mitigation costs for both countries. The discrepancy between the qualitative results of (IETA, 2019[25]) and (Fujimori et al., 2016[18]) result from the model choice (IAM versus CGE). CGE

[5] Savings from emissions trading are expressed in terms of welfare and not GDP (Fujimori et al., 2016[18]). So these numbers are not directly comparable to the ones reported in (Akimoto, Sano and Tehrani, 2017[20]) and (IETA, 2019[25]).

[6] (Akimoto, Sano and Tehrani, 2017[20]) do not explicitly report the cost savings from global emissions trading. However, assuming a global GDP of USD 117 trillion in 2030 (EIA, 2017[110]), the reported reduction of 0.16% in the co-ordinated case instead of 0.38% in the unilateral achievement of the NDCs would imply cost savings of around USD 259 billion. Note that (Fujimori et al., 2016[18]) uses welfare loss as cost metric.

models (Fujimori et al., 2016[18]) are better able to capture the terms-of-trade effect as well as the tax interaction effect[7] that could both offset the gains from trading as explained above.

Also several studies in Section 2.2 find that not all countries would gain economic benefits from carbon trading. This could increase the challenges related to enhanced co-operation on sub-global harmonisation of carbon prices or the advance of a global carbon market. Yet, the studies and models only capture the direct economic benefits and not indirect benefits (e.g. better health, reduced climate damages). Moreover, the direct economic gains from trading for other countries would provide scope to make a global carbon market beneficial for all countries. This could be done in different ways (e.g. via transfers of technology or finance), which are not further assessed here and which could vary widely in terms of political feasibility.

Global harmonisation of carbon prices would create substantial scope for improving environmental outcomes. Clearly, a uniform global carbon price that covers all sectors would, in theory, eliminate all international carbon leakage as all countries would face the same carbon price, but this is unlikely to be achieved in reality. In addition, the scale of saved mitigation costs would offer large scope for enhancing climate ambition. The result of one study suggests that reinvesting the savings from global co-operation (USD 249 billion) into actions that would enhance mitigation ambition could – in a best-case scenario - increase emission removal by up to 50%, equivalent to 5Gt CO_2e in 2030 (IETA, 2019[25]). If emissions from land-use are included, then emission removal could be as high as 9Gt CO_2e in 2030 (IETA, 2019[25]).

Co-ordination could also be beneficial in order to achieve more stringent mitigation targets than those in NDCs. Such targets could include those that are compatible with limiting global warming to 1.5 or 2°C relative to pre-industrial levels. Such co-ordination would have the following implications:

1. Higher mitigation costs. More ambitious mitigation targets would translate – at least in the shorter term and without accounting for the benefits of climate action (e.g. fewer and less severe extreme weather events and thus lower economic levels of climate damages) - into higher regional and global mitigation costs both in terms of GDP loss relative to BAU and in terms of shadow carbon prices (Figure B.1). While the global cost of achieving the current set of NDCs is estimated at 0.4% of global GDP by 2030, this number would increase to 1.2% of GDP in a scenario where mitigation from NDCs is compatible with limiting global warming to 2°C (Vrontisi et al., 2018[26]).[8] This result is in line with previous findings that reported an increase in global costs of co-ordinated action from 0.42% of GDP (for achieving the NDCs) to 0.72% of GDP relative to BAU (for updating NDCs to be in line with the 2°C target) (Vandyck et al., 2016[24]). In terms of welfare, aligning NDCs with the 2°C target would increase the global welfare loss from 0.2% to 1.5% relative to BAU (Fujimori et al., 2016[18]).
2. Higher gains from international co-operation. More ambitious targets would increase the gains from co-operation. As more stringent targets would translate into higher regional shadow carbon prices and higher regional divergence of carbon prices, this would also increase the absolute gains of international co-ordination (IETA, 2019[25]). For example, the gains from co-operation by 2030 could increase from USD 220 billion (for meeting countries' first NDCs) to up to USD 1240 billion for meeting NDCs that are in line with limiting global warming to 2°C, depending on the assumed burden-sharing mechanisms (Fujimori et al., 2016[18]). In addition, carbon price

[7] The tax-interaction effect implies that the welfare costs of additional abatement may outweigh the (private) abatement costs if externalities related to other goods (e.g. energy) are not fully internalised, so that the welfare of permit exporting countries is reduced (Babiker, Reilly and Viguier, 2004[116]).

[8] For the 2°C decarbonisation scenario, (Vrontisi et al., 2018[26]) assume global cost minimisation to keep temperature increase below 2°C with 67% probability. In other words, the authors assume a global mitigation framework in which the sectors and regions with the lowest abatement costs carry out emission reductions.

harmonisation with more stringent mitigation targets would unambiguously benefit all regions, including India and China, though the benefits are shared unevenly across countries (Fujimori et al., 2016[18]).

3. The absolute gains of co-ordination could increase beyond 2030, whereas the relative gains decrease. The result of (IETA, 2019[25]) suggest that absolute gains of full international co-ordination could increase from USD 249 billion in 2030 to USD 345 billion in 2050 and USD 988 billion in 2100. Yet, the relative gains could decrease from a cost reduction of 63% in 2030 to 41% in 2050 and 30% in 2100. Note that the underlying assumptions for these figures is that that global emissions are roughly kept constant after 2030 (at around 40GtCO_2 per year). Since BAU emissions would be expected to grow from around 50 GtCO_2 in 2030 to almost 100 GtCO_2 in 2100 the constant emission target would become more stringent over time, which would translate into higher shadow carbon prices and higher absolute gains from co-ordination. Updating the emissions pathway post-2030 to be in line with the 2°C target would decrease the volume of emissions trading (in terms of carbon units traded), but increase the regional and global carbon prices, leading to an increase of the size of the carbon market in monetary terms. However, no numbers on the resulting gains from co-operation are reported (IETA, 2019[25]).

2.2. Sub-global harmonisation of carbon prices

Sub-global harmonisation of carbon prices would bring economic (e.g. reduced mitigation costs of the sub-global coalition) and environmental benefits (e.g. raised ambition, reduced carbon leakage), but to a lower extent than the reduction under full global co-operation. Carbon price harmonisation can be achieved through linking existing or prospective ETSs or through co-ordinating on minimum carbon prices. Examples for existing linkages include the link between the EU ETS and Switzerland in 2020 and the link between the Californian and the Quebec Cap-and-Trade schemes under the Western Climate Initiative in 2014.

All of the 13 studies reviewed here include the EU ETS. Five studies assess a EU ETS-China linkage (Table B.1), three studies analyse a link between the EU ETS and different coalitions of countries (Table B.2), including G20 countries (e.g. Canada, Japan, Russia, Australia, India, Brazil) and the remaining five studies cover multi-regional linkages (e.g. Annex I countries[9], see Table B.3). In many cases, the studies use different assumptions regarding the (assumed) stringency of the reduction targets, the extent of sectoral coverage, countries involved and the timing and extent (unrestricted versus restricted) of linking, making it difficult to compare these studies. Nevertheless, some common points can be identified. The details on each of the studies regarding co-operating countries or regions, assumed mitigation targets, time horizon, carbon prices and welfare effects are presented in Table B.1, Table B.2 and Table B.3.

2.2.1. Economic benefits

Sub-global harmonisation of carbon prices can bring substantial economic benefits. Harmonisation of carbon prices would reduce the aggregate mitigation costs of co-operating countries compared to unilaterally achieving pre-determined national or regional targets. Country-specific mitigation costs can be reduced by as much as 66% compared to not linking, notably when the price difference pre-linking was very high as is the case in most EU ETS-China studies (Liu and Wei, 2016[27]).

[9] Annex I countries include mostly developed economies. For a list, see: https://www.oecd.org/env/cc/listofannexicountries.htm.

The direct economic benefits from sub-global harmonisation of carbon prices are uneven across individual countries. This mirrors the result from the previous section. The country-specific direct economic benefits from linking would depend strongly on the country's marginal abatement cost, the reduction targets and on whether the country is exporter or importer of emission allowances. In most studies, developed countries are assumed to have the strictest emissions mitigation targets (e.g. 40% absolute reduction of emissions for EU by 2030 relative to 1990 levels) and, thus, the highest shadow carbon prices pre-linking. Linking with jurisdictions with lower shadow carbon prices would reduce the permit price, leading to benefits in most cases. Mitigation costs of high abatement cost countries can be reduced by as much as 66% compared to not linking, notably when the price difference pre-linking was very high as is the case in most EU ETS-China studies (Table B.1). The economic gains for emerging or developing countries would be relatively lower in most studies.

When linking to high abatement-cost countries, low abatement-cost countries would not always gain direct economic benefits from linking (not accounting for indirect benefits related to health and reduced climate damages). This also resembles one of the findings from the previous section where a global carbon market would not lead to direct economic benefits for China and India (also excluding indirect benefits). Also some of the studies in this section come to a similar conclusion. For example, China (and countries in Africa and Latin America) would not benefit directly from a link to developed countries (Massetti and Tavoni, 2012[28]). (Massetti and Tavoni, 2012[28]) compare two scenarios to limit the concentration of CO_2 to 450 ppm by 2050: a global ETS versus two sub-global ETSs, one covering Asia (China, India, south Asia and south-east Asia) and one the rest of the world (e.g. OECD, Africa, Latin America). The results suggest that China and non-Asian non-OECD countries would gain higher direct benefits under sub-global co-operation compared to a global carbon market. China would be expected to become a permit buyer in 2050 and would face higher carbon prices in a global compared to a sub-global market (Massetti and Tavoni, 2012[28]). Energy exporting countries (e.g. Russia, MENA) would face a loss of oil revenue which tends to be higher under the global carbon market. Conversely, India and OECD countries would have higher gains under a global carbon market (Table B.3) as both are permit importers, benefiting from lower permit prices under global emissions trading.

In addition, in 2 out of the 5 studies that analyse an EU-China link, China as a whole would not benefit directly from linking to the European system (Table B.1, (Gavard, Winchester and Paltsev, 2016[29]), (Gavard, Winchester and Paltsev, 2013[30])). In one study, the welfare effect for China would be neutral, though this study only considers limited linking (see Box 2.1) (Hübler, Löschel and Voigt, 2014[31]). In the other two studies, China would gain from linking, though to a much lower extent than the EU. For example, co-operation would increase the welfare of China by 0.04%, but that of the EU by 0.34% compared to independent ETS by 2030 (Li, Weng and Duan, 2019[32]). To a lower extent this also holds true in the other study (Liu and Wei, 2016[27]). The reason for the asymmetry of China's welfare gains could originate from differences in increases of carbon prices across studies. While linking to the EU would increase China's carbon price by more than 35% in the former studies (Gavard, Winchester and Paltsev, 2016[29]), more recent studies find a price increase of around 11%. Hence, the negative effects of rising carbon prices (discussed above) are lower in the more recent studies, so that China would gain directly from linking. Yet, even if China (or other permit exporting countries) would not benefit directly, further transfers (e.g. finance or technology) could compensate these countries. Alternatively, placing a quantitative limit on emissions trading could, in theory, increase the economic gains for low-abatement cost countries (Box 2.1).

Linking of carbon markets between developed countries with high abatement costs would create fewer direct gains on aggregate than a link between developed and developing or emerging economies where the price differential is greater. In theory, this is due to the similar level of abatement costs across developed countries, resulting in relatively equal shadow carbon prices pre-linking and, thus, limited gains from trading. For example, the results of one study suggest that a link between the EU ETS and different coalitions of other developed countries (e.g. Canada, Japan, US, Russia, Australia) would improve the EU's welfare of linking by 4% or 0.03 percentage points (i.e. a reduction of welfare loss from -0.67% of GDP to -0.64% of GDP) (Alexeeva and Anger, 2016[16]). This pales against the EU welfare gains from linking reported for prospective EU-China links, reported in Table B.1, which can be as large as 66%. Similarly, linking an Australian ETS (that would cover all sectors) with different other countries yields the highest gains for Australia when linked to India and China (72% and 54% cost reduction) rather than to developed countries, including the EU (20%), South Korea (26%) and the US (39%) (Nong and Siriwardana, 2018[33]). The distribution of welfare gains across regions is difficult to generalise. Yet, some region-specific results include:

- Australia is expected to be a buyer of allowances in all scenarios and would gain in terms of welfare in all scenarios (e.g. (Böhringer, Dijkstra and Rosendahl, 2014[34])).
- The EU would be buying allowances and gaining in terms of welfare (with the exception of an EU – Australia ETS ((Nong and Siriwardana, 2018[33]) or an ETS that covers all Annex I regions (Dellink et al., 2014[35]).
- For Canada, Japan and the US, there is no clear conclusion.

Box 2.1. The welfare effects of quantitative limit on emissions trading

Quantitative limits would restrict trading to a specific number of allowances to be traded in each period or to a share of the emissions cap. This could, in theory, increase the gains from co-operation for low abatement cost countries while still benefiting developed countries with rather high abatement costs, but the evidence is mixed. Clearly, limited emissions trading would imply a lower overall benefit of co-operation compared to full linking as not all efficiency gains from trade can be realised (Li, Weng and Duan, 2019[32]). Yet, limited linking may improve the economic gains of all countries. The reason for these results is that limited linking would deliver some savings in mitigation costs, notably for developed countries without entirely eliminating the carbon price differential across co-operating regions. Hence, developing or emerging countries (e.g. China) would still face lower carbon prices so that the competitive advantage against developed countries would persist.

(Gavard, Winchester and Paltsev, 2013[30]) analyse the welfare implications for a China-EU link for different trading limits. Their result suggests that China would benefit directly from a link to the EU if trading were not to exceed 10% GHG emissions of the EU cap (Gavard, Winchester and Paltsev, 2013[30]). The result of another study also suggests that if trading is limited to 10% of the cap of China's respective trading partner (either EU or US), then China would slightly benefit directly from linking, reducing its welfare loss relative to BAU (no policy) from -0.62% (unilateral action) to -0.58% (link with US) or experiencing no change in welfare (-0.62% when linked to EU) (Gavard, Winchester and Paltsev, 2016[29]). The latter result also mirrors the finding of (Hübler, Löschel and Voigt, 2014[31]) who find that limiting carbon trading between the EU and China to one third of the EU cap would be welfare-neutral for China compared to unilateral emission reductions by both countries. At the same time, limited linking does not seem to be detrimental for China's trading partners as the trading partners would still gain from linking, yet to a lower extent then under full linking (Gavard, Winchester and Paltsev, 2013[30]) (Gavard, Winchester and Paltsev, 2016[29]). However, the difference in terms of welfare between full linking and limited linking is small, amounting to 0.01 percentage points (welfare loss of -0.22% versus -0.23%) for the US and 0.03 percentage points (welfare loss of -0.2% versus -0.23%) for the EU (Gavard, Winchester and Paltsev, 2016[29]), Table 1). More recently, however, the results of one study suggest that limited linking would be detrimental to the welfare of China compared to full linking, regardless of whether the limit is 5, 10, 15, 20 or 25% (Li, Weng and Duan, 2019[32]). One of the reasons for these contradictory findings can be related to assumptions about abatement costs and, thus, resulting shadow carbon prices. While the Chinese shadow carbon price would increase by 50% (from USD 6.78 to USD 10.2) when moving from a 5% limit to full linking in (Gavard, Winchester and Paltsev, 2013[30]), that price would only increase by 16% (from USD 14.87 to USD 17.2) for the same move in (Li, Weng and Duan, 2019[32]). Hence, the terms-of-trade effect (explained above) is substantially lower in the latter paper which can explain the different welfare implications.

Source: Authors.

Extending carbon pricing coalitions by including new countries or regions would bring direct economic benefits to most, but not all coalition members. Extending the geographical scope of carbon markets would reduce the aggregate mitigation costs of participating countries. Adding new coalition members could increase or decrease the permit price of the extended coalition, depending on the carbon price associated with the new member(s). If the permit price increased, former permit importing regions could not benefit directly compared to the status quo as they need to pay higher prices to offset their emission obligations. For example, if the EU or the US joined a US-China or EU-China link, the mitigation costs of the existing coalition members would increase whereas those of the new member would decrease (Gavard, Winchester and Paltsev, 2016[29]). Conversely, permit importing countries tend to gain if the entrance of new countries in the coalition reduces the permit price (Alexeeva and Anger, 2016[16]). If the permit price decreases with the extension of the existing coalition, allowance-selling countries would not always benefit directly relative to no extension (Böhringer, Dijkstra and Rosendahl, 2014[34]).

2.2.2. Environmental effects

Economic gains from sub-global harmonisation of carbon prices could potentially be used to enhance mitigation ambition. This could, in theory, happen, if co-operating countries or regions reinvested some or all of the gains from emissions trading to accelerate climate action as was investigated in the previous section (IETA, 2019[25]). Yet, in practise there would be some challenges, e.g. how to channel the gains from trading for private firms to more ambitious mitigation. The results of this section suggest that there is also some scope to channel the savings in mitigation costs to enhance ambition as carbon trading would bring mutual benefits to all co-operating countries and regions in most cases (Table B.1, Table B.2, Table B.3). One study explicitly compares a scenario of raised ambition with a scenario of current ambition in an EU-China link. The results suggest that a joint EU ETS – China ETS carbon market could support a more stringent emissions reduction target, which stipulates additional reductions by 5% (3% in China and 12% in the EU so that the additional abatement burden is shared equally between countries). In fact, both countries show higher welfare levels under a link with the enhanced mitigation targets compared to a scenario of independent (Li, Weng and Duan, 2019[32]).

Sub-global harmonisation of carbon prices could reduce the extent of international carbon leakage. In theory, the effect of sub-global co-operation on carbon leakage is not clear. On the one hand, sub-global harmonisation of carbon prices would eliminate carbon leakage between co-operating countries while reducing the extent of carbon leakage of the high-price country (which faces lower carbon prices after linking). On the other hand, linking would raise the carbon price of the low-price country which would lead to increased leakage compared to independent ETS, potentially outweighing the other two effects. Yet, modelling results suggest that sub-global price harmonisation would reduce international carbon leakage. For example, a potential US-China ETS would reduce cumulative international carbon leakage between 2020 and 2030 by 0.5 billion tCO_2 or 16% compared to independent ETS (Gavard, Winchester and Paltsev, 2016[29]). Similarly, an EU-China ETS would reduce leakage by 7% or 0.21 billion tCO_2 between 2020 and 2030 (Gavard, Winchester and Paltsev, 2016[29]). A more recent study also finds that an EU-China ETS would reduce leakage by 0.05 billion tCO_2 in 2030, comparable to the size of previous studies (Li, Weng and Duan, 2019[32]). Both studies, however, also find that limited trading would increase carbon leakage compared to unlimited trading, but would still imply lower leakage compared to independent ETS. Sub-national price harmonisation can reduce, but not eliminate the extent of carbon leakage. Section 6 provides results on instruments to reduce carbon leakage even further.

2.3. Distributional aspects of international co-ordination on carbon pricing

Economy-wide welfare effects as reported in the previous sections would usually mask any variation of benefits and costs within a given country. However, these intra-country variations could be large. If a country, on aggregate, derives economic benefits from international co-operation on carbon pricing, this does not necessarily need to hold true for all companies or households in that country. Similarly, if a country is expected to not benefit directly at an aggregate level from international carbon trading, there could still be several actors in that country who could benefit from such participation (e.g. entities that sell emissions credits).

The distributional effects of changing carbon prices due to international co-ordination would depend inter alia on the revenue recycling mechanism, the carbon intensities of consumption across different income groups, and varying income sources (labour vs capital income) of different household types.

These factors would determine how carbon prices and climate policy more generally would affect the income and expenditures of different household types. If lower-income households experience larger (smaller) relative income losses than richer households, the effects would be denoted as regressive (progressive). In some cases, the effects could be progressive until some level of income before turning regressive thereafter.

All but one study (Weitzel et al., 2015[36]) discussed here are single-country studies that analyse the distributional effect of specific scenarios within a given country. As such, these studies do not explicitly deal with the distributional effects of international co-ordination. However, these studies provide information on the distributional consequences of (different levels of) carbon pricing. Thus, combining the results from these studies with the results on the changes of shadow carbon prices (Section 2.1) or ETS prices (Section 2.2) would allow for an assessment of the distributional effects of international harmonisation of carbon pricing. This section first presents the results of the only study that analyses the distributional effects of international price harmonisation through carbon trading before turning to the results from the multiple single-country studies (the results of selected studies are summarised in Table B.4 in 6.3.Annex B).

Repercussions from international energy markets or trading international carbon credits matters for the within-country distributional effects of international co-ordination. Exemplified in India, (Weitzel et al., 2015[36]) couples a single-country CGE model for India to a multi-regional multi-sectoral global CGE model to assess the effects of permit trading and the impacts of international repercussions (e.g. through energy prices) on the income of different household types. The results include:

1. The revenue recycling mechanism of carbon price revenue has significant implications on the national income distribution. The study explores three different revenue recycling mechanisms, including (a) lump-sum transfer to all household groups based on number of household members (b) lump-sum transfer to poor households only and (c) increasing government investment into public goods. While options (a) and (b) would be progressive, using tax revenue for public goods tends to be regressive. However, strengthening government investment would decrease the overall cost of climate policy in India so that there is an efficiency-equity trade-off.
2. The distributional effects of the revenue recycling mechanisms would amplify if carbon prices increased. In one scenario where all countries in the multi-regional model reach their Copenhagen pledges[10] through international emissions trading, the harmonised international carbon price and, thus, India's revenue from carbon trading would increase towards 2050. The results suggest that the elevated carbon price and revenue would amplify the distributional effects of different revenue recycling mechanisms, implying that lump-sum transfers to households (i.e. options a and b) would become even more progressive whereas earmarked investments in public goods (option c) would become even more regressive.[11]
3. Distributional effects of international co-ordination due to repercussions from international energy markets are present, but relatively small. Such repercussions would originate from changes in international energy prices between regimes with and without international emissions trading. Meeting global climate pledges would reduce the global demand for fossil fuels and, thus, international energy prices. Given that India is an energy-importing country, this would increase the welfare of all Indian household types, covered in the study. Richer

[10] From 2009, countries pledged emission reductions by 2020. For example, the EU, Japan and Russia pledged to reduce emissions by 20–30%, 25%, and 15-15% respectively compared to 1990. India and China pledged to reduce its carbon intensity by 20-25% and 40-45% compared to 2005.

[11] The underlying assumption of this study is that all revenues of carbon trading would flow to the government that can decide about the use. Yet, depending on the design of the carbon market, some revenues may also flow to private firms, e.g. when linking bottom-up prospective carbon markets.

households tend to have higher welfare gains as they have a relatively energy-intensive consumption. International permit trading, however, would mitigate the decrease of international energy prices, implying that Indian households would benefit less than under unilateral achievement of emission reduction pledges. However, this reduction in welfare is much lower than the effect from revenue recycling, implying that lower-income households would still benefit from international emissions trading if revenues were allocated to households. If revenue recycling tended to be the dominant channel for distributional effects of carbon pricing in general, then the results from single-county studies are informative about within-country allocation of benefits in different co-operation scenarios because the international repercussions from energy markets is rather negligible.

For developed countries, higher carbon prices tend to be regressive (Ohlendorf et al., 2020[37]). The negative impacts are higher on poor households when the degree of substitution between GHG emissions and employment is high (Boccanfuso, Estache and Savard, 2011[38]). Importantly, the regressive effect can be mitigated through revenue recycling mechanisms such as income tax reforms, lump-sum transfers to households or infrastructure investments targeted towards the needs of lower-income households. Lump-sum transfers to households could even have a progressive effect (Rosenberg, Toder and Lu, 2018[39]). In contrast, income tax reforms, including reduction in labour taxes (Rosenberg, Toder and Lu, 2018[39]) (Landis et al., 2019[40]), value added taxes (Landis et al., 2019[40]) or corporate taxes (Pomerleau and Asen, 2019[41]), capital taxes (Rausch, Metcalf and Reilly, 2011[42]) as well as reductions in social security contributions (Landis et al., 2019[40]) would be still regressive, although to a lower extent.

For developing countries, the distributional effects of carbon prices are inconclusive, but with a tendency towards proportional or progressive impacts (Ohlendorf et al., 2020[37]). While earlier studies tend to find a regressive effect (Boccanfuso, Estache and Savard, 2011[38]), more recent studies tend to find carbon pricing to have progressive impacts (Ohlendorf et al., 2020[37]), including in Indonesia (Yusuf and Resosudarmo, 2015[43]) or ASEAN countries (Nurdianto and Resosudarmo, 2016[44]). The main drivers of the progressive effect tends to be the resource reallocation in the economy due to the introduction of carbon pricing. While rural or lower income households tend to consume less energy than urban households, they also tend to be better endowed with production factors that benefit from carbon pricing (e.g. low-skilled labour) (Yusuf and Resosudarmo, 2015[43]). Recycling the revenue from carbon pricing to households would make the carbon tax even more progressive (Nurdianto and Resosudarmo, 2016[44]).

Combining the insights on carbon pricing effects on developed and developing countries, harmonising carbon prices through international emissions trading between developed and developing countries could be progressive in both groups of countries. As seen in Sections 2.1 and 2.2, the harmonised carbon price from international emissions trading is expected to decrease in developed countries and to increase in developing countries compared to unilateral achievement of mitigation targets. As carbon pricing tends to be rather regressive in developed countries (Ohlendorf et al., 2020[37]), international emissions trading would be progressive in those countries. Similarly, carbon price increases in developing countries tends to be progressive (Ohlendorf et al., 2020[37]), implying that international emissions trading would amplify the progressive effect.

3 Extending coverage of carbon pricing schemes

Energy-related CO_2 emissions from electricity and energy-intensive sectors represent the largest share of emissions covered by existing explicit carbon pricing schemes although some large schemes also include other emissions sources (ICAP, 2019[45]). This means that current carbon pricing schemes exclude a number of low-cost abatement opportunities in other sectors (e.g. buildings, forestry, agriculture) or from non-CO_2 (NC) GHGs, including methane (CH_4), nitrous oxide (N_2O), and fluorinated GHGs (e.g. SF_6, NF_3, HFCs, and PFCs), which are not always included in the models of the previous section. Extending the coverage of carbon pricing to other sectors or to NC GHGs could involve practical challenges, including the measurement of real-world emissions or a common metric for the carbon equivalence. For example, NC GHGs differ from CO_2 both in terms of radiative efficiency and atmospheric lifespan, making it challenging to calculate a standardised metric that reports the climate effect of GHGs with different properties. UNFCCC uses the Global Warming Potentials[12] over 100 years, but this metric does not adequately capture different behaviours of short-lived (e.g. methane) versus long-lived (e.g. CO_2) climate pollutants (Cain et al., 2019[46]).

3.1. Extending sectoral coverage of pricing schemes

Broad sectoral coverage of carbon pricing would ensure economic efficiency, meaning that an aggregate emissions reduction target is met at the lowest cost. Yet, currently effective carbon prices (i.e. also those taking energy taxes into account) within countries vary considerably across sectors, ranging from more than EUR 300/tCO_2 in the road sector to zero in other sectors (e.g. buildings) (OECD, 2018[8]). Current ETS cover predominantly the power and industry sector (ICAP, 2019[45]). For example, 18 out of 21 existing ETS include power sector emissions as of 2019. The industry sector is also covered by 18 ETSs (not the same as those covering the power sector). Sectoral coverage of ETS is much lower for sectors with large number of diffuse emitters, e.g. buildings (10), transport (6), and waste (2) as well as for domestic aviation (6) (ICAP, 2019[45]). New Zealand's ETS is currently the only ETS covering the forestry sector and is currently planning to extend the coverage to the agricultural sector (ICAP, 2019[45]). Examples for extending sectoral coverage of ETSs are the inclusion of distributors of transportation and other fuels in the Californian ETS since 2015 or the inclusion of the (intra-European) aviation sector in the EU ETS since 2012. The EU is currently exploring options to include the maritime sector in its ETS. Expected to start in 2021, the Chinese ETS would initially cover the power sector (coal and gas-fired power plants), but is set to expand to seven other energy-intensive sectors (e.g. iron and steel) (IEA, 2020[47]).

Covering only some, but not all sectors can lead to inter-sectoral leakage. Inter-sectoral leakage refers to a situation in which a sector-specific climate policy leads to an increase of emissions in a non-

[12] The Global Warming Potential (GWP) is an index that enables the comparisons of the warming effects of nNC-CO_2 gases with CO_2. Over a 100 year time-horizon CH_4 has a GWP of 28 while N_2O has a GWP of 265 whereas the GWP for CO_2 is kept constant at 1 as a reference (IPCC, 2014[57]).

regulated sector in the same country. For example, some industrial sectors may substitute the direct use of fossil fuels for electricity as response to rising electricity prices caused by carbon pricing in the power sector. In addition, inter-sectoral leakage can also originate through the energy price channel, according to which energy demand in non-regulated sectors would increase as a response to lower fuel prices due to reduced demand for energy carriers in regulated sectors. For the EU ETS, the result of one study suggests that the inter-sectoral carbon leakage rate[13] to non-EU ETS sectors could be as high as 12% for a hypothetical case where the EU ETS permit price increased to USD 70t/CO_2e (EUR 50/tCO_2e) (Söder, Thube and Winkler, 2019[48]). This increase would be primarily driven by the energy price channel (see Section 6 for more details), notably due to lower fuel prices of coal and natural gas. Emission targets for non-regulated sectors would reduce the risk that climate policy in regulated sectors (e.g. strengthening the emissions cap) do not lead to an increase of emissions in non-regulated sectors. For example, the EU allocates sectoral emission reduction targets for non-EU ETS sectors for each country according to the burden sharing rule.

Expanding sectoral coverage would generally reduce mitigation costs at an aggregate level through harmonising carbon prices across sectors (Böhringer, Rutherford and Tol, 2009[49]) while reducing the risk of inter-sectoral leakage (Söder, Thube and Winkler, 2019[48]). The economic and environmental benefits from expanding sectoral coverage would be higher the greater the risk of inter-sectoral leakage and the higher the difference of marginal abatement costs before the extension. For example, if the scope for inter-sectoral leakage is large, then broadening the sectoral coverage of carbon pricing schemes could effectively prevent leakage, increasing environmental effectiveness. Expanding sectoral coverage of hypothetical international carbon markets (e.g. beyond electricity and energy-intensive industry) would reduce mitigation costs for the vast majority of countries (Böhringer, Dijkstra and Rosendahl, 2014[34]). Few countries, however, would not benefit directly from extending sectoral coverage. Yet, this may be due to very specific (and unusual) model assumptions in (Böhringer, Dijkstra and Rosendahl, 2014[34]).[14]

International emissions trading covering the power sector tends to yield the highest cost savings. The results of (Böhringer, Dijkstra and Rosendahl, 2014[34]) suggest that a hypothetical link between EU and US carbon markets, both covering only the power sector, would reduce aggregate mitigation costs by around 14% by 2020 compared to unilateral achievement of targets. Expanding the coverage to other sectors (e.g. energy intensive industry, road transport, aviation, all industrial sectors) from the EU-US

[13] A leakage rate of 10% implies that emissions in non-ETS sectors would increase by 10Mt for a 100 Mt decrease in the ETS sector.

[14] (Böhringer, Dijkstra and Rosendahl, 2014[34]) analyse a large set of international emission trading scenarios with different regional coverage (four different coalitions) and sectoral coverage (six degrees of sectoral coverage, starting from electricity only and subsequently including energy-intensive industry, transport, water transport, rest of industry and final energy demand), using a multi-regional, multi-sectoral CGE model. The assumed aggregate targets are the Copenhagen pledges in 2020. Importantly and in contrast to the usual assumption that the sectoral targets remain constant across scenarios, the authors assume that countries optimally adjust the sector-specific reduction targets (e.g. those covered and not covered by the ETS) to minimise their overall costs. Thus, when sectoral coverage of the ETS is extended for a given coalition, each country adjusts how much is reduced in the sectors remaining outside the international trading scheme. This gives rise to some strategic effects related to 'hot air', according to which permit selling countries would have an incentive to increase the cap of the sectors covered by international trading in order to maximise domestic welfare by boosting revenue from permit selling (Helm, 2003[114]). Yet, as sectoral coverage of international emissions trading increases, the scope to inflate covered emissions diminishes, potentially leading to a situation in which permit selling countries would not benefit from sectoral expansion. However, due to the strategic effect, permit-exporting countries, including Russia, China and India, would always benefit from joining the international carbon market as their revenues from permit exports more than offset the costs for their abatement efforts. In addition, one finding of this study suggests that cost savings from a regional extension of carbon prices are larger than for sectoral extensions.

power market link could further reduce mitigation costs by up to 4 percentage points in the same timeframe. This pattern of results also holds true for other combinations of countries, beyond an EU-US link. For example, a power sector ETS of a hypothetical coalition, encompassing the EU, US, Australia, Japan, Canada, South Korea, Mexico and Russia would reduce joint mitigation costs of those countries by 48%. Including energy intensive industries, road transport, or aviation would increase the savings in mitigation cost by 1-2 percentage points (Böhringer, Dijkstra and Rosendahl, 2014[34]). The relatively high potential of reducing mitigation costs for international carbon markets covering the power sector is related to the fact that power sector emissions account for the largest proportion of global energy-related CO_2 emissions, amounting to around 41% in 2018 (IEA, 2020[50]). In addition, differences in (marginal) abatement cost across countries tend to be large due to regional differences in existing fuel mixes, generation technologies as well as costs and resources for renewables.

Most of the existing studies focus on the extension of the EU ETS to include all non-EU ETS sectors (Böhringer, Rutherford and Tol, 2009[49]) (Abrell, 2010[51]), aviation (Anger, 2010[52]) or transport (Abrell, 2010[51]), (ECF, 2014[53]), (Flachsland et al., 2011[54]), (Heinrichs, Jochem and Fichtner, 2014[55]). In most scenarios of the studies, the sectors covered by the EU ETS face lower marginal abatement costs, translating into lower carbon prices compared to non-EU ETS sectors. For example, one early study reports EU ETS shadow carbon prices to be between USD 35-42/tCO_2e whereas shadow carbon prices for all non-EU ETS sectors combined to be in the range of USD 111–139/tCO_2e in order to meet the 20% reduction target with differentiated reduction targets for ETS and non-ETS sectors (Böhringer, Rutherford and Tol, 2009[49]). Hence, reallocating emissions from the non-EU ETS sector to the EU ETS sector would reduce overall mitigation costs as would carbon trading between EU ETS and non-EU ETS sectors. The uniform carbon price in a fully integrated European ETS, that would cover all economic sectors would be around USD 97/tCO_2e (Böhringer, Rutherford and Tol, 2009[49]).

Extending the coverage of the existing EU ETS to other non-EU ETS sectors would thus enhance economic efficiency. All studies reviewed for this report find that including other sectors in international emissions trading would reduce mitigation costs or enhance welfare. For example, the results of (Stenning, Bui and Pavelka, 2020[56]) suggest that incorporating the road transport and heat sector in the EU ETS would increase GDP by 0.3% compared to BAU. Older studies suggests that mitigation costs could be reduced by 80% when moving from the current EU climate policy framework towards a fully integrated European ETS, covering all sectors (Abrell, 2010[51]). As this study includes all non-EU ETS sectors, this can be seen as an upper bound for potential cost savings. Note that the current EU climate policy framework gives rise to three inefficiencies. First, carbon prices vary between EU ETS and non-EU ETS sectors. Second, carbon prices vary across Member States in the non-EU ETS sector. Third, (shadow) carbon prices for the non-EU ETS sectors vary within each country due to sector-specific targets for some sub-sectors (e.g. transport and buildings). The third inefficiency tends to be the largest. Eliminating this inefficiency, e.g. through a national ETS covering all non-EU ETS sectors or through a uniform carbon tax, would reduce mitigation costs by 57% (Abrell, 2010[51]). Removing the other two inefficiencies would reduce mitigation costs further by 57% (Abrell, 2010[51]). The latter result is qualitatively similar to those of (Böhringer, Rutherford and Tol, 2009[49]), who report a decrease of mitigation costs by between 23 and 34% when moving from a scenario, comprising the current EU ETS and uniform national carbon prices for non-EU ETS sectors towards a scenario with a fully integrated EU ETS. The result of this study also suggests that harmonising uniform national carbon prices in the non-EU ETS sector across Europe (e.g. through a hypothetical second ETS covering all non-EU ETS sectors) would roughly contribute to a similar extent to the reduction in mitigation costs as would a link between the hypothetical second ETS and the EU ETS, depending on the model used (Böhringer, Rutherford and Tol, 2009[49]).[15]

Incorporating road transport in the EU ETS would increase the EU ETS permit price. The result of a recent study suggest that the permit price could increase to USD 85 – 105 USD in 2030 when road transport is included in the EU ETS (Stenning, Bui and Pavelka, 2020[56]). If road transport was not included, the price would only marginally increase compared to 2018 levels (USD 15) (Stenning, Bui and Pavelka, 2020[56]). The reason is that road transport typically faces higher abatement costs due to less availability of alternatives compared to the industry and power sector. Older studies, however, suggest that sectoral extension of the EU ETS to road transport would have limited effects on the permit price (Flachsland et al., 2011[54]). This is despite relatively large pre-linking price differences between the EU ETS (USD 2/tCO_2e) and a hypothetical European transport ETS (USD 73/tCO_2e) (Abrell, 2010[51]). Yet, adding road transport to the EU ETS would increase the permit prices to (only) USD 6/tCO_2e though this is still more than three times more than before the coverage extension (Abrell, 2010[51]).[16] Based on a comparison of four different models that allow the estimation of marginal abatement cost curves (e.g. McKinsey, Enerdata-POLES), (Flachsland et al., 2011[54]) conclude that integrating transport to the EU ETS would not lead to substantial changes in the EU ETS permit price to meet the EU 2020 targets (reduction of GHG of 20% by 2020 compared to 1990 levels). The reason for these findings are i) the relatively modest emission reduction target in the road sector envisioned by the EU (7% below its 2005 level by 2020); ii) the scale of (relatively low-cost) abatement potential in the road transport sector as represented by the marginal abatement cost curves derived from the models[17], and iii) flexibility through the availability of purchasing CDM credits to fulfil installations' emission reduction obligation (Flachsland et al., 2011[54]).

Extending the coverage of existing ETS to the transport sector would enhance economic outcomes to some extent (Abrell, 2010[51]), (ECF, 2014[53]), (Flachsland et al., 2011[54]), (Heinrichs, Jochem and

[15] (Böhringer, Rutherford and Tol, 2009[49]) analyse three different CGE models (PACE, DART and Gemini E3) for three different policy scenarios: i) an EU-wide ETS covering all sectors; ii) a hypothetical scenario with two EU-wide ETS, one covering currently included EU ETS sectors and the other covering currently not included EU ETS sectors; iii) a scenario that roughly approximates the current EU policy framework: one EU-wide ETS, covering currently regulated sectors plus a set of national shadow carbon prices in the non-ETS sectors that is set endogenously at a level where the given national targets are met. These three scenarios enable the authors to decompose the relative contribution of reducing mitigation costs when moving from the current EU policy framework towards a fully integrated EU ETS.

When moving from scenario iii) to scenario ii), mitigation cost savings would equal 13% (DART) and 29% (Gemini E3) (PACE does not allow for a regional disaggregation). This indicates that there are some inefficiencies originating from national targets set for non-EU ETS sectors. In fact, implicit national carbon prices for non-EU ETS prices vary substantially, being lower than the EU ETS price in some countries, higher in others and close to the EU ETS in few countries. When moving from scenario ii) to i) mitigation costs would decrease by a further 11% (DART), 34% (PACE) and 0% (Gemini E3), so that the overall reduction in mitigation cost varies between 23 and 34%. Interestingly, the comparison between scenario i) and ii) does not involve any additional welfare costs, implying that the EU-wide reduction targets of the EU ETS and non-EU ETS sectors would be (close to) optimal, leading to similar hypothetic implicit carbon prices in both sector groups. Yet, the other two models come to a different conclusion, finding that the EU ETS carbon price would be substantially lower than that of the hypothetical ETS, covering non-regulated sectors non-EU ETS.

[16] Note that these price levels appear to be relatively low. This is because some of the studies were published some 10 years ago when EU ETS prices were relatively low, even approaching zero at the end of the first trading period in 2007.

[17] Contrary to conventional wisdom, all four models indicate relatively large amounts of low-cost abatement potential in the road sector.

Fichtner, 2014[55]). Some studies also mention welfare improvements (e.g. (ECF, 2014[53])), whereas others indicate that there is scope for permit trading between EU ETS sectors and road transport, which could result in welfare improvements (Flachsland et al., 2011[54]). Only one study quantifies the welfare improvement, concluding that integrating road transport into the EU ETS would reduce mitigation costs by 62% compared to a scenario in which the EU ETS and a hypothetical road transport ETS would coexist along national shadow carbon prices for other non-EU ETS sectors (Abrell, 2010[51]). Interestingly, the result of this study also suggests that a reallocation of mitigation obligations from transport to sectors currently covered by the EU ETS would reduce mitigation costs even more than including transport into the EU ETS (Abrell, 2010[51]).[18] The reason is that constraining transport emissions substantially would reduce tax revenues from pre-existing fuel taxes, leading to a negative welfare effect (Abrell, 2010[51]).[19] Yet, this study does not account for other externalities of road transport, including congestion, accidents, and health impacts due to noise or air pollution. These negative externalities tend to be at least as large as the current tax rates in European countries (OECD, 2018[8]). Hence, reallocating mitigation obligations from road transport to other sectors would lead to an increase in traffic, exacerbating the negative costs and likely outweighing the tax interaction effect.

3.2. Extending coverage of pricing schemes to NC-GHG emissions

The abatement potential of emissions other than energy-related CO_2 is very large with many near-term low-cost options available (IPCC, 2014[57]). Such abatement potential predominantly originates from the land-use, land-use change and forestry (LULUCF) sector, but also includes the energy sector (e.g. methane emissions from natural gas extraction and transmission) (IPCC, 2014[57]). Yet, some sources of NC-GHGs are difficult to reduce completely, including N_2O emissions from fertilizer use and CH_4 from livestock. While CO_2 accounts for the largest share of global GHG emissions in 2017 (74%), other sources of GHG include CH_4 (17%), N_2O (7%) and fluorinated GHGs (2%) (Gütschow, Jeffery and Gieseke, 2019[58]).

By definition, carbon taxes would primarily address CO_2 emissions, but could be extended to other GHGs. Most ETS (e.g. EU ETS, New Zealand, several Chinese pilots, California) cover multiple greenhouse gases (ICAP, 2019[45]). For example, the California Cap-and-Trade covers in addition to CO_2 also CH_4, nitrous oxide N_2O, and fluorinated GHGs (e.g. SF_6, NF_3, HFCs, and PFCs) (ICAP, 2019[45]). The EU ETS started covering N_2O and PFCs in addition to CO_2 since 2013.

Extending the coverage of pricing schemes towards NC-GHGs in all economic sectors would reduce mitigation costs in terms of the carbon price necessary to achieve specific mitigation targets. This was already seen in Figure 2.1 in section 2.1 where models that include multiple gases from different sources tend to require lower regional or global carbon prices to meet the NDCs. For example, the carbon price that would result from global and unrestricted international emissions trading would decrease from USD 38/tCO_2e (under unilateral achievement) to USD 8/tCO_2e (IETA, 2019[25]).

This result is in line with previous results. For a hypothetical 20% emission reduction in coalitions of different country groups (e.g. Europe, Annex I and Annex I with China), the implicit carbon price is always lower when NC-GHGs are included (Ghosh et al., 2012[59]). Depending on the coalition, the shadow carbon price in CO_2–only scenarios ranges between USD 47 to USD 151/tCO_2e whereas the price decreases to USD 19 to USD 52/tCO_2e when accounting for NC-GHGs, indicating a 60 to 66%

[18] Technically, (Abrell, 2010[51]) analyses a scenario in which the transport sector is excluded from carbon price regulation. To meet the EU's reduction goal by 2020, the cap of the EU ETS sector is tightened.

[19] In fact, existing fuel taxes in road transport can exceed USD 350/tCO_2e in some European countries (OECD, 2018[8]), so lower demand for transport fuels can substantially erode this tax base.

reduction in shadow carbon prices (Ghosh et al., 2012[59]). A cross-model comparison of 19 global energy models that are in line with stabilising radiative forcing at 4.5 watt per square meter relative to pre-industrial times by 2150[20] also concludes that carbon prices would be lower when including NC-GHG (Weyant, Francisco and Blanford, 2006[60]).[21] In fact, carbon (equivalent) prices in the multi-gas scenario would be, on average, between 23% (by 2075) and 48% (by 2025) lower than carbon prices in the CO_2-only scenario (Table B.5). The reduction in carbon prices can be as high as 73% in some models by 2025. All but one model show a reduction in carbon prices when including NC-CO_2 gases (Weyant, Francisco and Blanford, 2006[60]). Yet, some of these models do not adequately distinguish between short-lived and long-lived climate pollutants (as explained above) or do not use Global Warming Potential at all, meaning that the results should be treated with caution.[22]

Extending carbon pricing coverage to include NC-GHGs would also reduce mitigation costs in terms of GDP or welfare loss compared to BAU. The most recent study assessed for this paper indicates that annual aggregate savings of mitigation costs from a hypothetical global carbon market could increase by 29% from USD 249 billion to USD 320 billion in 2030 (IETA, 2019[25]). Previous studies suggest that including NC-GHGs in carbon pricing could reduce mitigation costs by as much as 66% (e.g. Europe) (Ghosh et al., 2012[59]). On average, cost savings would be around 50% compared to excluding NC-GHGs. In fact, after including NC-GHG, more than one third of the reduction target is met by low-cost abatement options of NC-GHGs (Ghosh et al., 2012[59]). Importantly, extending carbon pricing to NC-GHG would unambiguously benefit all countries or regions due to the gain in flexibility (Ghosh et al., 2012[59]). An earlier study that synthesises the results of 19 global energy models (Weyant, Francisco and Blanford, 2006[60]) suggests that average annual cost savings of between 25% (in 2100) and 42% (in 2025) (Table B.5). The cost reduction of 42% in 2025 when including NC-GHGs would amount to annual savings of USD 197 billion, almost equivalent to the reported size of global savings in mitigation costs from unrestricted emission trading to reach the NDCs (see Section 2.1).

[20] The representative concentration pathway (RCP) 4.5 is not compatible with the Paris Agreement as it is more likely than not to result in global temperature rise between 2 and 3 °C relative to pre-industrial levels (IPCC, 2014[113]).

[21] (Weyant, Francisco and Blanford, 2006[60]) conduct a multi-model study that synthesises the results of 19 different global energy-economic models from different modelling teams, comparing scenarios where only CO_2 emissions are reduced with scenarios where the same emission target is achieved by reducing all GHGs. The models include emissions from energy, industry, waste, land-use change and forestry (LUCF) and agriculture. The baseline scenario in all models was not harmonised and each modelling team could use its own assumptions on exogenous and endogenous parameters including population growth, economic growth, technical progress and future energy prices. All baselines excluded the emissions reductions derived from the Kyoto Protocol. The time horizon of the models is from 2000 to some point between 2025-2100.

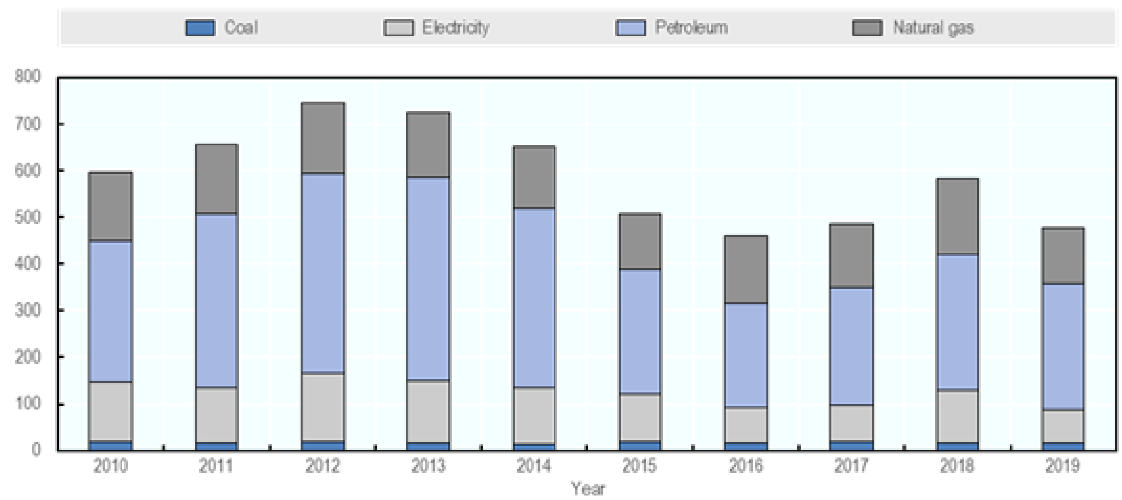
[22] Many models, notably those using the GWP metric, reduce CH_4 earlier in the multi-gas scenario. However, models not using GWP and not assuming intertemporal optimisation when minimising abatement costs reduce CH_4 emissions only towards the end of the model's time horizon (year 2150). This is because the atmospheric life-time of CH_4 (12 years) is shorter than that of CO_2 (several 100 years and more), but CH_4 is a much more potent GHG than CO_2, implying that mitigating CH_4 would reduce global warming in the very short-term. Hence, some models postpone the mitigation of CH_4 towards the end of the model's time horizon when the emission targets are approaching. In contrast, in models that use the GWP metric, CH_4 mitigation starts earlier-on if cost-effective mitigation options for CH_4 are available. This is because the GWP of CH_4 (28 for 100-year period and 85 for a 20-year period) is higher than CO_2, meaning that the effect of mitigating one ton CH_4 versus CO_2 is much higher.

4 Multilateral fossil fuel subsidy reforms

Fossil fuel support (FFS) result in artificially low energy prices, encouraging carbon-intensive modes of consumption and production and slowing down the transition to a zero-carbon economy. In 2009, G-20 leaders called countries to 'rationalise and phase-out inefficient fossil fuel subsidies that encourage wasteful consumption over the medium term' (G-20, 2009[61]). In 2016, G7 leaders committed to eliminate inefficient FFS by 2025 (G7, 2016[62]). This section provides insights on the environmental and economic effects of phasing out FFS. There are numerous studies on the environmental and economic implications of unilateral phase outs of FFS (see e.g. (IISD, 2019[63]) for a review), yet the focus of this section is on the environmental and economic effects of a multilateral approach, which was analysed in five studies.

Decreasing international oil prices, FFS reforms as well as international peer-reviews of national FFS (e.g. Canada, China, Germany, Mexico, US) contributed to a reduction of FFS between 2013 and 2016 based on an IEA–OECD estimate, covering 77 economies (OECD, 2020[64]).[23] FFS increased between 2016 and 2018, but dropped again in 2019 (Figure 4.1). Low global energy prices as a result of the Covid-19 pandemic provides a new opportunity to accelerate reform (IEA, 2020[65]). Yet, political barriers (e.g. impact on vulnerable consumers) may hinder such progress (IEA, 2020[65]).

Figure 4.1. IEA-OECD estimate on support for fossil fuels in 77 economies (USD billion)



Source: (OECD, 2020[64]).

[23] OECD categorises FFS into consumer support, producer support and general services estimate. Consumer support accounts for the largest share (75%) of support measures (IEA and OECD, 2019[73]).

4.1. Environmental effects

Global phase-out of FFS would limit global CO_2 and GHG emissions, but not enough to be in line with the goals of the Paris Agreement. The most recent study suggests that a global phase out of FFS by 2030 would reduce global CO_2 emissions by 1 to 4% or 0.5 to 2 $GtCO_2$ relative to BAU, depending on the future oil price (Jewell et al., 2018[66]). This is much less than the current NDC pledges, which add up to a reduction of 4-8 $GtCO_2$ by 2030 compared to BAU (Jewell et al., 2018[66]). Previous studies indicated that a global phase out of FFS by 2020 could reduce global CO_2 emissions by 5 (Schwanitz et al., 2014[67]) to 6% (IEA, 2011[68]) by 2035 and by 6 (Schwanitz et al., 2014[67]) to 8% (Burniaux and Château, 2011[69]) (Burniaux and Chateau, 2014[70]) by 2050 compared to BAU, respectively. Note that these early studies rely on early IEA-OECD data on fossil fuel subsidies (Burniaux and Château, 2011[69]), (IEA, 2011[68]), (Burniaux and Chateau, 2014[70]), (Schwanitz et al., 2014[67])). This data does not cover all countries, but only 37 non-OECD economies[24] which accounted for more than 90% of global FFS in 2008 (Jewell et al., 2018[66]) (Burniaux and Chateau, 2014[70]). Hence, phasing out FFS in those countries can be thought of as a first order approximation to a global phase out.

While FFS reform can deliver some emission reductions compared to BAU, it falls short of aligning incentives with the significant levels of emission reductions needed to be in line with the Paris Agreement. In the long-run, i.e. beyond 2050, emissions might start increasing again despite phasing out FFS (Schwanitz et al., 2014[67]) due to continued economic growth. In addition to the modest impact on emission reductions, FFS reform would also have a rather moderate effect on the use of renewable energy, increasing the share of renewables by 2 percentage points on average by 2030 compared to BAU (Jewell et al., 2018[66]). One of the reasons for the rather modest reduction potential of FFS reform is a fuel switch from natural gas (with high subsidies) to coal (with rather low subsidies) in major consuming countries, including India and Russia (Jewell et al., 2018[66]) (Schwanitz et al., 2014[67]). Complementary climate policy instruments, including carbon pricing or targeted support for renewables, would increase the effectiveness of FFS reform and would be necessary to meet ambitious mitigation targets (Magné, Chateau and Dellink, 2013[71]). For example, complementing the global fossil fuel phase out with a carbon tax in OECD countries and China that linearly increases from zero in 2012 to USD 100 (OECD) and 50 (China) by 2035 would reduce global energy-related CO_2 emissions by 21% in 2035 compared to BAU (Magné, Chateau and Dellink, 2013[71]). This reduction is 15 percentage points than that of a global FFS phase out alone.

Phase out of consumer FFS would reduce emissions in reforming countries, but could increase emissions elsewhere, leading to carbon leakage. While CO_2 emissions in non-OECD countries would decrease by 16%, emissions in OECD countries would increase by 7% by 2050 compared to BAU (Burniaux and Chateau, 2014[70]). Emission reductions due to FFS reform tend to be largest in energy exporting countries, including Russia and Middle Eastern and North African countries, amounting to 45% (Burniaux and Chateau, 2014[70]) and 20% by 2050 (Schwanitz et al., 2014[67]) and to 2-10% by 2030 (Jewell et al., 2018[66]) compared to BAU. Removing consumer FFS would increase domestic consumer prices, leading to a decrease of energy demand and, thus, international energy prices. For example, a global FFS phase out could reduce energy demand by 1–7% by 2030 compared to BAU (Jewell et al., 2018[66]).

Lower energy demand in energy exporting countries would translate into reduced global energy prices, which could increase fossil fuel consumption and emissions in energy importing countries (e.g. Europe and Japan). This is known as the ‘’energy price channel” (Burniaux and Chateau, 2014[70]). Due to this channel, carbon leakage can also arise if there is a global phase out of FFS (Jewell et al., 2018[66]). For

[24] In the years after the first publication of the FFS database in 2011, the IEA-OECD database successively enhanced the coverage. The database as of 2020 covers 77 economies (including all OECD countries).

example, this is the case for Europe where emissions could increase due to lower global natural gas prices despite the phase out of domestic FFS (Jewell et al., 2018[66]).

Sub-global phase out of FFS is less effective than global phase out. If only G20 countries removed FFS by 2020, then global GHG emissions would reduce by merely 1% by 2050 compared to BAU (Schwanitz et al., 2014[67]). This number would rise to almost 3%, half the reduction of a global phase out, if all Member countries of the Asia-Pacific Economic Co-operation (APEC) in addition to G20 countries removed their FFS (Schwanitz et al., 2014[67]). Carbon leakage, notably to Europe, the US and Japan, would be lower for smaller coalitions of reforming countries. For example, Japan's GHG emissions would hardly be affected by a phase out of G20 countries only, but would increase by 3 and 7% for phase outs of G20+APEC and global phase out respectively (Schwanitz et al., 2014[67]). The reason for this pattern is that the repercussions of FFS reform on international energy prices are lower for smaller coalitions. While in the G20 scenario, international oil prices would drop by 2% and international gas prices would be hardly affected at all, those prices would decrease by 5% and 10% respectively under a global phase out (Schwanitz et al., 2014[67]).

Phasing out producer FFS could lead to negative carbon leakage rates, i.e. a decrease of emissions in countries not phasing out FFS. Removing producer subsidies (i.e. transfers from taxpayers to producers of fossil fuels) leads to an increase of producer's production costs and, thus, increases both the domestic and international price for fossil fuels, reducing demand emissions both domestically and abroad (Böhringer, Schneider and Springmann, 2017[72]).[25] Yet, producer FFS account for a relatively small share of total FFS, estimated to range between 4% (Jewell et al., 2018[66]) and less than 20% (IEA and OECD, 2019[73]). The share varies across countries and tends to be higher in countries with abundant fossil fuel resources (IEA and OECD, 2019[73]).

4.2. Economic effects

Co-ordinated FFS removal would lead to aggregate welfare gains. All studies assessed for this paper indicate that joint global welfare would increase with co-ordinated FFS reform, ranging between 0.2% (Schwanitz et al., 2014[67]) by 2150[26] and 0.4% (Burniaux and Chateau, 2014[70]) in 2050 compared to BAU. Moreover, the gains in aggregate welfare would increase with an increasing number of co-operating countries and, thus, in the size of FFS removals (Schwanitz et al., 2014[67]). For example, global welfare increases for a FFS phase out in G20 countries and G20+APEC countries would amount to 0.05% and 0.1% by 2150 compared to BAU, respectively.

Yet, the welfare gains from FFS reform are expected to be shared unequally across countries. Global phase out of FFS could lead to a 0.5% welfare increase (due to lower energy prices) in OECD economies, but only to a 0.2% welfare increase in non-OECD countries in 2050 (Burniaux and Chateau, 2014[70]). Fossil-fuel importing countries, including China, India, Japan, other Asian economies, EU countries, and African countries tend to benefit most from FFS removal (Schwanitz et al., 2014[67]). Some countries, notably Russia, may not benefit directly from co-ordinated FFS removal (Schwanitz et al., 2014[67]) (Burniaux and Chateau, 2014[70]) (see next paragraph for explanation).

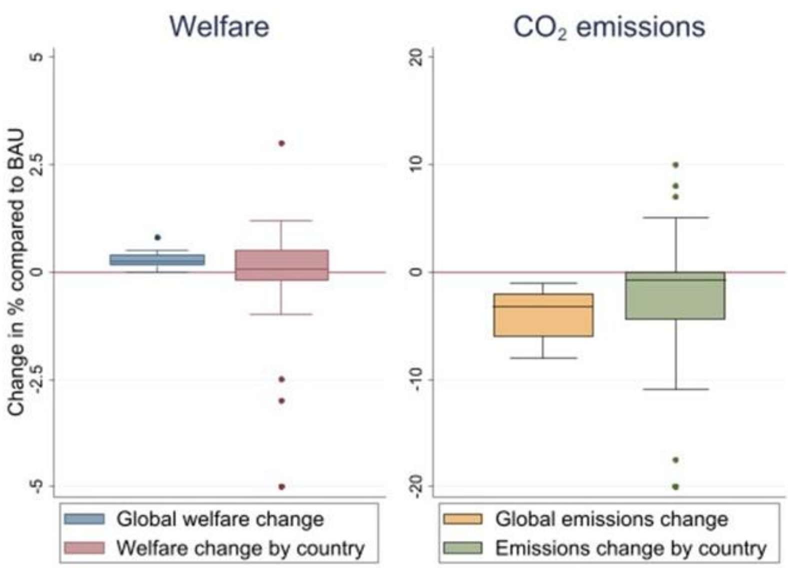
[25] Based on a scenario in which Annex II countries were to remove producer support subsidies worth (arbitrarily chosen) USD 60 billion would result in emissions reductions in Annex II and Non-Annex II countries of 175 and 150 Mt CO_2 respectively, implying a negative carbon leakage rate of 85% (Böhringer, Schneider and Springmann, 2017[72]). For 100 tons of mitigated CO_2 emissions in Annex II countries, non-Annex II countries would reduce emissions by 85 tons.

[26] (Schwanitz et al., 2014[67]) use the net present value of consumption between 2005 and 2150 as welfare metric.

Multilateral FFS removal has different welfare implications than unilateral phase outs. Unilateral FFS removal frees up public budget spent on FFS (that can be invested for other purposes or allocated to households) and could trigger a more efficient domestic allocation of resources, both of which would, in general, enhance domestic welfare. Under unilateral phase out, energy exporting countries would see the largest welfare gains in 2050 compared to BAU (4%), followed by India (2.3%), China (0.4%) and Russia (0.4%) (Burniaux and Chateau, 2014[70]). In contrast, multilateral phase out would alter the distribution of welfare gains and losses in 2050: Russia would face a direct welfare loss of 5.8%, oil-exporting countries would show no change in welfare and India and China would gain by 3.0 and 0.7% compared to BAU respectively (not accounting for indirect effects) (Burniaux and Chateau, 2014[70]). The reason is that a multilateral FFS removal would lead to a large decrease in energy demand and global energy prices, reducing the value of fossil fuel exports for energy exporters and offsetting the initial efficiency gains from the reform. A qualitatively similar result is also reported in (Schwanitz et al., 2014[67]): If only G20 countries phased out FFS, then Russia would experience welfare gains as a major reformer due to the efficiency gains, amounting to +0.4% compared to BAU. However, the gains would turn into a welfare loss compared to BAU if APEC countries joined the reform process (-0.3%) and if global subsidies were removed (-1%) due to the declining value of Russia's fossil fuel exports.

To summarise, global FFS reform would lead to an increase of welfare on aggregate, but the distribution of welfare would be unevenly distributed across countries (Figure 4.2). The boxes in Figure 4.2 show the distribution of point estimates for global welfare changes, welfare changes by country, global CO_2 emissions changes and CO_2 emissions changes by country compared to BAU from all studies assessed in this section.[27] All studies conclude that, on aggregate, global FFS reform would increase global welfare while reducing global emissions compared to BAU. Yet, as discussed above, some countries would not directly benefit from a global FFS phase out whereas other countries would actually increase CO_2 emissions compared to BAU.

Figure 4.2. Effects of multilateral FFSR on welfare and carbon emissions



Source: Authors

[27] For the interpretation of boxplots: The boxes cover the point estimates of the central 50% of data points across all studies and scenarios. The whiskers (i.e. the lines) depict the range of point estimates. The dots are outliers.

5 International sectoral agreements

Sectoral agreements can be one avenue through which (international) carbon prices can be implemented or harmonised for specific economic sectors. Such agreements have the potential to reduce sector-specific GHG emissions while addressing concerns on competitiveness and carbon leakage in industrialised countries and on economic development in emerging countries (Meunier and Ponssard, 2012[74]). Bottom-up sectoral approaches could set binding, but potentially regionally differentiated emission targets for specific sectors, including aviation and energy-intensive trade-exposed (EITE) sectors such as pulp and paper, chemicals, refining, iron and steel, nonferrous metals (primarily aluminium), and non-metallic minerals (primarily cement). In most of these sectors, the number of operating firms is limited, which reduces the cost of monitoring and eases the technical aspects of co-operation. Yet, agreement on ambitious and potentially differentiated sectoral targets among a large group of countries is still challenging politically.

Current sectoral approaches include the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming to stabilise global international aviation emissions at 2019 levels (ICAO, 2020[75])[28], and pledges of the International Maritime Organisation (IMO) to reduce GHG emissions from international shipping by at least 50% by 2050 compared to 2008 "whilst pursuing efforts to phase them out" (IMO, 2018[76]). Market-based measures (e.g. emissions trading schemes or carbon levies) would help achieve this target in a cost-effective manner. In 2019, major stakeholders, including ship-owners, put forward a USD 2/tCO_2 levy on bunker fuels in order to fund research and development projects for low-emissions ships (IEA, 2020[77]).

One study analyses the economic effects of a global carbon tax on international bunker fuels that is high enough to reduce CO_2 emissions from maritime transport by 5% in 2020 compared to 2000 (Sheng, Shi and Su, 2018[78]). The results of the study suggest that the carbon tax would have a very small impact on global trade and production. In fact, the tax would lead to a reduction of global GDP by less than 0.5% in 2020 compared to BAU. The global tax would affect countries unevenly, disproportionately reducing growth in GDP in developing or emerging countries (notably China). These countries tend to trade higher shares of low-value high volume goods (e.g. coal, iron ore) compared to developed countries. Yet, redistributing the revenues from the emission charge towards developing countries according to their trading volume could compensate for the loss in GDP growth, providing economic incentives to join a global price mechanism on international maritime transport.

Results from modelling the impact of sectoral agreements on GHG emissions in EITE sectors are limited to two studies. These studies suggest that such agreements could reduce GHG emissions - although not cost-effectively. Both studies are relatively old, and cover sectoral agreements in the cement sector

[28] In the original proposal, the ICAO Council envisioned the baseline to be the average of 2019 and 2020 emissions. Yet, as the international aviation sector has been heavily impacted by Covid-19, this baseline was changed to the pre-Covid-19 year.

(Voigt, Alexeeva-Talebi and Löschel, 2012[79]) and in energy-intensive sectors, including power and EITE (Akimoto et al., 2008[80]).[29]

Sectoral approaches could reduce GHG emissions in industrialised, emerging and developing countries regardless of whether they stipulate absolute emissions reduction targets (Voigt, Alexeeva-Talebi and Löschel, 2012[79]) or emission intensity targets (Akimoto et al., 2008[80]) in the sectors covered. Clearly, implementing sectoral emission intensity targets would reduce GHG emissions compared to BAU (Akimoto et al., 2008[80]). The result of one scenario in (Voigt, Alexeeva-Talebi and Löschel, 2012[79]) suggests that sectoral targets in the cement sector in China (46.6% of global cement production; 14.4% reduction of cement emissions by 2020 compared to BAU), Brazil (1.7%; 6.9%), and Mexico (1.6%; 8.3%) would reduce growth of global CO_2 emissions between 2005 and 2020 by a moderate 0.28 percentage point (from 25.39% to 25.01%) compared to a scenario without sectoral targets.[30] Yet, if China, Brazil and Mexico had the same percentage emissions reduction targets for their cement sectors, but would hypothetically be integrated in the EU ETS (which covers the cement sector) instead of unilaterally meeting their sectoral reduction targets, then global CO_2 emissions would actually increase compared to BAU (25.51%) (Table B.6). The reason is that the link with the EU ETS would raise the carbon prices of Brazilian, Chinese and Mexican cement producers, causing carbon leakage to other parts of the world, which have a higher carbon intensity of cement production.

Sectoral agreements could also lessen competitiveness concerns of sectors and could increase the welfare of participating countries compared to unilateral achievement of sectoral mitigation targets. For example, the EU countries' output reduction in the cement sector would decrease from 1.1% to 1% if emerging economies (China, Brazil, Mexico) also adopt sector-specific mitigation targets in the cement sector compared to those countries not having sector-specific targets (Voigt, Alexeeva-Talebi and Löschel, 2012[79]), (Table B.6). Hypothetically integrating these countries' cement sectors in the EU ETS so that all cement facilities face the same carbon price would decrease the EU cement output loss further to 0.7% (Table B.6). If the cement sector in Brazil, China and Mexico faced the same carbon price as facilities under the EU ETS, this would improve the welfare of all these countries (EU, China, Mexico, Brazil) compared to a scenario with unilateral sectoral targets. Yet, compared to BAU, the EU and China would gain in welfare while Brazil would experience no change and Mexico would not benefit. In contrast, unilateral sectoral targets would reduce the welfare in all emerging economies compared to BAU (Table B.6).

Sectoral approaches, in particular sector-specific emission intensities would not be cost-effective (Akimoto et al., 2008[80]). The results of (Akimoto et al., 2008[80]) suggest that emissions can be reduced more cost-effectively with other policy instruments than with global sectoral emission intensity targets. In this study, sectoral emission intensity targets are defined for a large set of sectors (e.g. power, iron

[29] Most of the studies on sectoral agreements explore the technical potential and the cost-effectiveness of international co-operation in the low-carbon transition of specific sectors, including cement (Cembureau, 2013[111]) or iron and steel (WSA, 2019[112]). While these studies are informative and give detailed insights into specific sectors and their potential for cross-country co-ordination, they generally lack international and cross-sectoral repercussions and are, thus, not further discussed here.

[30] Besides the BAU scenario, (Voigt, Alexeeva-Talebi and Löschel, 2012[79]) analyse in total 7 different scenarios out of which 3 are particularly relevant for this study. First, PLEDGES assumes that some countries reduce emissions according to their Copenhagen pledges (e.g. emissions reduction by 2020 compared to 1990 by 25% (EU), 20% (Japan), Russia (15%), US (3.86%), Canada (-2.93%), Australia and New Zealand (-13%). Second, in addition to PLEDGES China, Brazil and Mexico unilaterally reduce their cement sector emissions by 14.4%, 6.9% and 8.3% (UNI_H). Third, emissions reduction targets as in UNI_H, but cement factories in China, Mexico and Brazil are linked to the EU ETS (INT_0).

and steel), vehicles (e.g. bus, private cars) and appliances.[31] For example, a global uniform carbon price that exponentially increases from USD 10 in 2013 to USD 100 in 2050 would lead to a larger reduction of global emissions by 2050 than sectoral approaches, and would deliver the emissions reduction at 30% lower average cost per t/CO_2 abated (Table 5.1). Comparing the performance of sectoral approaches to a cost-optimal reduction of 50% GHG emissions by 2050 relative to 2004 ("Vision 50/50") indicates that the costs of the sectoral approach (measured as average global carbon price in USD/tCO_2) would be in a similar range to "Vision 50/50" whereas the mitigation potential would be only half as big compared to "Vision 50/50" (Table 5.1).

Table 5.1. Comparing environmental effectiveness and mitigation costs of sectoral approaches with alternative measures

Scenario	Global emissions by 2050 in GtCO_2e	Average global carbon price in USD/tCO_2e
BAU	60	NA
Global carbon price	21.7	31.8
Vision 50/50	13.0	49.6
Sectoral Approach	22.5	45.4

Note: For a description of the scenarios, see footnote 31.
Source: Authors, based on (Akimoto et al., 2008[80]).

[31] The scenarios in (Akimoto et al., 2008[80]) are as follows: First, in the 'carbon price' scenario a global carbon price is set at USD 10/tCO_2e in 2013 and rises exponentially to USD 100/tCO_2e in 2050. Second, the 'Vision 50/50' scenario assumes that global CO_2 emissions in 2050 are halved compared to 2004 and this is achieved through a uniform global carbon price. Third, the scenario 'sectoral approach' establishes emissions intensity targets for several sectors (power, EITE), vehicles (car, bus and truck), and appliances (TV, air conditioner and refrigerator) by model-region and by time for all 54 model regions. The intensity targets are similar to those that prevail in the 'Vision 50/50' scenario. Yet, as the 'sectoral approach' scenario does not cap emissions (compared to 'Vision 50/50), emissions are higher than in 'Vision 50/50' due to, e.g. economic growth.

6 International co-ordination on mitigating carbon leakage

Co-ordinated regional implementation or increase of carbon pricing can reduce carbon leakage within the coalition. Carbon leakage refers to a situation where the benefits of emissions reduction in a given location are partially offset by emissions increases elsewhere. As GHG-intensive economic activity may relocate to countries with lower carbon prices, this would lead to welfare losses in the implementing countries, including loss of jobs and tax revenues, while undermining the environmental effectiveness of carbon pricing. Carbon leakage predominantly results from two main channels (Branger and Quirion, 2014[81]) or (Paroussos et al., 2015[82]): First, the trade channel according to which firms in higher price countries would lose market share since their input costs increase relative to foreign competitors. To date, ex-post evaluation of carbon pricing schemes have not found evidence on negative competitiveness effects (Venmans, Ellis and Nachtigall, 2020[83]). Yet, this may be because of low carbon price levels or complementary measures, including free allocation of allowances. Second, the energy channel, stipulating that lower demand for fossil fuels as a response to carbon pricing in some countries would reduce global fossil fuel prices, leading to higher use of fossil fuels in less regulated countries. Estimates, mostly based on CGE models, have found the second channel to be the dominant one (Branger and Quirion, 2014[81]).

In the absence of deeper international co-operation, regional or unilateral anti-leakage policies could address carbon leakage.[32] Fostering international co-operation through extending the regional coverage of carbon pricing and reducing cross-country carbon price differences would limit the extent of carbon leakage in the first place. Yet, if deeper international co-operation is not feasible and cross-regional carbon price differences persist, anti-leakage policies could be employed in order to offset some of the negative effects of regional differences in carbon prices. However, these policies are clearly second best and result in a lack of global or international co-operation. Economic theory and the results of the modelling studies suggest that these policies could i) increase the environmental effectiveness (e.g. by reducing carbon leakage, section 6.1); ii) enhance economic outcomes, notably for coalition members (section 6.2); and/or iii) incentivise deeper international co-operation (section 6.3).

Policy makers have several instruments available to them to mitigate the extent of carbon leakage. Most existing carbon pricing schemes address carbon leakage through preferential tax rates in case of carbon or fuel excise taxes or free allocation of emission allowances in case of ETS, notably for the energy-intensive trade-exposed industry which are deemed to be most affected by differences in international carbon prices (Ellis, Nachtigall and Venmans, 2019[84]). Border carbon adjustments (BCA) – the instrument most assessed in the economics literature - would lead to the carbon content of imports being priced at the same level of carbon prices as for the national firms so that international competitors

[32] BCA, tax rebates or free allowances are generally a reaction to lack of co-operation, and aim to offset some of the negative effects of regional differences in carbon prices. A perfectly co-ordinated international climate policy (e.g. through a uniform global carbon price) would make these instruments redundant.

face the same conditions than national firms in a given national market.[33] BCA is in place in the Californian Cap-and-Trade system for electricity. In 2019, the European Commission announced that BCA could be an integral part of the Green New Deal to address carbon leakage and level the playing field of European industry with foreign competitors. BCA have a number of practical (e.g. measurement of the carbon content), legal (e.g. WTO compatibility) and political challenges (e.g. feasibility, risk of amplifying retaliation measures), which need to be carefully weighed against the potential benefits (Cosbey et al., 2019[85]).

6.1. Effects of international co-ordination and anti-leakage policies on GHG emissions

The leakage rates of regional or unilateral climate policy is estimated to range between 5 and 25% with a mean of 14% (Branger and Quirion, 2014[81]). This is based on a meta-analysis, covering 25 studies and 310 estimates of carbon leakage rates under different assumptions and models (Branger and Quirion, 2014[81]). The leakage rate is a key indicator to measure the extent of carbon leakage. A rate of 5% implies that a climate policy leading to a reduction of 100 units of CO_2e emissions within the climate coalition would increase emissions by 5 units of CO_2e in countries outside the coalition. A more recent literature review summarising 54 studies concludes that leakage rates would be in the range of 10 – 30% (Carbone and Rivers, 2017[86]). Studies find that the leakage rate would depend on a number of factors:

- More stringent mitigation targets would tend to result in higher leakage rates (Branger and Quirion, 2014[81]). The reason is that more stringent mitigation targets would imply higher implicit carbon prices, leaving more scope for carbon leakage. In view of the ambition needed to achieve the goals of the Paris Agreement, this highlights the importance of international co-operation enhance environmental effectiveness and mitigate carbon leakage. The results of one study suggest that that the leakage rate increases by more than a third from 15.3% to 21% if Europe increased hypothetical abatement targets from 10% to 30% relative to BAU (Böhringer, Carbone and Rutherford, 2012[87]). This pattern also holds true for larger coalitions (e.g. Annex I or Annex I + China). This implies that for environmental effectiveness cooperation becomes even more important for more stringent targets.
- Model assumptions and choice also have a large influence on estimated leakage rates. First, carbon leakage estimates are higher in CGE models than in partial equilibrium models because the former explicitly includes international repercussions that are driving leakage. Second, higher trade elasticities (i.e. fewer trade frictions) increase leakage, allowing price shocks to transmit more heavily in international energy markets.

Policymakers have a range of options to decrease the extent of carbon leakage and, thus, the need for anti-leakage policies. These options include

1. Fostering international co-operation: Larger coalitions would lead to a lower leakage rate while broadening the regional coverage of GHG emissions, making climate policy more effective. In fact, the size of the coalition of co-operating countries is the single most important factor that determines the extent of carbon leakage (Branger and Quirion, 2014[81]). This also highlights the importance of international co-operation as a first-best policy before turning to anti-leakage instruments. As the coalition size increases, the number of regions where emissions could leak to decrease (to zero, in the case of a global coalition with a uniform carbon price). The results from the meta study suggest, on average, a 37% reduction of the leakage rate if instead of only

[33] In addition to pricing the carbon content of imports, some proposals of BCA also suggest national firms to get refunded the carbon costs of their exported goods to level the playing field in the international market.

European countries, all Annex I countries except Russia reduced their CO_2 emissions by 15% relative to a benchmark (Branger and Quirion, 2014[81]). In some studies reduction of leakage rates for the same regional extension of the coalition could be as high as 60% (Ghosh et al., 2012[59]) (Böhringer, Carbone and Rutherford, 2012[87]). Adding China to the coalition would reduce the leakage rate by an additional 50% (Ghosh et al., 2012[59]).

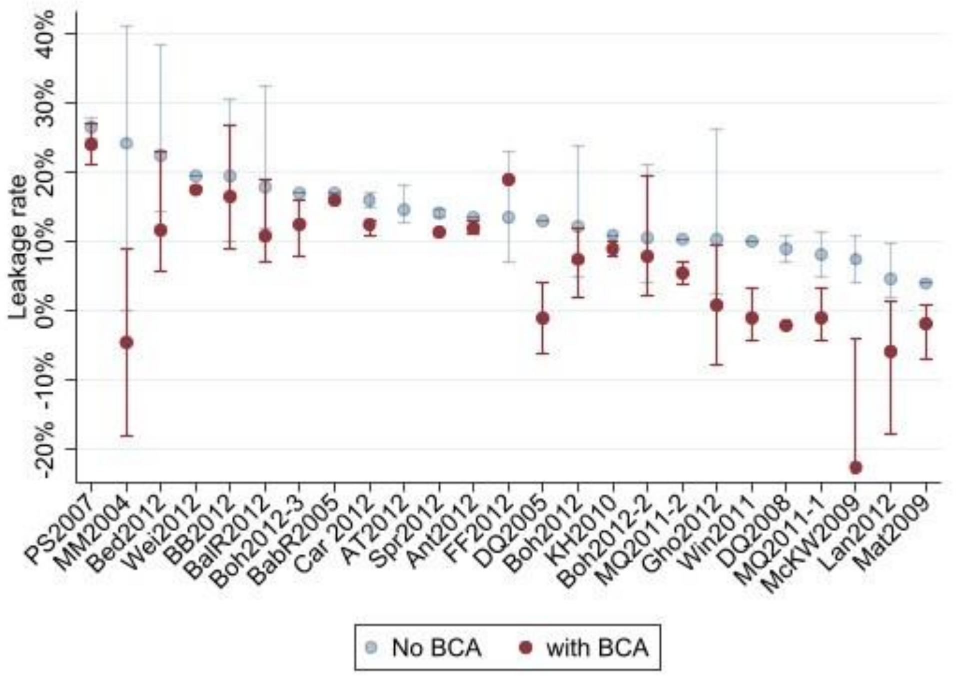
2. Extending the coverage of carbon pricing to other GHGs. Larger coverage of GHGs (including NC-GHGs) would decrease carbon leakage (see section 3.2) due to increased flexibility of meeting abatement targets. Increased flexibility would reduce mitigation costs as well as implicit carbon prices, lowering the incentives for firms to offshore emissions and limiting the decline in domestic fossil fuel demand, which could trigger repercussions in global energy markets through the energy market channel. The results of one study suggest that including NC-GHG to meet mitigation targets (reducing GHG emissions by 20% compared to a benchmark) would reduce the leakage rate for a coalition of European countries by 54% (from 26% to 12%) (Ghosh et al., 2012[59]). Reductions of leakage rates are in a similar order of magnitude for other coalitions, including Annex I without Russia (44%) and Annex I + China (53%) (Ghosh et al., 2012[59]).
3. Harmonising the carbon price within the climate coalition would tend to reduce the leakage rate (Branger and Quirion, 2014[81]). This is because a harmonised price minimises the trade repercussions in global energy markets, as discussed in Section 2.2.2. In fact, linking carbon markets within the coalition could lead to a 22% reduction (from 4.1% to 3.2%) of the leakage rate (Lanzi, Chateau and Dellink, 2012[88]).

All unilateral anti-leakage policies are expected to reduce the risk of leakage to some extent. For example, BCA would reduce the leakage rate on average by 6 percentage points from 14 to 8% (Branger and Quirion, 2014[81]). Yet, the reduction in the leakage rate is estimated to be between 1 and 15 percentage points with some outliers as high as 30 percentage points (Figure 6.1). The results of more recent studies show estimated reductions in leakage rate of similar magnitude (Antimiani et al., 2016[89]); (Böhringer, Rosendahl and Storrøsten, 2017[90]), (Böhringer, Carbone and Rutherford, 2018[91]); (Larch and Wanner, 2017[92]).

Among all anti-leakage instruments, BCA would be one of the most effective instruments. BCA would have the largest effect on reducing the leakage rate compared to free allocation of allowances and industry tax exemptions (Böhringer, Carbone and Rutherford, 2012[87]), (Monjon and Quirion, 2011[93]). The results from one study suggest that BCA would reduce the leakage rate by between 34 and 51% across scenarios with different hypothetical coalitions (Europe, Annex I, Annex I + China) and different mitigation targets (10% , 20%, 30% reduction compared to BAU) (Böhringer, Carbone and Rutherford, 2012[87]). In contrast, free allocation of allowances would reduce the leakage rate between 10 and 15% whereas tax exemptions would lead to a reduction of 7–15% (Böhringer, Carbone and Rutherford, 2012[87]).

The reason for BCA's relative effectiveness is that it would directly level the playing field between regulated firms in coalition countries and firms outside the climate coalition compared to other instruments. In fact, the output loss of EITE firms under BCA is significantly smaller than the loss under free allocation or tax exemptions, in some scenarios by up to 75% (Böhringer, Carbone and Rutherford, 2012[87]). Yet, a combination of free allowances and very high levels of product-specific consumption taxes on all purchases of EITE goods would prevent carbon leakage even more effectively (Böhringer, Rosendahl and Storrøsten, 2017[90])). In fact, output-based allocation of free allowances in combination with a consumption tax would be equivalent to imposing BCA if the consumption tax is equal to the rate of output-based allocation (Böhringer, Rosendahl and Storrøsten, 2017[90]). For higher consumption tax rates than that of output-based allocation, the leakage rate would be reduced further because it would further reduce domestic demand and, thus, production of EITE goods in foreign countries.

Figure 6.1. Leakage rate in selected studies with and without BCA



Note: Mean, minimum and maximum values with or without BCAs, ranked by mean value without BCAs. Intervals refer to different scenarios in the studies (e.g. different coalitions, different mitigation targets, different sectors covered).
Source: (Branger and Quirion, 2014[81]).

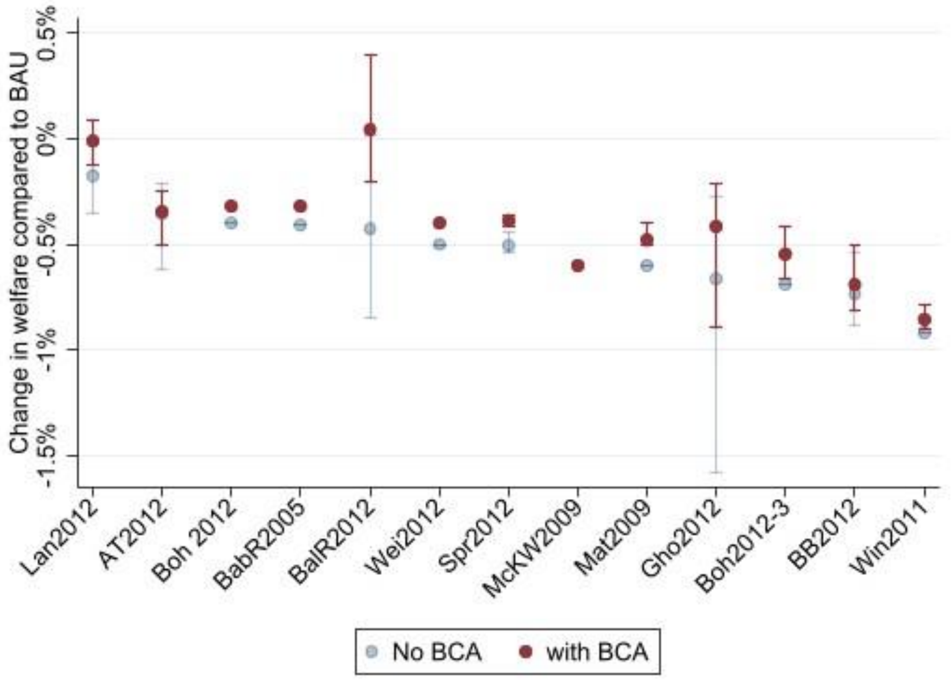
In most studies, however, anti-leakage policies would be unable to completely offset leakage. For example, the majority of studies in (Branger and Quirion, 2014[81]) show positive leakage rates even after the implementation of BCA (Figure 6.1). This is because these policies only target the trade channel, but do not explicitly address the energy channel. Hence, some studies also suggest that BCA would be more effective in terms of reducing leakage for rather small coalitions which have less influence on global fossil fuel prices (Burniaux, Chateau and Duval, 2013[94]). The results of a few studies suggest that implementing BCA would even result in negative leakage rates, meaning that BCA offsets the negative competitiveness effect, and reduces emissions in non-coalition countries (Branger and Quirion, 2014[81]). [34] Regarding other anti-leakage instruments (e.g. tax exemptions and free allocation), the results from (Böhringer, Carbone and Rutherford, 2012[87]) suggest that leakage rates are still substantial after employing these instruments, ranging between 14-19% for different emission reduction targets of the European Union (compared to 15-21% without any anti-leakage instrument).

[34] Negative leakage rates imply that BCA leads to emission reductions in non-coalition countries. In these cases BCA would lead to decreased imports of carbon-intensive goods relative to a scenario without any climate policy.

6.2. Economic and welfare effects of anti-leakage instruments

BCA would be expected to increase welfare for the coalition countries compared to not implementing BCA.[35] Climate policy typically involves mitigation costs (or welfare losses) for coalition countries, which could be aggravated by negative competitiveness effects due to sub-global action because coalition members would face higher carbon prices than non-members. The results of (Branger and Quirion, 2014[81])'s meta-study suggest that BCA would reduce the welfare loss of coalition countries in all studies reviewed (Figure 6.2). The change in welfare compared to BAU in the abating coalitions would range from -1.6% to -0.02% without BCA and from only -0.9% to +0.4% with BCA. Hence, BCA would reduce coalition countries' welfare loss by up to 44%. The results of newer studies ((Böhringer, Rosendahl and Storrøsten, 2017[90]), (Böhringer, Carbone and Rutherford, 2018[91]); (Larch and Wanner, 2017[92])) are also within the range of Figure 6.2.[36]

Figure 6.2. Welfare variation in different models with and without BCA



Note: Mean, minimum and maximum values with or without BCAs, ranked by mean value without BCAs. Intervals refer to different scenarios in the studies (e.g. different coalitions, different mitigation targets, different sectors covered).
Source: (Branger and Quirion, 2014[81]).

[35] Note that the environmental impact is not taken into account in the welfare estimation. In addition, the calculation of welfare typically refers to the whole country. Some actors within the country can be affected differently by anti-leakage policies.

[36] The result of (Böhringer, Rosendahl and Storrøsten, 2017[90]) suggest that coalition countries' welfare would reach a maximum for consumption tax rates between 80 and 160% of the output-based allocation rate for free allowances, depending on the substitutability between foreign and domestic goods. Given that a consumption tax rate of 100% is equivalent to BCA (see above), choosing other rates would be welfare-improving.

One of the drivers for the reduction in welfare losses of coalition countries could be that BCA tend to limit the reduction of production volume in EITE sectors due to climate policy. The vast majority of studies show that BCA would increase the production in EITE sectors, but would not be able to restore output levels that would have prevailed without any climate policy (Figure B.2). Output change of coalitions' EITE sectors would vary from −0.1% to −16% without BCA and from +2.2% to −15.5% with BCA compared to BAU (Figure B.2). In 5 out of 18 studies that report output of EITE sectors, the output of coalitions' EITE industries in countries with BCA would even exceed that under BAU (i.e. without any climate policy). The reason could be that coalition's EITE firms have a relatively low carbon intensity and, thus, would increase their international competitiveness vis-à-vis international competitors if all firms faced the same carbon price.[37] Yet, in most studies BCA would not be able to restore the output levels of EITE sectors to BAU levels. This is because EITE industries tend to be more adversely affected by carbon pricing itself than by any losses in international competitiveness (Burniaux, Chateau and Duval, 2013[94]). In addition, but less importantly, BCA would also increase the prices of EITE sectors' imported intermediate inputs such as steel products used in the petrochemical and chemical sector (Böhringer, Müller and Schneider, 2015[95]). Interestingly, the results relating to EITE's output reduction strongly differ between different model types. While CGE models would estimate output reductions, ranging from 0% – 3%[38], output reductions in sectoral partial equilibrium models would range between 8% - 15% (Branger and Quirion, 2014[81]).[39] A more recent literature review on CGE models concludes that unilateral climate policies that would reduce economy-wide GHG emissions by 20% would reduce EITE output by 5% percent and EITE exports by 7% (Carbone and Rivers, 2017[86]).

Most studies suggest that BCA would increase the coalition countries' welfare compared to a situation without BCA, but would not be able to restore the welfare levels of BAU scenarios (i.e. without climate policy) (Figure 6.2). The reason is that coalition countries still face direct abatement costs associated with the mitigation targets (and the carbon prices) which translates into higher consumer prices. Surprisingly, a few studies even suggest that the welfare of coalition countries under BCA could be higher than under BAU (Böhringer, Balistreri and Rutherford, 2012[96]), (Böhringer, Carbone and Rutherford, 2018[91])). This result can derive from trade effects, according to which indirect terms-of-trade benefits from taxing exports of foreign countries realised by coalition countries (e.g. OECD) more than offset direct abatement cost for major industrialised regions such as Germany, the United States and Japan (Böhringer, Carbone and Rutherford, 2018[91]). Conversely, one study finds that BCA would imply slightly larger welfare losses of a coalition of EU27 countries (-5.78%) than unilateral action without BCA (-5.52%) compared to BAU (Antimiani et al., 2016[97]). The reason is that tariffs on imports would increase the production costs of downstream firms which would reduce output and would lose international competitiveness vis-à-vis foreign firms.

BCA are expected to have large distributional effects, reducing the welfare of most countries outside the coalition. BCA would transfer part of the mitigation costs to the non-coalition countries whose exports are taxed (Branger and Quirion, 2014[81])**.** This finding is consistent with that of more recent studies ((Burniaux, Chateau and Duval, 2013[94]), (Dong and Walley, 2012[98]), (Böhringer, Carbone and Rutherford, 2018[91]), (Larch and Wanner, 2017[92])). Energy-exporting countries (OPEC, Russia) and countries with high shares of carbon-intensive export-oriented industries (e.g. China) would

[37] This results also depends on the assumed design of BCA. In some cases, BCA also includes export rebates in addition to import tariffs, meaning that regulated firms do not face carbon costs for exports to level the playing field on global product markets.

[38] With the exception of two studies in which the numbers are slightly higher.

[39] Sectoral partial equilibrium models usually focus on one or few sectors that are affected by a specific regulation, not accounting for interactions with the rest of the economy and with other countries (Carbone and Rivers, 2017[86]). The missing interactions may explain the relatively high output losses in partial equilibrium models compared to CGE models.

typically incur the largest welfare loss due to BCA (Weitzel, Hübler and Peterson, 2012[99]) (Böhringer, Carbone and Rutherford, 2018[91]). The reason is that BCA would increase the production costs of non-coalition countries' exports to coalition countries (thus reducing the welfare of export-oriented countries). This would not only reduce output in non-coalition countries, but also demand for energy carriers, further reducing international energy prices and welfare of energy-exporting economies. In contrast, low-income countries may experience an increase in welfare in response to BCA because they benefit from lower international fuel prices (through mitigation action of coalition countries and BCA) while having only little trade with coalition countries and thus, little exposure to import tariffs (Böhringer, Carbone and Rutherford, 2018[91]).

BCA could reduce aggregate global welfare compared to unilateral policy implementation without BCA. Model results indicate that the welfare losses incurred by non-coalition countries would more than offset the welfare gains of coalition members, resulting in lower aggregate welfare levels. This is the case in all three studies in (Branger and Quirion, 2014[81])'s review that report global welfare (Lanzi, Chateau and Dellink, 2012[100]) (Böhringer, Carbone and Rutherford, 2012[101]) (Mattoo et al., 2009[102])) More recent studies are also in line with this finding, suggesting that global welfare would decrease by roughly 6% when comparing a scenario of BCA versus no-BCA (Böhringer, Carbone and Rutherford, 2018[91]).[40]

Addressing carbon leakage with other anti-leakage instruments instead of BCA (e.g. by allocating free allowances or tax exemptions) would change the welfare implications for both coalition and non-coalition countries. Allocating free allowances or tax exemptions for industry would transfer income from governments to industrial sectors without necessarily changing international prices for energy or final products and trade patterns. In contrast to BCA, this would not negatively affect the welfare of non-coalition countries, but would also not benefit the coalition countries (Böhringer, Carbone and Rutherford, 2012[101]). As such, free allowances or tax exemptions would preserve the distribution of costs between coalition countries and non-coalition countries (which may or may not benefit from unilateral climate action depending on trade linkages) of unilateral climate action (Böhringer, Carbone and Rutherford, 2012[101]). Yet, both instruments would lead to higher global economic costs (in terms of GDP) compared to implementing BCA because they are less effective in meeting a given emissions reduction target (Böhringer, Carbone and Rutherford, 2012[101]) However, when accounting for the distribution of costs between (relatively wealthy) coalition countries and (less wealthy) non-coalition countries, both instruments could increase global welfare compared to both BCA and a scenario of unilateral climate action without anti-leakage policies, depending of the degree of inequality aversion (Böhringer, Carbone and Rutherford, 2012[101]).[41]

[40] The study of (Böhringer, Carbone and Rutherford, 2018[91]) assumes that OECD countries would decrease their emissions by 20% compared to BAU. In the reference scenario without any additional policy, OECD countries would experience a welfare loss of -0.5% and non-OECD countries of -0.7%. The welfare losses for non-OECD countries are due to policy-induced spill-overs of international product prices (energy and final product). With BCA OECD countries would actually improve the welfare (+0.1%) whereas non-OECD countries' welfare would decrease to -2.3% compared to BAU.

[41] Complementing output-based allocation of free allowances with a consumption tax would shift part of the mitigation costs from coalition members to non-coalition members, implying that non-coalition members would have lower welfare levels compared to scenarios without consumption tax (Böhringer, Rosendahl and Storrøsten, 2017[90]). Yet, the consumption tax is expected to reduce the welfare loss of coalition countries (due to unilateral climate policy) and also the joint welfare loss of coalition and non-coalition countries compared to free allocation of allowances. The joint welfare loss in this study could be minimised for consumption tax rates that would be equivalent to BCA (Böhringer, Rosendahl and Storrøsten, 2017[90]).

6.3. Strategic incentives to join climate coalitions

BCA's potential to provide incentives for non-coalition countries to join any climate coalition is limited. As noted above, BCA would usually be expected to reduce the welfare of non-coalition members compared to a situation without BCA, providing incentives for countries to avoid the negative welfare effects by joining the climate coalition (Al Khourdajie and Finus, 2018[103]). In fact, the potential use of BCA by coalition members would provide incentives for most countries to join a climate coalition (Böhringer, Carbone and Rutherford, 2016[104]). However, BCA would entice more ambitious climate policy outside the coalition only for very low levels of climate ambition (and thus carbon prices) of the coalition (Nordhaus, 2015[105]). In fact, BCA would not be able to create a stable global climate coalition even for very low levels of carbon prices. While club participation could be 13 out of 15 model regions for carbon prices below USD 10, participation decreases to 2 regions for carbon prices above USD 10 (Nordhaus, 2015[105]). Energy-exporting countries tend to have the largest incentive to join the coalition as they are most adversely affected by BCA and benefit from joining the coalition to avoid carbon tariffs (Böhringer, Carbone and Rutherford, 2016[104]); (Weitzel, Hübler and Peterson, 2012[99]).[42] Other countries and regions (e.g. middle income countries) would be expected to only join the coalition for very high hypothetical border tax rates, being 10 to 6.6 times larger than the carbon price in the coalition, which is clearly not compatible with WTO provisions (Weitzel, Hübler and Peterson, 2012[99]). Some countries and regions (e.g. low income countries) would never have an incentive to join the coalition even for very high levels of border tax rates (Weitzel, Hübler and Peterson, 2012[99]). This is because India and low income countries are net importers from coalition countries. Hence, they benefit from export rebates of coalition countries while being hardly affected by the increased import tariff of the coalition.

Other hypothetical measures (e.g. trade tariffs) would be more effective than BCA to incentivise non-coalition countries to join the coalition, but would likely breach multilateral trade rules, questioning the political feasibility. The use of trade tariffs against non-coalition members could also trigger participation in global climate coalitions because tariffs would increase the cost of non-participation (Lessmann, Marschinski and Edenhofer, 2009[106]) (Nordhaus, 2015[105]).[43] Trade tariffs of 1% (Nordhaus, 2015[105])

[42] (Böhringer, Carbone and Rutherford, 2016[104]) assume that a coalition of Annex-I countries unilaterally reduces *global* emissions (e.g. 10% compared to BAU) through regulation of domestic emissions. Coalition members may deploy carbon tariffs against non-coalition countries with unregulated emissions. Non-coalition countries may respond by adopting emission regulations, implementing carbon tariffs or by taking no action. Carbon tariffs would be a credible threat for all coalition model-regions. BCA would entice China and Russia - two major polluters outside the coalition - to accept binding emission reduction targets whereas all other model-regions would retaliate through implementing tariffs. The motivations to co-operate are twofold. First, both countries would benefit from avoiding carbon tariffs. Second, China and Russia would profit from less emission reductions in Annex I countries – the major destination market for China and Russia's exports and the origin of some imports. This is because the assumption of the model is that global emissions are kept constant in all scenarios. Hence, if China and Russia join the climate coalition, emission reductions in Annex I countries needs to be lower. Allocating emission reductions across a larger coalition would also result in a 50% decrease of global welfare cost of achieving a 10% reduction in global emissions compared to a scenario in which only Annex I countries abate emissions. These key findings also hold for different emission reductions targets of the coalition and different key parameters of the CGE model.

[43] (Nordhaus, 2015[105]) uses the static C-DICE (coalition DICE) model – an IAM with game-theoretic extensions with only one time period (2011), covering 15 model regions. The tariff rate on imports (to incentivise non-coalition countries to join the club) is varied between 0% and 10% in intervals of 1. The levels of club participation are analysed for agreements on four different levels of carbon prices USD12.5, USD25, USD50 and USD100/tCO_2e. Model regions would join the carbon club if this improved their welfare. They need to decide between the costs of trade tariffs when staying outside the coalition and the costs of climate mitigation when joining the coalition. One important deviation from usual model assumptions is that Nordhaus' model includes climate damages so that more

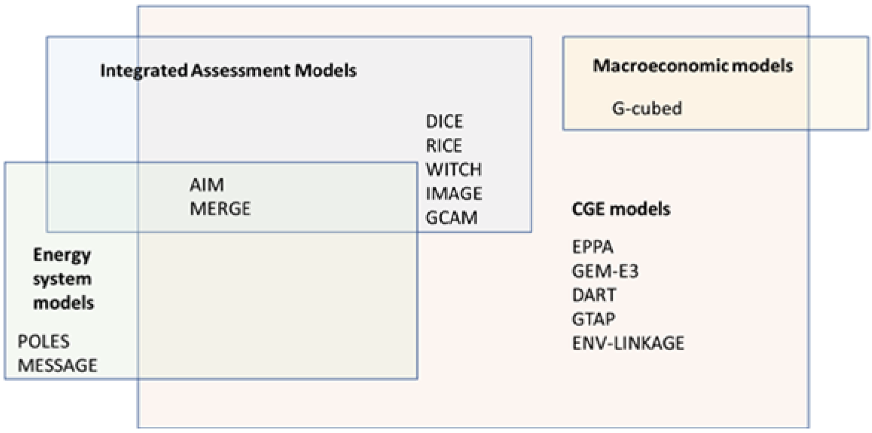
and 1.5% (Lessmann, Marschinski and Edenhofer, 2009[106]) would be sufficient to form a stable global climate coalition for low levels of climate ambitions (e.g. global carbon price of USD 12.5 per tCO_2e) or low (assumed) trade elasticities. The level of trade tariffs to maintain global co-operation would need to increase for higher trade elasticities (e.g. to 4%, (Lessmann, Marschinski and Edenhofer, 2009[106])) and higher mitigation ambition (e.g. to 3% for USD 25 per tCO_2e, (Nordhaus, 2015[105])). However, for higher global carbon prices (USD 50 and USD 100 per tCO_2e), trade tariffs of even 10% would not be sufficient to constitute a stable global climate coalition although could lead to participation of some regions (Nordhaus, 2015[105]).

stringent climate policy leads to reduced global climate damages that accrue to all countries (regardless of whether being club member or not). Economic gains from co-operation could be substantial, amounting to USD 312 billion per year in the most successful coalition with a price of USD 50/tCO_2e. Lower levels of ambition and lower participation rates in the coalition would reduce the gains of the coalition.

Annex A. Background information on types of models

This section gives some background information on economic modelling. It categorises and describes the main types of models that are used in the studies of this literature review to assess the economic and environmental outcomes of different climate policy settings. In some cases, this is helpful to understand the differences in effects when the same policy scenarios are analysed different with different models. A graphical representation of different model classes is presented in Figure A.1

Figure A.1. Types of models



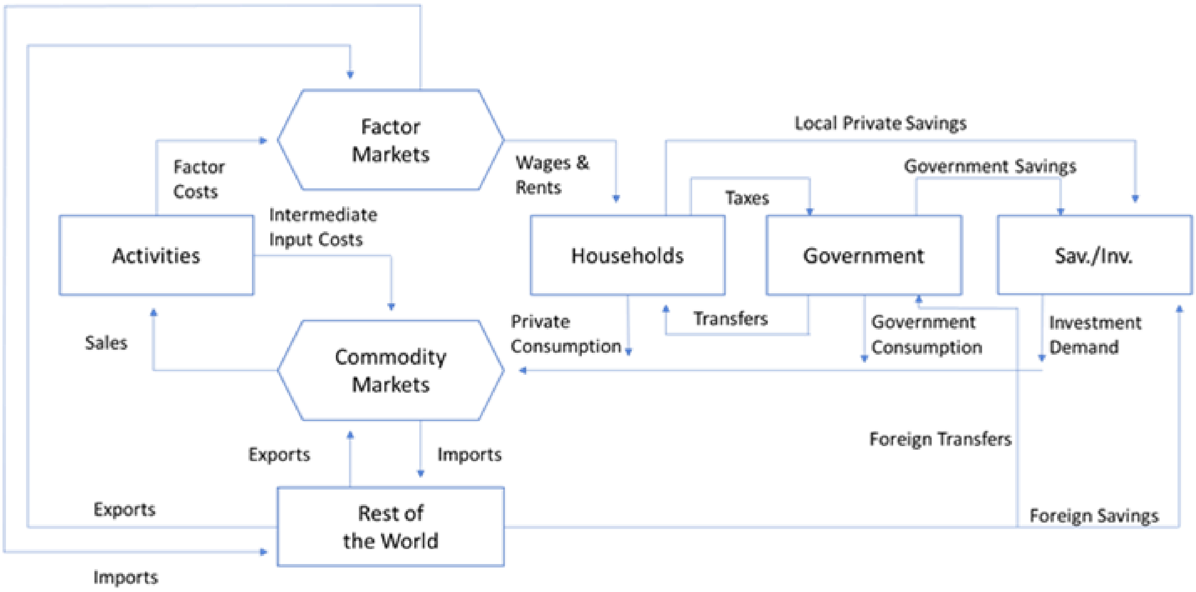
Source: Based on (Springer, 2003[12]).

Most studies in this literature review employ Integrated Assessment Models (IAMs) and Computable General Equilibrium (CGE) models. Other models like energy system models or macroeconomic models can also be employed to analyse the economic or environmental effects of international co-ordination. Typically, the time horizon of CGE models is rather short, ranging between 2030 or 2050, whereas that of IAMs is rather long, deriving results for as far in the future as 2100 and in some cases even further.

IAMs are used to explore scenarios and roadmaps of different policy objectives (e.g., limiting warming to 2°C, achieving NDCs). Given assumptions on, among others, GDP growth, population growth policies and technology, IAMs would inform researchers and policy makers about economic and environmental outcomes as well as energy pathways and land use based on intertemporal cost minimisation of firms and utility maximisation of representative agents (Figure 1.1 in Box 1.1). IAMs have a representation of economic, energy, environmental systems with the latter mostly including land and climate systems and are, thus, useful to see the interdependencies and trade-offs between choices made in these systems. The climate module also informs about climate impacts, including regional sea level rise, temperature increase and the damages thereof, yet significant uncertainty on the impacts and the damages remains. In addition, due to the relatively long time horizon, results from IAMs tend to be very sensitive to the choice of the discount factor, e.g. when calculating the so-called social cost of carbon, used in cost-benefit analyses and policy appraisal (Smith and Braathen, 2015[107]).

CGE models are large multi-sectoral and multi-regional models, comprising (representative) households, firms in different sectors, governments and banks. A graphical representation of the main elements and the payment flows between different actors in a CGE model is given in Figure A.2. Different world regions are connected through trade and sometimes also capital flows. CGE models are typically employed to assess the effects of policies ex ante. The granular representation of sectors and regions enables CGE modellers to capture important international trade effects and repercussions between different sectors of the economy. Yet, on the downside CGE models rely on the (unrealistic) assumption of perfect markets and are typically not able to explain the transition path towards outcomes.

Figure A.2. Payment flows in standard CGE models

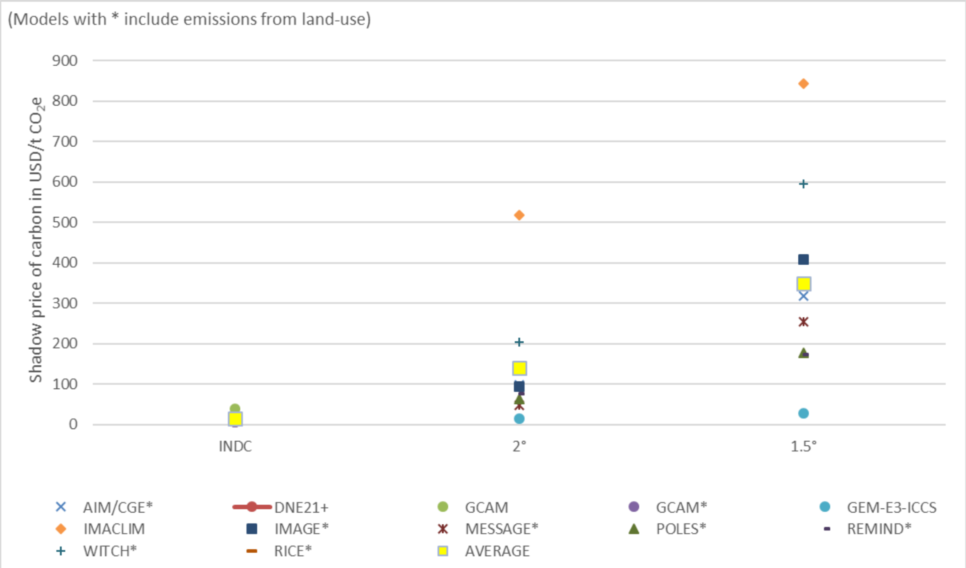


Source: adapted from http://www.fao.org/3/y5784e/y5784e08.htm.

IAMs, CGEs and macroeconomic models are top-down modelling approaches, representing technologies by aggregated production functions. In contrast, partial equilibrium (PE) models are bottom-up and model single economic sectors (e.g. agriculture, energy or electricity) in much more technological detail. For example, energy system models provide a more detailed representation of the energy sector, deriving the optimal mix of technologies to supply an (exogenously) given demand. Clear limitations of PE models include the omission of inter-linkages between different sectors of the economy and the assumption of exogenous energy demand.

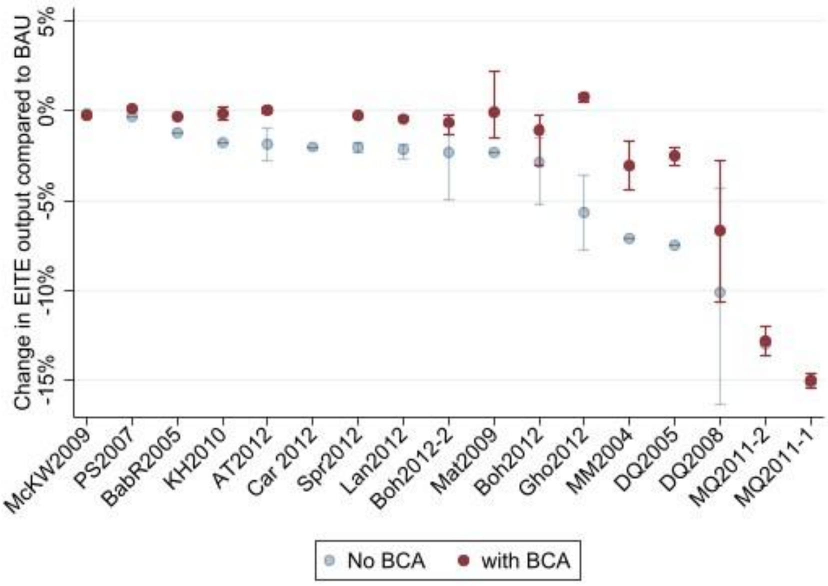
Annex B. Supporting Figures and Tables

Figure B.1. Shadow carbon prices for NDC, 2° and 1.5° targets in 2030



Source: Authors based on (Akimoto, Sano and Tehrani, 2017[20]); (Aldy, Pizer and Akimoto, 2016[21]); (Fujimori et al., 2016[18]); (IETA, 2019[25]); (Nordhaus, 2015[105]); (Vrontisi et al., 2018[26]).

Figure B.2. Output change for EITE industries with and without BCA



Source: Provided by (Branger and Quirion, 2014[81]).

Table B.1. Linking EU ETS and (hypothetical) Chinese ETS

Study	Linking-scenarios	Welfare effects in terms of HEV rel. to BAU	Reduction targets in ETS	Carbon prices (all in $/ tCO_2-eq)	Results for year
Gavard et al.(2013)	**EU** with **China** (power sector in both countries; energy-intensive sector in EU); unlimited & limited trading: EU can only import 5%,10%, 15% or 20% of regulated EU emissions	**China**: -0.23% (full trade), -0.14% (no trade); **EU:** -0.17% (full trade), -0.27% (no trade). China gains for any limit below 10%, EU gains the more can be traded	Changes rel. to BAU 2030 **China**: -10%; **EU**: cumulative emissions. (2005 – 2030) reduced by 7.7 Mt (-42% in ETS sectors rel. to 1990)	**China**: 6.24,**EU** 43.4; **full linking**: 10.2 5% limit: **China** 6.78, **EU**: 31.4 10% limit: **China** 7.2, **EU**: 25.9 15% limit: **China** 8.05, **EU**: 20.3 20% limit: **China** 10.2, **EU**: 15.7	2030
Gavard et al.(2016)	Limited and full linking (power & energy intensive sectors in both countries): **EU** with **China** **US** and **China**; **US, EU, China** Separate ETS in EU, China, US In case of limited linking: Limit = 10% of either US or EU cap;	**China**: separate ETS: -0.62%, US-China: -0.7%, US-China (limited) -0.58%; EU- China: -0.67%, China-EU (limited) -0.62%; EU-China-US: -0.71% **US**: separate ETS: -0.38%, US-China: -0.22%; US-China (limited): -0.23%, EU-China-US: -0.26% **EU**: separate ETS: -0.3%, EU-China: -0.2% EU-China (limited): -0.23%; EU-US-China: -0.21%	**China**: 25% **EU**: 43%; **US**: 29% compared to 2005 levels	Single markets: **China** 17.5; **US** 80; **EU** 49.3 linking **US & China**: 23.9; **China & EU**: 20.1; **China/EU/US**: 26.5 linking with limited trading US&China: **US**: 50.6, **China**: 19.3. EU&China: **EU:** 34; **China** 18.5	2030
Hübler et al.(2014)	**EU** with **China** (power sector & energy intensive sectors in both countries), different growth scenarios for China; Trade limit of 1/3 of EU cap (300 $MtCO_2$)	**China**: no linking: -1.8% to -2.7% (HEV) or -1.6% to -2.3% (GDP) Linking: -1.8% to -2.8% (HEV) or -1.5% to -2.3% GDP. no reported results for EU	**China**: -45% in emission intensity of GDP in 2020 rel. to 2005, **EU:** not stated explicitly, probably actual ETS targets	Separate ETS **China**: 16.7 - 22.4; **EU**: 65 - 92.8; Limited Linking: **China**: 19.1 - 25.0; **EU**: 37.2 - 66.2	2030
Liu and Wei(2016)	Linking **EU** with **China** (power sector & energy intensive industry in both countries)	**EU**: no linking: -0.24% (GDP), linking: -0.08% (GDP); **China**: no linking: -0.23% (GDP), linking: -0.1% (GDP)	**EU ETS**: -30% below 1990 in 2020; **China**: -40% carbon intensity red. rel. to 2005	Linking: **China &EU** 0.7 Separate ETS: **China:** 0, **EU:** 13.6	2020
Li et al.(2019)	**EU** with **China** (power sector & energy intensive industry in both countries) Independent ETS, Full linking of ETS, ETS+: Full linking with 5% additional reduction, rel. to single ETS Limited linking ETS+: same cap, but with limits of 5, 10, 15, 20 and 25% of cap.	Welfare impacts compared to independent ETS case: full linking: EU +0.34% China: +0.04% Linking ETS+: EU: +0.29%, China: +0.00% Limited linking: EU: -0.21% (5% limit) to +0.17% (25% limit) China: -0.05% (5% limit) to -0.01% (25% limit).	**EU**: 40% red. in 2030 rel. to 1990 **China**: 60-65% red. of carbon intensity compared to 2005 level (or: 50% reduction rel. to 2015); ETS+: implements stricter target: full linking and additional 5% red. versus normal ETS scenario	No linking: **China**: 13.4, EU: 45.5; full linking: **China&EU**: 15.0 Linking ETS+:**China&EU** 17.2 ETS+ 5% limit: **China** 14.87, **EU** 62.9, ETS+ 10%:**China** 15.2, **EU** 52.9, ETS+ 15%:**China** 15.6, **EU** 44.0, ETS+ 20%:**China** 16.07, **EU** 35.9, ETS+ 25%:**China** 16.5, **EU** 28.5	2030

Source: Authors

Table B.2. Linking EU ETS and other ETS

Study	Linking-scenarios	Welfare effects rel. to business-as-usual (BAU)	Reduction targets	Carbon prices (all in USD/tCO_2e)
Alexeeva and Anger (2016)	**ETS** linked to - Canada, Japan, - Canada, Japan, Russia, - Canada, Japan, Russia, Australia/New Zealand, US; in all regions only energy intensive sectors are covered by trading	lose in HEV reduces from 0.67% to 0.62% in c), **EU:** all linking steps reduce HEV by 0.1 to 0.2 percentage points; Russia gains most (selling allowances). Effects in other regions differ. e.g. Canada, Japan, later Russia lose if others also join	**EU27**: -32.5%; **Canada & Japan** -25%, **Australia & US** : -20%, **Russia**: 0%	No linking: **EU**: 36.7, **Canada**: 10.7, **Japan** 4.4, **Russia** 1.6, **Australia** 5.1, **USA** 6.5; Linking scenarios**:** **EU& Canada& Japan**: 24.6, **EU& Canada& Japan& Russia**: 15.0, **EU& Canada& Japan& Russia& AuNz& USA**: 9.7
Gavard et al. (2011)	Linking of EU ETS with in either China, India, Brazil or Mexico or all Sectors: ETS covered sectors linked to power sectors in either China, India, Brazil or Mexico or all	not reported	**ETS**: -28% in 2020; - 42% in 2030 rel. to 1990; emissions in **China, Mexico, India, Brazil** are capped at level of no-policy emissions	**EU** : ca 31, **EU-China**: ca. 4, **EU-India** ca. 6, **EU-Brazil** & **EU-Mexcio** ca. 30. **Linking EU with China, India, Brazil, Mexico**: ca 3
Vöhringer (2012)	Linking of ETS and Swiss ETS, Since analysis is in single country model for Switzerland, different ETS prices are assumed	Switzerland slightly loses: up to 0.005% relative to scenario with tax.	20% rel. to 1990 in 2020 for ETS	**ETS** prices vary between 22.3 and 89.3 in 2020, **Swiss carbon tax** without linking of 137.5 in 2020

Source: Authors.

Table B.3. Multi-Regional Linking

Study	Linking-scenarios	Welfare effects rel. to business-as-usual (BAU)	Reduction targets	Carbon prices (all in $/ tCO_2-eq)	Results for year
Böhringer et al.(2014a)	**None;** **C1**: EU27 + USA; **C2:** C1 + Japan, Canada, Australia **C3:** C2 + Russia, S. Korea, Mexico; C4: **C4:** C3 + China, India, Brazil, S. Africa; All	Only direct abatement costs reported for trading in power & energy intensive sectors Cost reduction for full rel. to no cooperation. **Japan** ca. 90%, **Brazil** ca. 72%, **Europe** ca. 65%, **Canada** ca. 60%, **Mexico** ca. 58%, **Australia** ca. 40%, **S. Korea** ca. 30%, **USA** ca. 29%, **S Africa** ca. 9%, **Russia**: ca. 100%, **China and India** ca. 500%	Reductions in % rel. to BAU 2020 **EU-27**: -25.4, **USA**:-17.1, **Canada**:-22.7, **Japan**:-35.2, **Russia**:-7.7, **Australia**:-24.7, **China & India & RoW**: -5; **Brazil & Mexico & S.Korea & S.Africa**: -17.1	No linking: **USA**: 25.9, **Canada**: 57.4, **EU27**: 75.5, **Russia**: 5.9 **Japan**: 326.8, **Australia**: 41.3 **China**: 4.2, **India**: 4.7, **Brazil**: 95.7 **Mexico**:48.5 **South Korea**: 30.4, **South Africa**: 8.5; Coalition price with full coverage **C1**; ~42, **C2**, ~50, **C3**: ~38, **C4**: ~12	2020
Dellink et al.(2010)	Direct linking (trade of Permits between countries) Indirect linking (through crediting mechanisms) for **Annex I countries.**	Direct linking: Mitigation cost decreases by 0.2% relative to unlinked case (measured in **HEV**) Indirect linking can reduce mitigation costs by 40% relative to direct linking. (If 20% of unilateral commitments are reduced through CDM).	**All Annex 1 countries** reduce emissions by 20% in 2020 50% in 2050 both rel. to 1990.	No linking: **Australia /New Zeal**. ~140, 2050:~400, **Canada**:~130, 2050: ~600, **EU27**:~60, 2050: ~200, **Japan** ~180, 2050: ~ 210; **East. EU**: ~2.0, 2050: ~200; **Russia**: ~ 5, 2050: ~90; US: ~105, 2050: ~140. Direct linking **(and similar indirect linking)**:~80 in 2050: ~ 180	2020 (first number) and 2050
Massetti and Tavoni(2012)	Linked Global carbon market vs. two markets: **one in Asia** (China, India, South East Asia and South Asia) and **Rest of the world**	**China**: -7% (linked), -5.5% (non-linked); **India**: +7% (linked), +3% (non-linked); **OECD**: -5% in both scenarios; **RoW**: -13% (linked), -10.5% (non-linked); **Overall**: -5% in both cases	Regional reduction targets not defined; implementation corresponds to 50% decrease of global emissions rel. to BAU	No linking: **Asia**: ca. 450 **RoW**: ca. 790 in RoW; Linking: **Global price**: ca. 700.	2050
Nong and Siriwardana(2018)	Linking: Australia's ETS with South Korea, US, China, EU India, Japan; All sectors covered by ETS.	Only given for **Australia**: Domestic ETS: -26.323%. Bilateral linking with: **South Korea**: -19.37, **China**: -12.18, **EU**:-20.94, **US**:-15.84, **Japan**: -16.04, **India**: -7.31, in million $ rel. to BAU 2030	**Australia**: -34%, **South Korea**: -30%, **China**: -25%, **EU**:-17%, **US**:-18%, **Japan**:-6%, **India**:-17% all rel. to 2007	Domestic ETS: **Australia**: 54.7. Bilateral linking with: **S. Korea**: 33,2, **China**: 18,3, **EU**:36,8, **US**:26,4, **Japan**: 24.4, **India**: 11,2	2030
Qi et al.(2013)	no ETS, separate ETS in EU, China, US, Australia/New Zealand(ANZ), **Linking ANZ** & **EU**, **Linking ANZ**, **EU, China,** **Linking ANZ**, **EU, US** **Linking ANZ, US, EU, China**	Linking EU – Australia:, **EU** loses 0.02% rel. to separate case, **Australia** gains 038%. Linking EU, AU, Chian: **Australia**: +0.5% **EU** +0.01%, **China** +0.02%; Linking EU, ANZ, US: **ANZ** +0.29%, **US**: -0.01%, **EU**: -0.03%; linking all: **US and EU** -0.01%, **ANZ** +0.48%, **China** +0.13% **Rel. to BAU (unclear if HEV or GDP)**	relative to BAU in 2020: EU 7%, US 16%, ANZ 29%, China 7%	No linking: **EU**: 12, **US**: 38, **Australia** 132, **China** 7, Linking: **One price**: 17.5	2020

Rose et al.(2018)	Step1: (until 2020) Linked ETS in **Canada, US, EU, Brazil Australia**, **Argentina, Japan, Saudi Arabia, Russia, India, South Korea China,** regional ETS in other G20 Step2: **Full G20** linking in 2025 Step3: Full linking of **all 90 countries with unconditional COP21 targets** in 2030	**Stage 1**: Reduction of mitigation costs from $73 bill. to $30 bill. (59%) **Stage 2**: higher mitigation costs, but cost savings from trading increase to 75%. **Stage 3**: cost reduction from $900 bill to $252 billion (72.1%) Cost savings mainly in high income countries. Low income countries lose rel. to high income countries with linking of their respective ETS	Total Emission reductions: (compared to BAU) **Stage 1**: G20: 3.13% **Stage 2**: G20: 8.76% **Stage 3:** Global: 13.98% Emissions reduced through ETS in 2030: 6%.	**Stage 1**: 68.24 **Stage 2**: 65.99 **Stage 3**: 83.78 no non-linking CO_2 prices were presented	2020 (Step1) 2025 (Step2) 2030 (Step3)

Source: Authors

Table B.4. Distributional effects of climate policies for different countries

Study and regional focus	Policy Scenario and Household Types	Revenue Recycling	Key findings on distributional effects
(Liang and Wei, 2012[108]) China	Carbon tax on fossil fuels of USD 1.31/tCO_2e Rural vs urban, no further income classes	-No recycling -HH exempt from carbon tax -Lump-sum transfers proportional to rural /urban population -Increase existing transfers reduction of income tax at uniform rate -Reduce indirect tax by proportional rate adjusted transfers	Rural HH face larger negative income losses than urban HH in all scenarios except when government transfers to household are increased. The most advisable scenario is the one where indirect taxes are reduced. Here, the increased gap between rural and urban is very small.
(Nurdianto and Resosudarmo, 2016[44]) Indonesia (IND) Malaysia (MAL), Philippines (PHI) Singapore (SIN) Thailand (THA) Vietnam (VIE)	Carbon tax of USD 10/tCO_2e in all countries in parallel; Income percentiles; rural vs. urban	-Proportional increase in Government expenditure -50% of revenues is recycled to poor urban and rural households -50% of revenues is used to decrease indirect taxes	Tax is strictly regressive in SIN (developed country) and strictly progressive in VIE (LDC). Other countries show progressivity for 70-90 percentiles and regressivity for richest percentiles (u-shape) except when revenue is directly recycled to HH. Poverty rates decrease everywhere for rural and urban households. Rural HH are more affected in IND, PHI, THA; and urban more in MAL.
(Rosenberg, Toder and Lu, 2018[39]) USA	3 carbon tax scenarios: USD 14, USD 50, USD 73/tCO_2e starting in 2020 and increasing 1-3% p.a. until 2040 Income quintiles	-Reduce payroll taxes -reduce corporate income tax -per capita dividends to HH	A carbon tax alone is moderately regressive, recycling can offset negative effects. Reduced payroll taxes is regressive until 95% percentiles, a reduction in corporate income tax is regressive and p.c. dividends progressive
(Weitzel et al., 2015[36]) India	Copenhagen Pledges in all model regions 5 rural, 4 urban types of HH of which two rural and one urban type are defined as poor.	Revenues transferred to i) HH based on population share, ii) only poor HH, iii) the government all scenarios with/without international transfers from permit sales of India either in rupee or USD	Without international transfers policy is progressive in i) and even more so in ii). For iii) the effects are rather similar but slightly regressive. Gap between rural and urban increases. using the revenue for investment decreases overall costs of climate policy

Source: Authors.

Table B.5. Carbon prices and cost savings through multi-gas mitigation strategies

Cost measure	Scenario	2000	2025	2050	2075	2100
Carbon permit price in USD/tCO_2-eq	CO_2 only scenario	2.7	101.3	314.2	406.2	877.0
	Multi-gas scenario	2.0	57.8	158.7	241.8	480.3
	% difference in CO_2 only scenario compared to multi-gas scenario	44%	48%	41%	23%	39%
Global GDP in trillion USD	GDP in reference case	33.0	65.8	116.7	194.4	295.4
	% reduction of GDP in CO_2 scenario compared to BAU	0.1%	0.7%	2.2%	3.8%	6.4%
	% reduction of GDP in multi-gas scenario compared to reference	0.1%	0.4%	1.4%	2.8%	4.8%
	% difference between CO_2-only and multi-gas scenario	0	42%	36%	26%	25%

Source: Authors based on (Weyant, Francisco and Blanford, 2006[60]).

Table B.6.Economic and environmental effects of a sectoral approach in the cement sector in China, Brazil and Mexico

Scenario name	PLEDGES	UNI_H	INT_0
EU			
Welfare (% change HEV vs. BaU 2020)	-0.61	-0.60	-0.59
ETS-price (USD/tCO_2-eq) in 2020	23.5	23.7	16.2
Sectoral output Cement - (% change vs. BaU 2020)	-1.1	-1.0	-0.7
China			
Welfare (% change HEV vs. BaU 2020)	-0.12	-0.17	-0.03
MAC in cement production in 2020 (USD/tCO_2-eq)		10.0	10.0
Sectoral output Cement - (% change vs. BaU 2020)	0.0	-2.2	-2.2
Mexico			
Welfare (% change HEV vs. BaU 2020)	-0.42	-0.43	-0.43
MAC in in cement production in 2020 (USD/tCO_2-eq)		53.0	16.2
Sectoral output Cement - (% change vs. BaU 2020)	0,1	-0.6	-0.1
Brazil			
Welfare (% change HEV vs. BaU 2020)	0.03	0.02	0.03
MAC in in cement production in 2020 (USD/tCO_2-eq)		44.9	16.2
Sectoral output Cement - (% change vs. BaU 2020)	0.3	-1.7	-0.4
Global emissions increase by 2020 from 2005 in %	25.39	25.01	25.51

Note: See Footnote 30 for a description of the scenarios.
Source: Authors based on (Voigt, Alexeeva-Talebi and Löschel, 2012[79]).

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