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The economic and environment benefits from international co-ordination on carbon pricing: a review of economic modelling studies [*]

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Abstract

This paper reviews quantitative estimates of the economic and environmental benefits from different forms of international co-ordination on carbon pricing based on economic modelling studies. 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 could deliver benefits, both economic (e.g. lower mitigation costs) and environmental (e.g. reducing greenhouse gas (GHG) emissions and carbon leakage). There is scope to considerably increase the coverage of carbon pricing, since until 2021 only around 40% of energy-related CO_2 emissions in 44 OECD and G20 countries face a carbon price. There is also significant scope to improve international co-ordination on carbon pricing: moving from unilateral carbon prices to a globally harmonized carbon price to reach the 1st round of NDC targets for 2030 can reduce global mitigation cost on average by two thirds or $229 billion. Benefits tend to be higher with broader participation of countries, broader coverage of emissions and sectors and, more ambitious policy goals. Extending carbon pricing to non-CO_2 GHG could reduce global mitigation costs by up to 48%. Absolute cost savings from harmonized carbon prices increase by almost 70% in 2030 for reductions in line with the 2 °C target. 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 potentially ensure that co-operation provides economic benefits for all countries.

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' as per the target of the Paris Agreement (UNFCCC 2015). Yet, the aggregate emission reductions associated with countries' initial unconditional Nationally Determined Contributions (NDCs) would imply a 66% chance to only limit warming to 3.2 °C by the end of the century (UNEP 2019). The NDC updates that several countries have made by mid-2021 are still expected to lead to global warming of more than 2 °C (CAT 2021) though (Höhne *et al* 2021) show that globally the 2 °C target might be within reach if the national net-zero targets are implemented.

Pricing carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions through emissions trading schemes (ETSs) or taxes is a key element of an economically efficient climate strategy. It incentivises private and public actors to reduce emissions cost-effectively while spurring innovation into zero-carbon technologies. 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 an increase in public investments or reducing distortionary taxes (OECD 2019). 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 needs to be accompanied by complementary policies (innovation, information provision, etc) (Tvinnereim and Mehling 2018, Stiglitz 2019). Indeed, carbon pricing so far has had only limited effects on aggregate emission reductions (Green 2021).

While the number of national and sub-national carbon pricing schemes has increased from 16 to 64 between 2009 and 2021 (World Bank 2021), around 60% of energy-related CO_2 emissions in 44 OECD and G20 countries do not face a carbon price (OECD 2021a). Indeed, only 3.8% of global emissions are priced above USD 40 per ton of CO_2—a low-end estimate for carbon prices necessary in order to meet the goals of the Paris Agreement (World Bank 2021, OECD 2021a).

International co-operation especially but not limited to harmonized carbon pricing in a broader sense, and on meeting individual countries' emissions reduction targets is expected to bring important economic (e.g. reduce climate policy costs, fiscal revenues from allowance sales), environmental benefits (e.g. reducing GHG emissions and air pollution emissions as well as carbon leakage) and political benefits (e.g. signalling a commitment to climate mitigation to domestic and foreign stakeholders) that could potentially enhance the ambition of

co-operating countries (Nachtigall 2019). Combining these benefits—for example reinvesting the savings in mitigation costs into additional mitigation or energy efficiency measures—could significantly enhance global mitigation ambition. International climate agreements have explicitly enshrined mechanisms to foster international co-operation, including in Article 6 of the Paris Agreement. Yet, evidence on the economic and environmental benefits of international co-operation is scarce and scattered. Quantifying the benefits of international co-ordination especially on pricing of GHG emissions, including 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.

This review provides a comprehensive overview of the economic and environmental benefits of a variety of forms of co-operation between countries, mainly based on economic modelling studies that can provide quantitative estimates.

2. Methods

This paper synthesises estimates of the economic and environmental benefits of international co-operation based on the economic modelling literature mostly from the past 10 years. We conducted the literature search on Google Scholar and Web of Science as the main search engines due to their vast scope and easy accessibility. On a couple of occasions, we used ECONIS to supplement our literature search. ECONIS is the online catalogue of the ZBW—German National Library of Economics—Leibniz Information Centre for Economic, which broadly collects economic literature and includes all major economic journals and grey literature from all major institutions undertaking economic research. We applied three general criteria for selecting studies (dominantly peer-reviewed studies and some reports and working papers from OECD, IEA, and conference papers):

(a) We only consider studies that use ex-ante policy analysis methods. This literature typically uses numerical modelling techniques, particularly integrated assessment models (IAMs) and computable general equilibrium (CGE) models (see Annex for an overview of these modelling methods) to quantify the socio-economic and/or environmental effects of climate policies[3]. Therefore, we focus only on studies that use either of these models.

(b) We only consider studies that provide quantitative estimates of economic costs measured either as a carbon price, gross domestic product (GDP) changes or welfare changes (mostly in terms of Hicksean-equivalent variation—HEV).

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[3] Political benefits are hard, if not impossible, to quantify.

Table 1. List of keywords used in literature search.

Section 3 Harmonising carbon prices	Paris Agreement, NDCs, intended NDCs	+	Integrated assessment, general equilibrium	+	Abatement cost, mitigation cost	—	—
Section 4 Extending the coverage of pricing schemes	Sectoral agreements, sectoral coverage	+	Integrated assessment, general equilibrium	+	Abatement cost, mitigation cost	+	Multigas mitigation
Section 5 Multilateral FFS reform		+	Integrated assessment, general equilibrium	+	Abatement cost, mitigation cost	+	FFS
Section 6 International sectoral reforms	Sectoral agreements	+	Integrated assessment, general equilibrium	+	Abatement cost, mitigation cost	—	—
Section 7 Co-ordination mechanism for mitigating carbon-leakage	Border carbon adjustment, border carbon	+	Integrated assessment, general equilibrium	+	Abatement cost, mitigation cost	+	Carbon leakage

(c) We focus on review studies with a multi-regional or global focus and therefore exclude articles that use a single country model. This criterion is needed because the goal of our study is to synthesise economic and environmental gains of co-operation and models need to have a multi-regional or fully global representation of countries to simulate co-operation between regions. Only in very few cases where sufficient multi-regional evidence was missing have we included single-country studies.

In addition to these three general criteria, specific search terms were used to select studies for each of the sections (see table 1). Particularly, our study reviews five independent instruments for initiating co-ordinated and co-operative action between countries. These are harmonising carbon prices (e.g. through linking carbon markets), extending the coverage of pricing schemes, phasing out fossil fuel subsidies (FFS), developing international sectoral agreements, and establishing co-ordination mechanisms to mitigate carbon leakage.

Section 3 focuses on price harmonization and so in this section we only selected studies that report the cost estimates for the most recent emission targets i.e. the initial NDC pledges submitted by countries under the Paris Agreement. We went through the results from these searches and selected only those studies that met the three general criteria and modelled scenarios with both unilateral prices and harmonized prices. Additionally, few papers (Springer 2003) focusing on the agreements passed in accordance with the previous Conference of Parties were looked at to supplement the full scope of the global climate change debate. For sections 4–7, topic-wise literature searches were done to expand the study to include these other four co-ordination instruments.

A snowball approach followed the first step of systematic identification of studies. This step included identifying literature from the reference list of the relevant studies found via the search engines. The final tally of 59 studies included in our study is supported by the literature search and the authors' experience. Table 2 gives an overview of the number of studies considered in each section. In addition, we include two meta-analyses (Kuik *et al* 2009, Branger and Quirion 2014) and two cross-model comparison studies (Weyant *et al* 2006, Böhringer *et al* 2021a). Therefore, the papers that are included within these four meta-analyses are not separately included in our review unless they provide unique insights.

This paper is structured as follows. Sections 3 and 4 focus on carbon pricing and discuss the benefits of harmonizing carbon prices across countries and extending the scope of carbon pricing, respectively. Section 5 deals with international co-operation in phasing out FFS which act as negative carbon prices and section 6 with international sectoral agreements. Finally, section 7 discusses options to address carbon leakage if international harmonization of climate policy fails. Finally, section 8 provides a conclusion.

3. Benefits of harmonising carbon prices

International climate agreements have explicitly enshrined mechanisms to foster international co-operation, including most recently via Article 6 of the Paris Agreement. This section reviews the economic and environmental benefits of global (section 3.1) co-operation, largely focussing on, but not limited to the goals of the Paris Agreement, and the benefits of regional co-operation (section 3.2).

<div align="center">**Table 2.** Publications included in this paper.</div>

Section	Name	Number of studies	Publication year of latest study
3	Benefits of harmonizing carbon prices	24	2021
3.1	Global co-operation	14[b]	2021
3.2	Regional co-operation	10[b]	2021
4	Extending coverage of carbon pricing schemes	11	2019
4.1	Extending sectoral coverage	8	2019
4.2	Extending GHGs	3[a,b]	2012
5	Multilateral FFS reform	6	2021
6	International sectoral agreements	2	2012
7	International co-ordination on mitigating carbon leakage	16	2018
7.1	Environmental effects	13[a,b]	2018
7.2	Economic effects	13[a,b]	2018
7.3	Strategic incentives to join climate coalitions	3	2016
	Total	59	

Note: The superscripts a and b indicate that the sections include a meta-analysis or a multi-model study, respectively. Source: Authors.

Flexibility in the location of mitigation efforts allows for increased mitigation in countries with low abatement costs and reduced mitigation in countries with high abatement costs, achieving the aggregate emission target at a lower cost. A uniform global carbon price would, in theory, ensure that the resulting emission reductions are reached with the lowest global economic cost, regardless of whether the global price is implemented through uniform national carbon taxes (and transfer mechanism), a global ETS or full linking of national ETS (Baranzini *et al* 2017). Sub-global harmonisation of carbon prices could only realise some of the economic benefits. Assessing the economic and environmental benefits from harmonised carbon prices requires a comparison of achieving a specific target unilaterally (e.g. meeting NDC pledges) with achieving the same target jointly.

The aggregate cost of reaching both national and international emission reduction targets depend on four main drivers (Peterson and Weitzel 2015):

- The stringency of emission targets relative to the business-as-usual (BAU) scenario.
- The national abatement costs which are dependent on the emission intensity of production and consumption patterns, the sectoral composition of economies and technology costs.
- National and international feedback effects of climate policy through changes in relative prices of fossil energy which affect energy markets and input prices with implications on (inter)national value chains, production and consumption of other goods.
- The level of international co-operation as this could harmonise abatement costs across different sources and locations, and for some countries could also generate fiscal income from allowance trading if there are international carbon markets.

Several caveats need to be kept in mind when comparing different modelling studies.
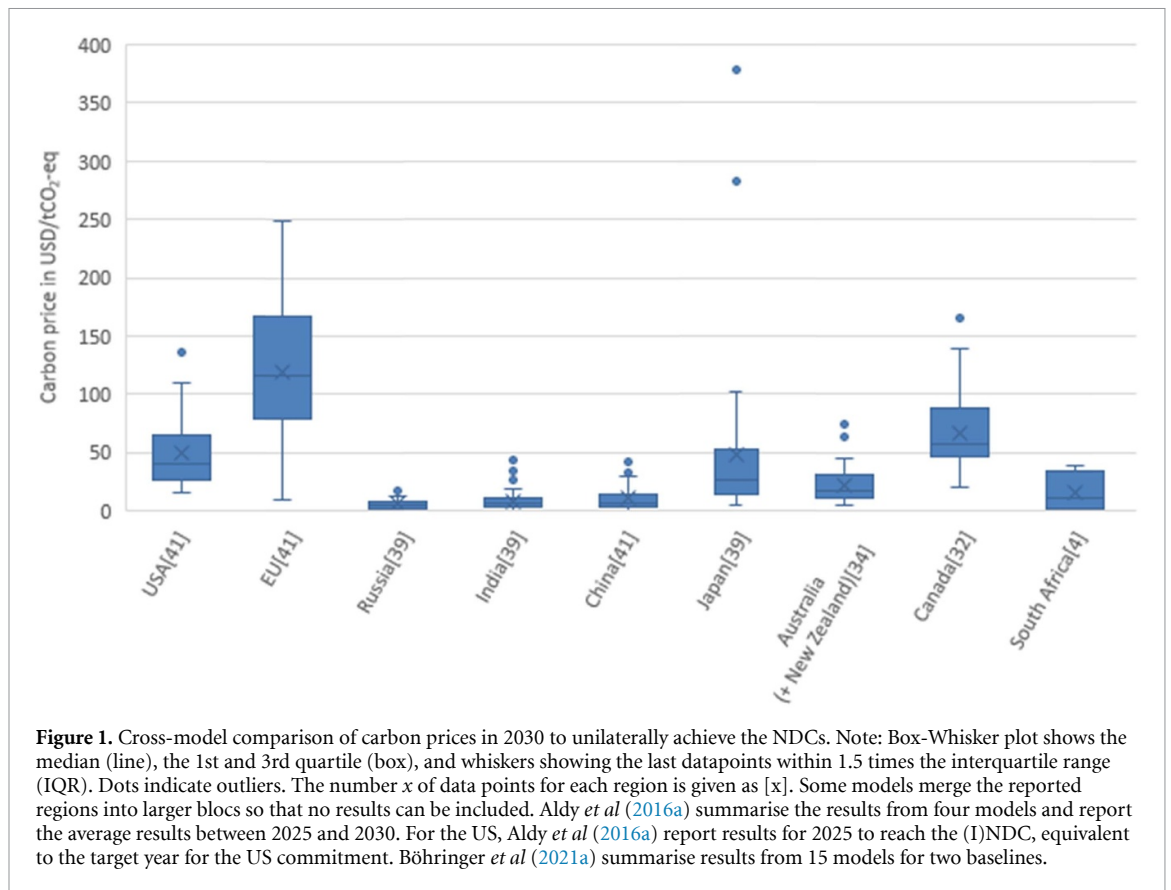
- Different models assume different economic structures for countries and regions and make a range of different assumptions on the above-mentioned drivers.
- Quantifying mitigation pledges is not straightforward for NDCs that are not expressed as absolute emission reductions. Additional assumptions are necessary for pledges made with emissions intensity targets, emission reductions relative to pre-specified baseline emissions or for different target years (2025 or 2030).
- Translating international goals related to specific temperature targets into national emission reduction targets is even more challenging in the absence of a globally agreed burden sharing agreement[4].

Results presented here focus on aggregate results for a particular country or region; the impact for individual actors within a country or region could be significantly different from the aggregate average.

3.1. Global harmonisation of carbon prices

There is significant intra- and inter-regional variation in estimated carbon prices needed to achieve the NDCs unilaterally. Figure 1 shows the carbon prices from different models and modelling studies to achieve the NDC targets through a uniform regional carbon price compared to a global carbon price. Results diverge the most for Japan, the USA and the EU, where estimated carbon prices under unilateral action vary between USD 4–645/tCO_2-eq, USD 16–607/tCO_2-eq and USD 10–2745/tCO_2-eq, respectively. With the exception of South Africa, for the rest of the regions, the higher estimates are derived

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[4] Researchers typically analyse a number of burden sharing rules to determine the stringency of the national mitigation target for limiting global warming to 2 °C or 1.5 °C. These rules may be based on cumulative emissions, GDP, population, baseline emissions or a combination thereof (Fujimori *et al* 2016).

Figure 1. Cross-model comparison of carbon prices in 2030 to unilaterally achieve the NDCs. Note: Box-Whisker plot shows the median (line), the 1st and 3rd quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Dots indicate outliers. The number *x* of data points for each region is given as [x]. Some models merge the reported regions into larger blocs so that no results can be included. Aldy *et al* (2016a) summarise the results from four models and report the average results between 2025 and 2030. For the US, Aldy *et al* (2016a) report results for 2025 to reach the (I)NDC, equivalent to the target year for the US commitment. Böhringer *et al* (2021a) summarise results from 15 models for two baselines.

from models that include only energy-related CO_2 emission reductions and exclude lower-cost land-use emission reductions. Yet, it should also be noted, the full set of 49 models, includes 44 models with only energy-related CO_2 emissions and only five that include land-use emissions.
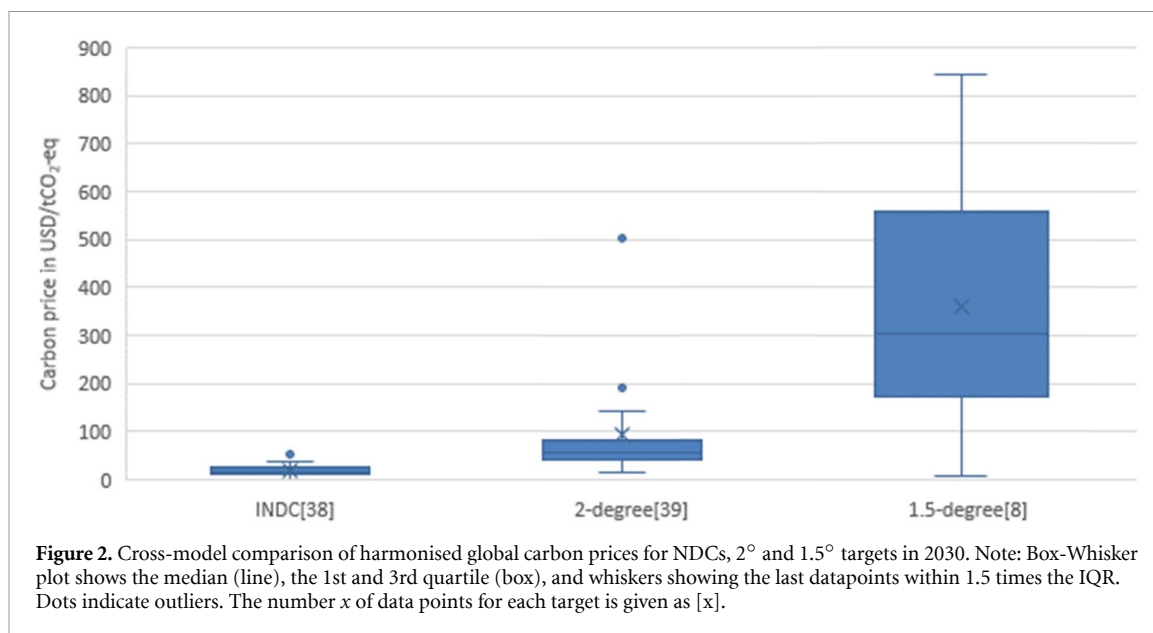
Included studies: (Fujimori *et al* 2016, Vandyck *et al* 2016, Aldy *et al* 2016a, Aldy *et al* 2016b, Akimoto *et al* 2017, Dai *et al* 2017, Liu *et al* 2020, Böhringer *et al* 2021a).

The substantial difference in carbon prices across regions to meet a given target in all reviewed studies highlights the large potential gains from international co-operation in reducing the costs of emission reductions. Regional carbon prices tend to be highest in advanced economies (US, EU, Japan, Canada) with average carbon prices around USD 47–119/tCO_2-eq. Note that for all regions this is significantly higher than currently observed carbon prices. Also, the current EU-ETS price of above USD 50/tCO_2-eq is well below the USD 119/tCO_2-eq average price the reviewed studies find for Europe. Altogether, in OECD and G20 countries, less than 10% of GHG emissions were priced above USD 100/tCO_2-eq in 2018 (OECD 2021a).

Given this divergence between actual and modelled carbon prices, the results reported in this section should be interpreted as an upper bound of real-world effects of international co-operation. Simulated prices tend to be lowest in emerging economies (e.g. Russia, India, China and South Africa).

In some regions (Russia and India), some model results suggest carbon prices to be zero, implying that those regions would reach their NDC targets under BAU. Low carbon prices could reflect the limited ambition of mitigation targets or a large potential of low-cost abatement options. Other metrics of mitigation costs (e.g. loss of GDP compared to BAU) would result in different regional orderings of costs. If NDCs were achieved jointly (e.g. through a global carbon market), the global carbon price is estimated to be between USD 0.2 and USD 58/tCO_2-eq with an average of USD 18.3/tCO_2-eq. This result of requiring a lower carbon price with joint effort relative to the unilateral effort is in line with the findings for the Kyoto Protocol of 13 models reviewed in Springer (2003). They showed that the average carbon price for unilateral action in the regulated annex B countries to meet their Kyoto target was three times higher than with global trading (USD 27/tCO_2-eq vs USD 9/tCO_2-eq, respectively).

In the studies that include global cost measures and global co-operation, harmonization of carbon prices would reduce total mitigation costs relative to the unilateral achievement of NDCs. Relative to unilateral carbon pricing, 80% of the models show that harmonized carbon prices result in cost reductions (either in GDP or in terms of welfare) in the order of 48%–83% (Fujimori *et al* 2016, Akimoto *et al* 2017, IETA 2019, Böhringer *et al* 2021a) and the average is a cost reduction of 64%. This would translate into annual cost savings (see figure 3), estimated variously

Figure 2. Cross-model comparison of harmonised global carbon prices for NDCs, 2° and 1.5° targets in 2030. Note: Box-Whisker plot shows the median (line), the 1st and 3rd quartile (box), and whiskers showing the last datapoints within 1.5 times the IQR. Dots indicate outliers. The number *x* of data points for each target is given as [x].

from zero to USD 1240 billion in 2030[5]. Eighty per cent of the values are in the range of USD 51–365 billion.

Included studies: (Nordhaus 2015, Fujimori *et al* 2016, Qi and Weng 2016, Aldy *et al* 2016b, Akimoto *et al* 2017, Vrontisi *et al* 2018, Wei *et al* 2018, IETA 2019, Böhringer *et al* 2021a).
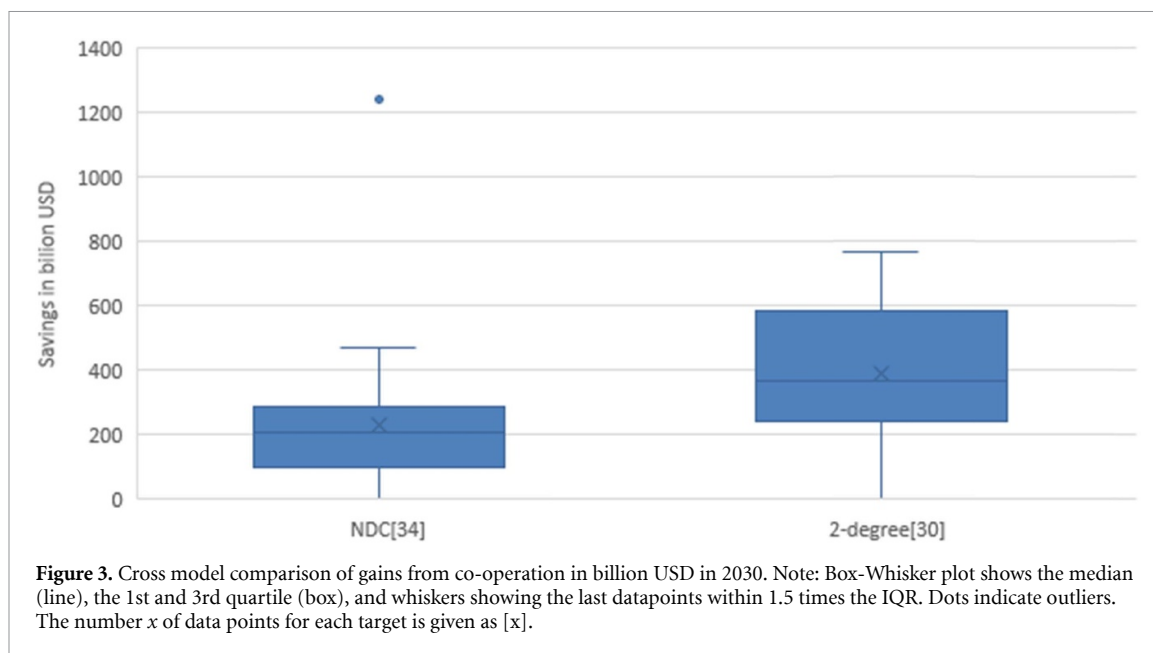
Going beyond achieving current NDCs jointly, co-ordination on achieving more stringent mitigation targets including those that are compatible with limiting global warming to 1.5 °C or 2 °C relative to pre-industrial levels has a number of implications. First, more ambitious mitigation targets are likely to translate—at least in the shorter term and without accounting for the benefits of climate action—into higher direct regional and global mitigation costs both in terms of necessary global carbon prices to achieve this global target (see figure 2) and of GDP/welfare loss relative to BAU. In the 2 °C scenarios, carbon prices increase by on average 4.4 times compared to the NDC scenarios with a range of 2–10.8 times. In the 1.5 °C scenarios they increase on average by five times compared to the 2 °C scenarios with a range of 1.6–5.3 times. Only Fujimori *et al* (2016) report carbon prices for all three climate targets and in the results the price for 1.5 °C target is 35 times that for the NDC targets and ten times that for the 2 °C target. Reported changes in GDP/welfare are of the same order. As more stringent targets

would translate into higher regional carbon prices that would further diverge, and hence, price harmonization would also increase the absolute gains of international co-ordination (IETA 2019). The model comparison study of (Böhringer *et al* 2021a) finds that through co-operation, the costs (measured as changes in welfare relative to unilateral action) on average reduce by 50% in 2030 for emission reductions in line with the 2 °C target and that 80% of the models report cost reductions within the range of 32%–68% reductions. The full range of costs reductions across all models is 0%–82%. In absolute terms, this translates into average welfare gains of USD 391 billion in 2030 (see also figure 3). Thus, absolute gains of co-ordination increase under more ambitious mitigation targets, whereas the relative gains decrease. This is also stressed by one study (IETA 2019) that analyses targets further in the future which are also more ambitious. This study, (IETA 2019) estimates absolute gains of full international co-ordination would increase from USD 249 billion in 2030 to USD 345 billion in 2050 and USD 988 billion in 2100. Relative gains would decrease from a cost reduction of 63% in 2030, 41% in 2050 and 30% in 2100.

Included studies: (Fujimori *et al* 2016, Qi and Weng 2016, Akimoto *et al* 2017, Hof *et al* 2017, IETA 2019, Böhringer *et al* 2021a).

The identified gains are not shared equally across countries. This is in particular shown by country-level results in Böhringer *et al* (2021a) where at least some of the models show that Africa, Australia/New Zealand, China, Middle East, Russia, South Korea, USA, Other Americas, and especially, Japan and India have lower welfare costs when NDCs are reached without co-operation and unilateral carbon prices than under a global carbon price. For India, this is even the case for the average across all models. Only Europe, Canada, Brazil and the rest

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[5] Akimoto *et al* (2017) do not explicitly report the cost savings from global emissions trading. However, assuming a global GDP of USD 117 trillion in 2030 (EIA 2017), 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 both Böhringer *et al* (2021a). and Fujimori *et al* (2016) uses loss in terms of welfare measured as HEV as cost metric. The values for Böhringer *et al* (2021a) are not included in the paper but were provided by the authors.

Figure 3. Cross model comparison of gains from co-operation in billion USD in 2030. Note: Box-Whisker plot shows the median (line), the 1st and 3rd quartile (box), and whiskers showing the last datapoints within 1.5 times the IQR. Dots indicate outliers. The number *x* of data points for each target is given as [x].

of Asia unambiguously gain from co-operation in all models. On average, gains are most pronounced in Russia and the Middle East. These findings, are (Böhringer *et al* 2021a) driven especially by changes in fossil fuel prices and fossil fuel demand and also (Fujimori *et al* 2016) competitiveness effects on world markets. Under global co-operation, abatement shifts to the cheap reduction of coal consumption in China and India implying fewer reductions in oil and gas. This is beneficial for large oil and gas producers (Böhringer *et al* 2021a). Producers in countries with projected high unilateral carbon prices such as Canada and Europe that can import allowances under global co-operation significantly benefit from the lower carbon prices brought about by global co-operation on carbon pricing, since this improves their position on world-markets.

Through the same mechanism, producers in allowance-selling countries (e.g. China and India) incur higher costs despite the revenues from selling allowances. Both China and India are characterised by a carbon-intensive economic structure and low abatement costs (and carbon prices) under unilateral NDC achievement. A global carbon market would raise their carbon prices, putting a relatively large burden on their emissions-intensive economy and negatively affecting their international competitiveness vis-à-vis more developed and less emissions-intensive economies (Fujimori *et al* 2016). The same is also true for consumers that gain from co-operation if this decreases national carbon prices relative to unilateral action and suffer from global cooperation if it increases national carbon prices relative to unilateral action. In principle, the 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.

Besides differences in the gains from co-operation across countries, also different household-types are affected differently from carbon pricing and potentially also from co-operation. In general, the distributional effects of carbon pricing depend on the chosen ways of revenue recycling, the differences in carbon intensities of consumption across different income groups, and varying income sources (labour vs capital income) of different household-types. As laid out in Böhringer *et al* (2021a), carbon pricing without revenue recycling is typically regressive—hurting lower income groups that spend a larger share of their income for energy relatively more than richer households. Revenue recycling e.g. through lump-sum transfers to households can still lead to overall progressive impacts (Böhringer *et al* 2021a). Unfortunately, we did not identify studies that analysed the distributive effects of co-operation on within country burden sharing.

3.2. Regional harmonisation of carbon prices
Regional harmonisation of carbon prices would reduce mitigation costs of the regional coalition, but to a lower extent than the reduction under full global co-operation. Regional harmonisation could be achieved through linking existing or prospective ETSs which will achieve a uniform price in all regions or through minimum carbon prices as in Canada under the Pan-Canadian Framework on Clean Growth and Climate Change for climate change which will at least reduce the price gap and the resulting inefficiencies. All of the 14 studies we review

include the EU. Six of the studies including one multi-model study assess an EU ETS-China linkage, three studies analyse a link between the EU and different coalitions of countries, including G20 countries (e.g. Canada, Japan, Russia, Australia, India, Brazil) and six of the studies cover multi-regional linkages (e.g. annex I countries[6]). The studies evaluate different reduction targets, extent of sectoral coverage in countries involved and timing and extent (unrestricted versus restricted) of linking, making it difficult to compare these studies. Nevertheless, some common points can be identified.

Studies show that not all countries would gain from linking compared to not linking. The country-specific economic benefits from linking would depend strongly on the country's marginal abatement cost, assumed reduction targets and whether the country is an exporter or importer of emission allowances. In most studies, developed countries are assumed to have the strictest emissions mitigation targets and, thus, the highest carbon prices pre-linking. Linking with jurisdictions with lower carbon prices would reduce the allowance price, leading to benefits in most cases. For instance, in the EU ETS-China studies (Liu and Wei 2016) find that mitigation costs could be reduced by as much as 66% compared to not linking, notably when the price difference pre-linking was very high as do most of the other studies. Conversely, allowance-selling countries would not always have economic benefits from linking compared to no-linking as such countries would be negatively affected by rising carbon prices (Hübler *et al* 2014, Gavard *et al* 2016, Böhringer *et al* 2021a) and thus, require compensation. The aggregate gains compared to no-linking would be lower if linking was restricted as in Li *et al* (2019). Region-specific results include:

- Australia is expected to be a buyer of allowances in all analysed scenarios and would gain in terms of welfare in all scenarios (Böhringer *et al* 2014a).
- The EU would be buying allowances and gaining in terms of welfare (with the exception of an EU—Australia ETS (Nong and Siriwardana 2018) or an ETS that covers all annex I regions (Dellink *et al* 2014).
- China is found to be a seller of allowances in all studies, but would not benefit from linking in some studies relative to unilateral achievement of mitigation targets in the absence of additional transfers (Gavard *et al* 2011, Böhringer *et al* 2021a) or raised climate ambition of linking partners (Liu and Wei 2016).
- In a linked Asian ETS covering China, South Korea and Japan set-up to jointly reach the NDC targets, induces gains mainly for South Korea, while all 15

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models of the cross-model comparison only report minor changes in adjustment costs for China and Japan (Böhringer *et al* 2021a).
- For Canada, Japan and the US, there is no clear conclusion.

Extending the geographical scope of carbon markets would reduce the aggregate mitigation costs of participating countries but would again not benefit all countries. Adding new coalition members could increase or decrease the allowance price of the extended coalition, depending on the carbon price associated with the new member(s). If the allowance price increased, former allowance importing regions would likely experience a decrease in welfare compared to the status quo in the absence of additional transfer payments as they need to pay higher prices to offset their emission obligations. For example (Gavard *et al* 2016) find that if the EU or the US joined a US-China or EU-China coalition, the mitigation costs of the existing coalition members would increase whereas those of the new member would decrease. Conversely, in Alexeeva and Anger (2016) allowance importing countries tend to gain if the entrance of new countries in the coalition reduces the allowance price. Also Böhringer *et al* (2014a) find that if the allowance price decreases with the extension of the existing coalition, allowance-selling countries may not benefit relative to no extension.

4. 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 carbon pricing schemes although some large schemes also include other emissions sources (ICAP 2019). This means that current carbon pricing schemes exclude a number of low-cost abatement opportunities in other sectors (e.g. buildings, agriculture) or from non-CO_2 (NC) GHGs (e.g. methane, nitrous oxide and F-gases), which are not always included in the models reviewed in the previous section. NC-GHGs differ from CO_2 both in terms of radiative efficiency and atmospheric lifespan, making it challenging to calculate a standardised metric. UNFCCC (and the reviewed models) use the global warming potentials 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).

4.1. Extending sectoral coverage of pricing schemes
Expanding sectoral coverage would generally reduce aggregated mitigation costs through harmonising carbon prices across sectors (Böhringer *et al* 2009, 2014a, Mu *et al* 2018) while also reducing the risk

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

of inter-sectoral leakage[7] (Söder *et al* 2019). The benefits from expanding sectoral coverage are higher the greater the risk of inter-sectoral leakage and the higher the difference of marginal abatement costs before the extension.

Böhringer *et al* (2014a) show that step-wise expanding sectoral coverage (e.g. beyond electricity and energy-intensive industry) of hypothetical international carbon markets would reduce mitigation costs for the vast majority of countries. This study also finds that international emissions trading covering only the power sector yields the highest cost savings. They find that a hypothetical link between an EU and US ETS covering only the power sector would reduce aggregate mitigation costs by around 14% by 2020 compared to the 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 power market link could further reduce mitigation costs by up to 4% points. This pattern of results also holds true for other combinations of countries, beyond an EU–US link.

The multi-model study by (Böhringer *et al* 2021a) also includes a scenario with a global ETS covering all sectors versus a scenario where only the energy and trade exposed (EITE) sectors plus the power sector are covered. Global gains from such a partial ETS relative to no co-operation in the reported NDC scenario are still positive in all models but average gains are reduced by around a 3rd. In a study for China, Mu *et al* (2018) find that real GDP in 2030 is reduced by 2.1% relative to a no policy scenario if China reaches its NDC through an economy-wide ETS. This GDP reduction relative to the no-policy case increases to 10.5% if the ETS only covers eight energy intensive sectors (petrochemicals, chemicals, construction materials, iron and steel, non-ferrous metals, paper, electricity, and air transport) that were responsible for 52% of Chinese CO_2-emissions in 2012. With an ETS that adds nine additional energy intensive sectors so that the ETS covers 76% of 2012 CO_2-emissions, real GDP reduces by only 3.3% relative to a no policy case. Thus, the analysed sectoral expansion reduces costs by almost a 3rd. The reviewed studies on specifically extending the coverage of the existing EU ETS to the transport sector find that this would enhance economic efficiency (Abrell 2010, Flachsland *et al* 2011, ECF 2014, Heinrichs *et al* 2014). In all these studies, the transport sector would be an allowance buyer. Including transportation into the EU ETS could lower mitigation costs compared to a scenario in which transport is excluded from the EU ETS, but faces additional (e.g. on top of existing gasoline taxes) carbon prices to reduce transport emissions. Yet, the

result of (Abrell 2010) is that a reallocation of mitigation obligations from transport to the sectors currently covered by the EU ETS would reduce mitigation costs even more than including transport into the EU ETS[8].

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

The abatement potential of NC-GHG emissions is large and predominantly originates from the land-use, land-use change and forestry (LULUCF) sector, but also the energy sector (e.g. methane from natural gas extraction and transmission) (IPCC 2014). Some ETS cover multiple gases, but only a few (e.g. New Zealand) are currently planning to price emissions and removals from the LULUCF sector (ICAP 2019).

Extending the coverage of pricing schemes towards NC-GHGs in all economic sectors would reduce mitigation costs as shown in figure 1. A cross-model comparison (Weyant *et al* 2006) of 19 global energy models simulate a least-cost policy scenario that is in line with stabilising radiative forcing at 4.5 W m^{-2} relative to pre-industrial times by the year 2150[9]. Their results show that in the 21st century, carbon (equivalent) prices in the multi-gas scenario would be, on average, between 23% and 48% lower than carbon prices in the CO_2-only scenario (Weyant *et al* 2006). This result holds for all but one model in this study. At the same time, the global GDP losses with multi-gas mitigation are between 0.1% and 4.8%, while those with only CO_2 mitigation range between 0.1% and 6.4%. The maximum difference in cost reduction of 0.3% points by 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 3.1).

The general results are confirmed by two other studies. Ghosh *et al* (2012) provide an analysis of CO_2 mitigation policies versus all GHG mitigation policies and generally, extending carbon pricing coverage to include NC-GHGs would also reduce mitigation costs in terms of GDP loss compared to BAU. Ghosh *et al* (2012) also find that a uniform price on global GHG emissions would unambiguously benefit all countries or regions due to the gain in flexibility. The 2nd study

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[7] Inter-sectoral leakage refers to a situation, in which a sector-specific climate policy leads to an increase of emissions in a non-regulated sector in the same country.

[8] 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). Yet, this study does not account for other externalities of road transport, including congestion, accidents, and health impacts due to noise, which tends to be larger than the social cost of carbon. Reallocating mitigation obligations from road transport to other sectors would lead to an increase in traffic, exacerbating the negative costs and potentially outweighing the tax interaction effect.

[9] 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 °C and 3 °C relative to pre-industrial levels (IPCC 2014).

is a meta-analysis based on 26 models by Kuik *et al* (2009) and also includes results from Weyant *et al* (2006). They conduct a meta-regression analysis and estimate that the MAC estimates in 2025 are lower by 48% and by 40% in 2050 with multi-gas mitigation rather than CO_2-only mitigation (in line with the results from Weyant *et al* (2006)).

5. Multilateral FFS reforms

FFS result in artificially low energy prices, encouraging carbon-intensive modes of consumption and production. In 2009, G-20 leaders called countries to 'rationalise and phase-out inefficient FFS that encourage wasteful consumption over the medium term' (G-20 2009). Decreasing international oil prices, the FFS reform momentum, as well as international peer-reviews of national FFS (e.g. Canada, China, Germany, Mexico, US) led to a reduction of FFS between 2013 and 2016 in 76 countries (IEA and OECD 2019). However, estimates also show that in 2017, FFS increased by 5%, reaching USD 340 billion. Despite the pledges of G20-leaders in 2009, FFS in 2020 are still at the same level as in 2010 (OECD 2021b). Consumer FFS account for around 75% of FFS in OECD and partner countries. In Jewell *et al* (2018), a global phase out of FFS by 2030 is estimated to reduce global CO_2 emissions by 1%–4% relative to BAU. Previous studies indicated that a global phase out of FFS by 2020 could reduce global CO_2 emissions by 5% to 6% by 2035 (Schwanitz *et al* 2014) and 6%–8% by 2050 compared to BAU (Burniaux and Chateau 2014). A more recent analysis by Chepeliev and Dominique (2020) shows that depending on the oil prices, removal of consumption FFS could reduce global emissions by 1.8%–3.2% in 2030. Figure 4 provides a range of global and country-specific emission reductions in response to a global FFS phase-out.

The reviewed studies show that phase out of consumer FFS would reduce emissions in reforming countries, increasing emissions elsewhere, leading to carbon leakage. For example, Burniaux and Chateau (2014) find that FFS removal in non-OECD countries would reduce global CO_2 (and GHG) emissions by 10% compared to BAU. However, while CO_2 emissions in non-OECD countries would decrease by 16%, emissions in OECD countries would increase by 7% compared to BAU by 2050. All relevant studies find that emission reductions in 2050 with FFS reform tend to be largest in fossil fuel exporting countries, including Russia and Middle Eastern and North African countries, amounting to 45% (Burniaux and Chateau 2014), 20% (Schwanitz *et al* 2014) and 2%–10% (Jewell *et al* 2018). 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). Due to this so-called 'energy price channel', carbon
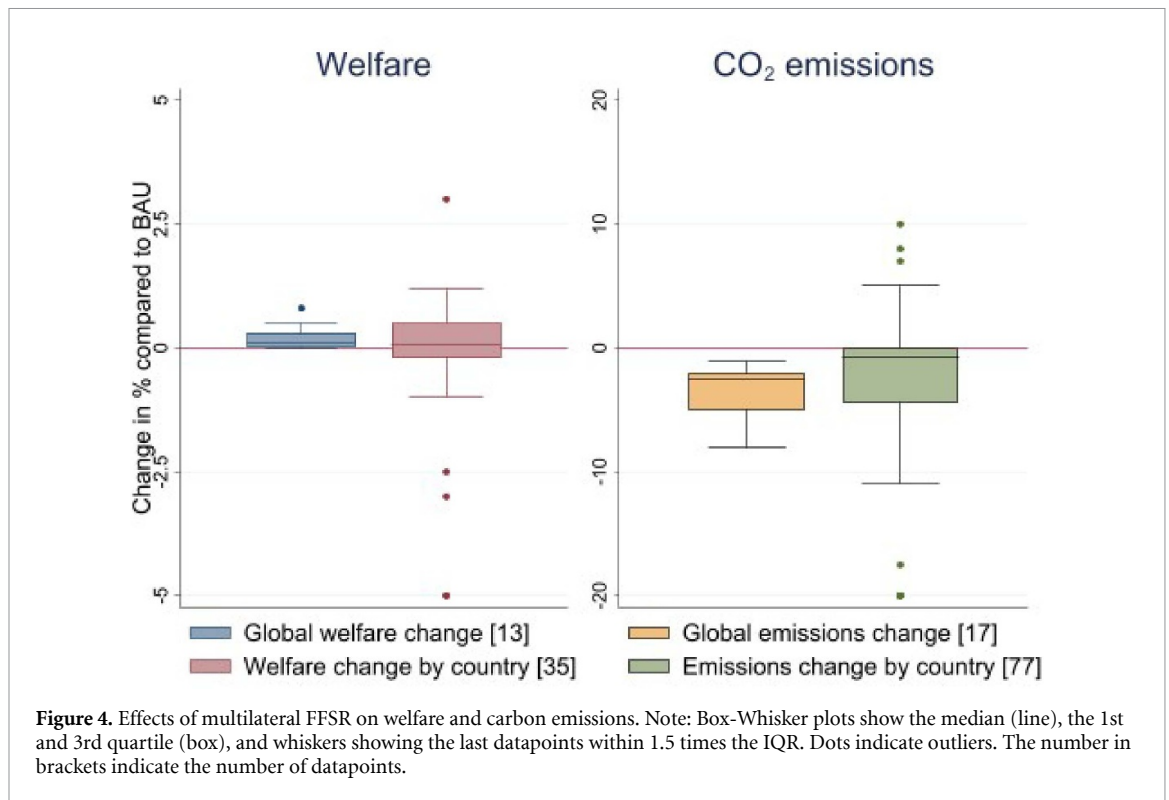
leakage could also arise in case of a global phase out of FFS (Jewell *et al* 2018).

Sub-global phase out of FFS is less effective than global phase out. If only G20 countries removed FFS by 2020 ('G20 scenario'), then global GHG emissions would reduce by merely 1% by 2050 compared to BAU (Schwanitz *et al* 2014). This number would rise to almost 3%, half the reduction of a global phase out, if in addition to the G20 countries all member countries of the Asia–Pacific Economic Co-operation (APEC) removed their FFS (Schwanitz *et al* 2014). 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 FFS in G20 countries only, but would increase by 3%–7% for phase outs of G20 + APEC and global phase out, respectively (Schwanitz *et al* 2014). This pattern is seen because 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%–10%, respectively, under a global phase out (Schwanitz *et al* 2014).

Böhringer *et al* (2021b) show that phasing out producer FFS could lead to negative carbon leakage rates, i.e. decreased emissions in countries not phasing out FFS. Removing producer subsidies (i.e. transfers from taxpayers to producers of fossil fuels) leads to an increase in producer's production costs and, thus, increases both the domestic and international price for fossil fuels, reducing demand emissions both domestically and abroad.

Included studies: (Burniaux and Chateau 2014, Magné *et al* 2014, Schwanitz *et al* 2014, Jewell *et al* 2018, Chepeliev and Dominique 2020).

All studies assessed for this paper indicate that joint global welfare would increase with a co-ordinated FFS reform. Moreover, Schwanitz *et al* (2014) finds that the gains in aggregate welfare would increase with an increasing number of co-operating countries and, thus, in the size of FFS removals. Burniaux and Chateau (2014) find that removing consumer subsidies in non-OECD countries could lead to a 5% welfare increase (due to lower energy prices) in OECD economies, but only to a 0.2% welfare increase in non-OECD countries. They also find that some countries (e.g. Russia) may not benefit from co-ordinated FFS removal in the absence of additional transfers. Chepeliev and Dominique (2020) find that the total removal of all FFS would increase global welfare between 0.02% and 0.1% in 2030 relative to BAU, depending on the oil prices. Similar to Burniaux and Chateau (2014), Russia also faces welfare losses in Chepeliev and Dominique (2020). The results on welfare and emissions are summarised in figure 4. Unilateral FFS phase-outs frees up public budget spent on FFS, that could be invested

Figure 4. Effects of multilateral FFSR on welfare and carbon emissions. Note: Box-Whisker plots show the median (line), the 1st and 3rd quartile (box), and whiskers showing the last datapoints within 1.5 times the IQR. Dots indicate outliers. The number in brackets indicate the number of datapoints.

for other purposes or allocated to households, and could trigger a more efficient domestic allocation of resources, both of which would generally enhance domestic welfare. Burniaux and Chateau (2014) find that under unilateral phase out, energy exporting countries would see the largest welfare gains by 2050 compared to BAU (4%), followed by India (2.3%) and China and Russia (0.4%). In contrast, multilateral phase out of all non-OECD countries would alter the distribution of welfare gains and losses to 2050: Russia would face a 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. 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.

6. International sectoral agreements

Sectoral agreements could be one avenue through which (international) carbon prices could 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, as well as on economic development in emerging countries (Meunier and Ponssard 2012). Bottom-up sectoral approaches could set binding, but potentially regionally differentiated emission targets for specific sectors, including aviation and EITE

sectors. Current sectoral approaches include the Carbon Offsetting and Reduction Scheme for International Aviation, aiming to stabilise global international aviation emissions at 2019 levels (ICAO 2020), 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).

Results from modelling the impact of sectoral agreements on GHG emissions are limited, but suggest that such agreements could reduce GHG emissions although not cost-effectively. The conclusion is based on only two studies for the cement sector (Voigt *et al* 2012) and the energy-intensive sectors (Akimoto *et al* 2008)[10]. Sectoral approaches could reduce GHG emissions in industrialised, emerging and developing countries regardless of whether they stipulate absolute (Voigt *et al* 2012) or emission intensity (Akimoto *et al* 2008) targets in the sectors covered. These agreements would also mitigate competitiveness concerns of sectors and could increase the welfare of participating countries compared to unilateral achievement of sectoral mitigation targets[11]. However, compared to policy scenarios with a uniform global carbon

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[10] Other studies are exploring the technical potential and the cost-effectiveness of international co-operation in the low carbon transition of specific sectors, including cement (Cembureau 2013) or iron and steel (WSA 2019). Since they lack international and cross-sectoral repercussions they are not further discussed here.

[11] For example, Voigt *et al* (2012) find that the decrease of EU countries' output relative to BAU in the cement sector (which is

price, sectoral approaches would incur larger welfare losses.

7. International co-ordination on mitigating carbon leakage

Climate policy that is not internationally harmonized faces the risk that economic activities and their associated emissions relocate from countries with higher carbon prices or stricter climate policy to countries with lower prices or less stringent climate policy. This is referred to as carbon leakage and denotes a situation where the benefits of emissions reduction in a given location are partially offset by emissions increases elsewhere. Co-ordinated regional implementation of carbon pricing, e.g. through carbon clubs (IISD 2018) or climate coalitions (see section 3.2) could reduce carbon leakage within the coalition, but could increase the risk of carbon leakage outside. Furthermore, as 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.

In the absence of deeper international co-operation, regional or unilateral anti-leakage policies could address carbon leakage but these are always second best to co-ordinated international climate policies. Anti-leakage policies could increase the environmental effectiveness of international co-operation on carbon pricing by ensuring that emission reductions in a climate-coalition are not offset by emissions increases outside the coalition. As such, anti-leakage policies could, enhance economic outcomes (for coalition members), and/or incentivise more international co-operation.

Most existing carbon pricing schemes address carbon leakage through preferential tax rates, fuel excise taxes or free allocation of emission allowances for ETS, notably for the energy-intensive trade-exposed industry which are most affected by differences in international carbon prices (Ellis *et al* 2019).

Border carbon adjustments (BCAs) was recently also proposed as part of the European Green Deal package. 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 weighed against the potential benefits (Cosbey *et al* 2019). Our interest here is in how far they can address the carbon leakage problem.

7.1. Effects of anti-leakage policies on GHG emissions

A meta-analysis by Branger and Quirion (2014) that reviewed 25 modelling studies shows that in the absence of any anti-leakage policy the leakage rates of regional or unilateral climate policy is estimated to range between 5% and 20%[12]. This contrasts to the empirical ex-post literature, which does not find any evidence of carbon prices on carbon leakage (Dechezleprêtre *et al* 2019, Naegele and Zaklan 2019, Venmans *et al* 2020). Most of the ex-post studies also do not find negative and statistically significant effects of carbon pricing on firms' competitiveness (Venmans *et al* 2020). Part of the reason is that actual carbon prices have been low and safeguards for the industry were in place (e.g. free allowances).

In the modelling literature, the leakage rate depends on a number of factors:

- More stringent mitigation targets would result in higher leakage rates (Böhringer *et al* 2012b, Branger and Quirion 2014). 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 finding highlights the importance of international co-operation to enhance environmental effectiveness and mitigate carbon leakage. Larger coverage of GHGs would decrease carbon leakage (see section 4.2) due to increased flexibility of meeting abatement targets.
- Increasing coalition size would reduce the leakage rate (Böhringer *et al* 2012a, 2014a, Branger and Quirion 2014). Böhringer *et al* (2014a) systematically assess the effects of coalition size on different anti-leakage measures and report that the differences in leakage rates between anti-leakage instruments reduce with increasing coalition size.
- Harmonising the carbon price within the climate coalition would tend to reduce the leakage rate. This is because a harmonised price minimises the trade repercussions in global energy markets. Model assumptions and choices 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 affecting the leakage rate. Second, higher trade elasticities (i.e. fewer trade frictions) increase

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covered by the EU ETS) would be 9% lower when emerging economies (China, Brazil, Mexico) also adopt sector-specific mitigation targets in that sector. Including these countries' cement sectors in the EU ETS so that all cement facilities face the same carbon price would reduce the loss in EU cement output by even 36%. If the cement sector in all countries faced the same carbon price, this would reduce the welfare loss in the EU and China relative to a climate scenario without sectoral targets while only slightly lessening the welfare of Mexico, leaving Brazil's welfare unchanged. In contrast, unilateral sectoral targets would lessen the welfare in all emerging economies.

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[12] A leakage rate of 5% implies that a climate policy leading to a reduction of 100 CO_2e emissions within the climate coalition would increase emissions by five CO_2e in countries outside.

leakage, allowing price shocks to transmit more heavily in international energy markets. This finding is strengthened through Böhringer *et al* (2017) that includes scenarios with different trade elasticities.

Studies that compare different anti-leakage instruments find that all of them would reduce the risk of leakage, but BCA are expected to be the most effective instrument. BCA would lead to the lowest leakage rate compared to free allocation of allowances and industry tax exemptions for different coalitions and different emission reduction targets (Böhringer *et al* 2010, 2012a, 2012b, Monjon and Quirion 2011). Yet, no anti-leakage policy could entirely mitigate leakage. Branger and Quirion (2014) in their meta-study find that BCA would reduce the leakage rate on average by 6% points compared to scenarios where emission reduction targets are reached without BCA. The reduction in the leakage rate is estimated to be between 1% and 15% points with some outliers as high as 30% points. More recent studies (Antimiani *et al* 2016, Böhringer *et al* 2017, 2018, Larch and Wanner 2017) also report results within the range of the meta-study and in most studies, none of the anti-leakage policies would be able to completely offset leakage. This is because these policies only target the trade channel but do not explicitly address the energy channel. Hence, Burniaux *et al* (2013) find that BCA would be more effective in reducing leakage for rather small coalitions that have less influence on global fossil fuel prices[13]. Böhringer *et al* (2017) also stress that the negative leakage rate they find for BCA stems from the fact that energy market effects are not considered here.

Most relevant for this paper is the finding that 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). 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 European countries, all annex I countries except Russia reduced their CO_2 emissions by 15% relative to a benchmark (Branger and Quirion 2014). 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, Böhringer *et al* 2012a). Adding China to the coalition would reduce the leakage rate by an additional 50% (Ghosh *et al* 2012).

7.2. Economic and welfare effects of anti-leakage instruments

BCA would be expected to be beneficial for the coalition countries. The results of Branger and Quirion (2014)'s meta-study suggest that the change in welfare (not accounting for the welfare effect from emission abatement) 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%. One of the drivers is that BCA tend to mitigate the reduction in output from climate policy in EITE sectors (Böhringer *et al* 2014b). Yet, BCA would usually not be able to restore the welfare levels of BAU scenarios (i.e. without climate policy) since coalition countries still face direct abatement costs[14].

In many but not all studies BCAs reduce negative welfare effects of unilateral climate policy in the model-regions undertaking this climate policy but mostly they do not establish a cost-neutral situation in the sense that with BCAs, the model regions do not reach the same level of welfare as without any climate policy. BCA would transfer part of the mitigation burden to the non-coalition countries whose exports are taxed (Walley 2012, Burniaux *et al* 2013, Böhringer *et al* 2014b, Larch and Wanner 2017, Böhringer *et al* 2018). Energy-exporting countries would typically incur the largest welfare loss due to BCA (Weitzel *et al* 2012, Böhringer *et al* 2018). The welfare losses incurred by non-coalition countries would partly offset the welfare gains of coalition members. Yet, global welfare would decrease as a result of BCA relative to a policy scenario without BCA, also because it causes additional emission reductions (Branger and Quirion 2014).

Allocating free allowances or tax exemptions for industry transfers income from governments to industrial sectors without necessarily changing trade patterns. In contrast to BCA, this would not negatively affect non-coalition countries, but would also not benefit the coalition countries. Yet, the joint welfare loss of both country groups would be higher for allocating free allowances than for BCA (Böhringer *et al* 2017).

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[13] The results of 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).

[14] Few studies suggest that the welfare of coalition countries under BCA would be higher than under BAU. This surprising result can derive from trade policy 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 *et al* 2018).

7.3. Strategic incentives to join climate coalitions

As noted above, BCA would usually reduce the welfare of non-coalition members compared to no BCA, providing incentives for countries to avoid the negative welfare effects by joining the climate coalition Such incentives are mostly analysed using stylized and partly also parameterized game theoretic models[15] and a few CGE models (Weitzel *et al* 2012, Böhringer *et al* 2016). Overall, they find that BCA could induce participation in climate coalitions but only under very specific assumptions (Böhringer *et al* 2016, Al Khourdajie and Finus 2020) or countries. 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). 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 two regions for carbon prices above USD 10 (Nordhaus 2015). Energy-exporting countries tend to have the largest incentive to join the coalition as they are most adversely affected by BCA (Weitzel *et al* 2012, Böhringer *et al* 2016) while the studies find incentives only under unrealistic assumption or not at all for other countries and regions. Other hypothetical measures, notably trade tariffs would be more effective than BCA to incentivise non-coalition countries to join the coalition, but would likely breach multilateral trade rules (Nordhaus 2015)[16].

8. Summary and conclusions

This paper assesses quantitative estimates of the economic and environmental benefits from different types of international co-ordination on carbon pricing based on economic modelling studies. Better awareness and understanding of these benefits could encourage governments to increase their ambition on climate action, and thus facilitate countries' efforts to collectively meet the goals of the Paris Agreement. Quantifying the benefits of international co-ordination on pricing of CO_2 emissions and the distribution of these benefits across country groupings could help policy makers to make better-informed decisions about the implications of and potential forms for international co-ordination. Such forms could include harmonisation of carbon prices (e.g. through global or regional linking of carbon markets), extending coverage of pricing schemes, phasing out FFS, developing international sectoral agreements and co-ordination mechanisms to mitigate carbon leakage.

Our review shows that all forms of international co-operation on carbon pricing could deliver benefits which include economic benefits (e.g. lower mitigation costs) and environmental benefits (e.g. reducing GHG emissions and carbon leakage). Increasing mitigation in low-cost regions and reducing mitigation in high-cost regions achieves a given aggregate emissions target at a lower cost. 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).

Yet, the economic benefits of international co-operation are likely to vary across countries and regions. Most countries would have substantial economic benefits from co-operation because of savings in mitigation cost (for international emissions trading) or reduced energy prices (for multilateral 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) would not always generate economic benefits for all countries. Redistributing the economic savings from co-operation across countries (e.g. via carbon market transactions, or potentially direct monetary transfers or technology transfers) could ensure that co-operation provides economic benefits for all countries. However, this may be politically challenging. Reinvesting the economic gains from co-operation into raised climate ambition would reduce long-term climate risks for all countries. Table 3 summarizes the core quantitative results and main findings regarding the different forms of co-operation.

All studies show substantial variation of carbon prices that would be implied by each region unilaterally meeting its specific mitigation targets, indicating a large potential for cost savings from harmonising carbon prices. Using carbon markets to help countries meet the mitigation goals in their NDCs with

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[15] This literature is summarized by Al Khourdajie and Finus (2020).

[16] The result of one study suggests that international compensating transfers in form of additional emission allowances are a more efficient instrument to create a stable global coalition than BCA, leading to larger global welfare levels (Weitzel *et al* 2012). Trade tariffs could also trigger participation in global climate coalitions when used against non-coalition members because tariffs would increase the cost of non-participation (Lessmann *et al* 2009, Nordhaus 2015). Trade tariffs of 1% (Nordhaus 2015) and 1.5% (Lessmann *et al* 2009) 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 *et al* 2009)) and higher mitigation ambition (e.g. 3% for USD 25 per tCO_2e, (Nordhaus 2015)). 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. Yet, trade tariffs would still trigger participation of some regions (Nordhaus 2015).

Table 3. Main quantitative findings for each co-operation instrument.

Main results	Specific evidence
National carbon prices needed to unilaterally reach submitted NDCs vary greatly across countries leaving room for efficiency gains from international co-ordination on carbon pricing	Average regional simulated carbon prices in 2030 necessary to reach initial NDCs vary between $6/tCO$_2$ in Russia and $119/tCO$_2$ in the EU.
Instead of unilateral carbon pricing, global carbon pricing can significantly reduce the overall costs of reaching NDCs	Global abatement costs for reaching NDCs in 2030 can on average be reduced by 64%. The implied average global costs savings are $229 billion in 2030.
For stricter targets, cost savings through a globally harmonized price increase in absolute but decrease in relative terms	For the 2 °C target, global costs can be reduced by on average by 50% or $391 in 2030 for a global carbon price compared to regional carbon prices.
Harmonization of carbon prices does not necessarily benefit all regions	There is no country/region that always gains or loses across all studies from global harmonization of carbon prices. Generally, but especially for regional harmonization, developed regions mostly gain. Especially China, which is the most important exporter for basically all analysed targets and scenarios, does not gain from joining a trading regime in many studies.
Extending the sectoral coverage of pricing schemes reduces aggregate abatement costs	The highest positive effects of sectoral harmonization are found for the electricity sector. Extensions of carbon pricing to smaller sectors like transport or cement have positive, but much smaller effects.
Allowing flexibility in whether to abate CO$_2$ or other non-CO$_2$ GHGs reduces abatement costs	On average abatement costs would be between 23% and 48% lower in 2030 and 40% lower in 2050 with multi-gas mitigation rather than CO$_2$-only mitigation.
Sectoral agreements can reduce negative competitiveness effects of the covered sectors and imply welfare gains for participating countries, yet emission reductions are limited and policy scenarios with a uniform global carbon price are preferable	For the cement sector, one study finds that the decrease of cement production in the EU relative to a no policy case is reduced by around 36% through a joint ETS with the cement sectors of China, Brazil and Mexico.
Globally phasing out FFS reduces GHG emissions and increases global welfare	Globally phasing out FFS reduces global CO$_2$-emissions of 1%–4% by 2030 relative to a no policy case and of 6%–8% by 2050. Emission reductions are largest in fossil fuel exporting countries. Global welfare increases slightly.
Anti-leakage instruments are only an imperfect substitute for co-operation on carbon pricing	BCA reduces leakage on average by 6% points compared to scenarios where emission targets are reached without BCA and can reduce coalition countries' welfare loss by up to 44%.

a uniform global carbon price has the potential to reduce global mitigation costs by on average 64%, translating into annual cost savings of on average USD 229 billion by 2030. The absolute, but not relative gains are higher for more ambitious mitigation targets. Regional emissions trading (e.g. through linking carbon markets) also brings benefits, albeit to a lower extent than global co-operation. Though there is no country or region that benefits in all studies from global harmonization of carbon prices, most developed countries/regions (e.g. Japan, EU, USA) would benefit economically and even more so from regional emissions trading, whereas this might not be the case for emerging economies (notably China). China could see 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. Similarly, extending the geographical scope of carbon markets by adding new countries would benefit most,

albeit not all countries in the absence of additional transfers.

Extending the coverage of carbon pricing schemes by including more sectors or non-CO$_2$ GHGs 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 estimated to have the largest potential for saving mitigation costs. Extending the coverage of (harmonised) 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 would lead to average lower carbon prices by 23%–48% by 2030 compared to scenarios covering only CO$_2$ emissions. Sectoral agreements could potentially reduce sector-specific GHG emissions and mitigate competitiveness concerns but are overall not efficient, though the evidence is scarce.

Global FFS removal by 2030 is estimated to reduce global CO_2 emissions by 1%–4% compared to BAU. Phasing out consumer FFS would increase domestic energy prices, reducing energy demand and emissions in the reforming countries, but may cause carbon leakage as a result of lower global energy prices, leading to increasing energy demand and emissions in other countries. Unilateral FFS removal would typically lead to economic gains for the reforming country due to more efficient resource allocation. Multilateral FFS reforms would also benefit most countries, notably energy-importing countries, compared to BAU, but would not be beneficial for some energy-exporting economies due to lower global energy prices. Globally, a multi-lateral FFS removal leads to slight welfare gains.

Co-ordinated implementation or increase of carbon pricing on a sub-global level (e.g. in form of a climate coalition or carbon club) would reduce carbon leakage within the coalition, but could increase carbon leakage outside. In the absence of multilateral agreements or co-ordinated efforts to reduce leakage, specific policy instruments (BCAs), carbon tax exemptions, allocation of free allowances) could reduce the risk of carbon leakage. Among those, BCA is expected to be most effective and would reduce leakage on average by 6% points and reduce welfare losses of the coalition by up to 44%. Yet, no instrument would be able to eliminate leakage entirely. BCA would bring economic benefits for coalition countries, but would, in general, disbenefit countries outside the coalition as it would transfer part 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 is expected to be limited.

The review is based on economic modelling studies, which are subject to some caveats. First, the studies and models reviewed here, including IAMs and CGE models, are stylised models that rely on a number of assumptions such as perfect rationality, information, and foresight of actors (e.g. households, firms) as well as perfect and complete markets. These assumptions are rarely observed in the real world. These assumptions lead to results where harmonized carbon pricing always leads to global economic benefits and thus, more broadly the global cost-reductions of the analysed scenarios should be interpreted as an upper bound of potential real-world effects. In fact, the estimated effects from modelling results far exceed those of empirical ex-post studies (see e.g. section 7). This can be explained by both the underlying assumptions of modelling studies and/or the discrepancy between actual and modelled policy variables (e.g. the level of carbon prices). Second, the results reported in the literature neither capture all benefits associated with international co-operation nor all of its costs. Some models, notably IAMs assess the benefits associated with reduced long-term climate damages, but may not capture the full range of benefits from co-operation, including a reduced risk (and cost) of extreme events, or broader well-being benefits (reduced air pollution, reduced income inequality). Furthermore, most models quantify the short-term economic benefits, but inadequately evaluate the economic dynamics over the long-term. Regarding costs of co-operation, modelling studies typically do not account for the costs of setting up and maintaining co-operation, for harmonizing policies across nations or for monitoring cross-national carbon pricing schemes. The failure to capture the full costs is most pertinent in the most commonly discussed option for international co-operation i.e. international emission trading systems, which brings economic gains, but also results in on average lower international carbon prices in the absence of these costs. These low carbon price estimates that models report without fully capturing the full costs of establishing and maintain an international emissions trading system should not be misunderstood as if the mitigation costs are low. Such a misinterpretation may deter economic transformation and investments in innovation that would be needed to enable deep decarbonisation to reach net-zero emissions by mid-century.

Lastly, overall our paper focuses on the quantitative results of the identified studies. Each of the proposed types of co-ordination could face challenges which could be political (e.g. domestic barriers to carbon pricing and FFS reforms; international burden sharing rules), practical (e.g. measuring emissions for different sectors) or legal (e.g. compatibility with international trade laws) that may impede implementation of carbon pricing. Also, implementing co-ordination mechanisms would require high levels of trust between the participating jurisdictions. However, the discussion of these challenges is beyond the scope of this paper.

Given these limitations, the reviewed studies nevertheless provide information about the potential reductions in economic abatement costs and/or additional emission reductions through the analysed co-operation scenarios. Even though our paper shows that the literature provides already many insights about the potential gains from international co-operation on carbon pricing and related climate policies, we also identified some problems, gaps and avenues for future research. First of all, it is often challenging to compare different studies due to different regional aggregations, target years, policy stringency, specific scenarios and reported variables and results. For this reason, multi-model studies within a harmonized setting and with harmonized reporting are especially helpful to identify the range

of results. The same is true for quantitative meta-analyses. These studies help at the same time to better understand the drivers of results, which even the multi-model studies mostly only touch upon without really explaining what is driving model results. More meta-analyses on issues where already sufficiently many studies exist (e.g. a linking of an EU and Chinese ETS or the gains from moving from unilateral do global carbon pricing under the Paris Agreement) could help to derive robust quantitative results and to understand what factors are driving them. Furthermore, some issues like a sectoral extension of carbon pricing, sectoral agreements as well as FFS reforms have received relatively little attention compared to the classical comparison of unilateral versus global carbon pricing, even though these topics might be of great political interest and practical relevance. Finally, another avenue for future work is to relax the neoclassical assumptions of models (e.g. perfect market, fully rational actors and more linking of economic models) with climate models to include feedback effects.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix

Structure, metrics and caveats of economic models

Researchers use economic models, including CGE models and IAMs, to assess the effects of climate policy and international co-operation ex-ante. Economic models are a representation of the global economy, covering (representative) households and firms in different sectors (usually 2–15, but also up to 60) and different world regions (usually 5–20) 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.

Studies in this survey make use of multiple metrics on the (economic) effects of climate policies. All metrics are usually reported against a BAU scenario. 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).

- Carbon price represents the marginal cost of an extra unit of emission reductions. Hence, this metric can be interpreted as mitigation effort, but not necessarily as the total cost of a policy.
- Loss in 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). 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 specific model parameters such as production 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.

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