Comparing different approaches to tackle the challenges of global carbon pricing*

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Abstract

The introduction of carbon pricing faces two main challenges: the need for global cooperation to tackle the collective action problem and the need to share the its burden in a fair way following the principle of common but differentiated responsibility (CBRD). In this paper we explore different ways to build a carbon pricing coalition while minimizing the welfare losses for low-income countries using simulations with a recursive dynamic computable general equilibrium (CGE) model. We first present the need for and efficiency and urgency of global carbon pricing policies. Global carbon pricing is needed to tackle climate change, is more efficient than regional carbon pricing, and is urgent to prevent a patchwork of carbon pricing policies leading to calls for border carbon adjustment (BCA). Because the impact of global carbon pricing on the GDP of most regions is negative, complementary policies are required to tackle the two challenges. We explore four complementary policies: BCA, Nordhaus's climate club, a global carbon incentive fund, and emission trading with progressive emission reduction targets. We evaluate these proposals based on their projected effects on average income and income inequality among countries, as well as their effectiveness as an incentive to introduce carbon pricing. BCA scores poorly along the three dimensions; Nordhaus's carbon club performs well as an incentive tool but has a negative impact on average global income and inequality between regions; the global carbon fund has a positive impact on average income and inequality but performs poorly as an incentive tool; and emission trading with progressive reduction targets scores well across all dimensions. We conclude with a discussion of the feasibility of emission trading.

Keywords: Climate change, carbon pricing, international trade.

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1 Introduction

Climate change is a global phenomenon. Without additional policy action, the temperature on the planet could increase by 2.7C in 2100 (with a 50% probability (IEA (2021)). To limit global warming to 1.5-2C by 2100, emissions should be limited to zero by 2050 on net. To realise this goal, global policy coordination is needed. However, the emissions of a single country affect warming in all regions, so individual countries have an incentive to wait for other countries to take measures. More formally there is a common pool problem.

To tackle climate change at the global level, countries are currently following a process of pledge-and-review under the Paris Agreement (Dimitrov et al. (2019)).[1] Each region makes pledges by submitting plans for reductions in emissions in Nationally Determined Contributions (NDCs), which are reviewed by other regions. The main problem of this approach is that pledges are voluntary, thus implying that countries can renege on their commitments without consequences. Some scholars even argue that the voluntary nature of the pledges could aggravate the free rider problem. When countries observe the lack of action in other countries, they will be inclined to reduce their level of ambition (Cramton et al. (2017)). Empirical research based on surveys generates conflicting results on the impact of carbon policies in one region on support for carbon policies in other regions.[2]

Nevertheless, the voluntary approach suffers from a lack of binding commitments and thus risks missing the targets to limit climate change. Therefore, two alternative approaches with more binding commitments have been proposed both involving carbon pricing: emissions trading and carbon taxation. [3] With a global agreement on emissions trading, emission reduction targets are set per country and countries can sell/buy the surplus/deficit of emission rights compared to actual emissions (Nordhaus, 2013; Gollier and Tirole, 2017). An international agreement about carbon pricing would involve the obligation for countries to introduce a (minimum) tax on CO2 emissions and is favoured for example by the IMF and the World Bank.[4]

Regardless of the exact format of the global target, i.e. a price target or a quantity (emission) target, global carbon pricing poses two main policy challenges. First, a global carbon price requires global cooperation and second the burden of a global carbon price should be shared in a fair way between countries following the principle of common but differentiated responsibility in the global negotiations on climate change policies (UNFCCC, 1992). Although historically the developed economies are responsible for most emissions implying that they would have to bear most of the burden of climate change mitigation policies, looking forward the climate change problem can only be tackled if also developing countries take ambitious climate change action, because a large share of emissions will come from developing countries.

[1]Dimitrov et al. (2019) discuss the Paris Agreement based on the trilemma of climate treaties identified in Barrett (2008). Climate treaties have to be broad in terms of the number of countries covered, contain sufficient commitments to tackle climate change, and be enforceable. Reaching all three objectives is hard to realize. The Paris Agreement has a broad coverage and ambitious targets, but enforceability of the targets is weak.

[2]Beiser-McGrath and Bernauer (2019) for example find in surveys in China and the US that the support for international climate agreements is not affected by climate policy action. However, Beiser-McGrath et al. (2021) find that the level of carbon taxes in other regions do affect support for domestic carbon taxation.

[3]A more binding approach with carbon pricing can be complementary to the more voluntary pledge-and-review approach of the Paris Agreement.

[4]The introduction of a global carbon price is supported by a large list of organizations and individuals (see https://www.carbonpricingleadership.org/)

In this paper we compare different policy proposals to confront these two challenges exploring which policy would be best at incentivizing all regions in the world to join a group of ambitious regions with already existing carbon pricing policies while at the same time sharing the burden of the costs of climate change mitigation. Hence, we start from the assumption that a small group of high-income countries forms a carbon club by introducing ambitious carbon policies and explore the incentives for other regions to join the ambitious regions and introduce ambitious policies as well. The objective of our paper is not to formally address the existence and stability of carbon coalitions as in other research discussed below, but rather to explore the potential of different approaches to build cooperation and the role of trade policies in this

We explore the potential to build a carbon pricing coalition for four different policies: (i) a carbon club, whose members introduce a carbon tax, with a common external tariff imposed by the club (Nordhaus (2015)); (ii) border carbon adjustment with carbon pricing; (iii) a global carbon fund combining global carbon pricing with the redistribution of the revenues of carbon taxation based on income per capita (Stoft (2008); Cramton (2010)); (iv) differences in carbon prices depending on a country's level of development (Parry et al. (2021)); and (v) emissions trading with large differences in emission targets between regions as a function of income per capita. We measure the potential for non-club members to join a club based on the change in real income when non-ambitious countries decide to introduce carbon pricing policies and thus avoid BCA-tariffs/external tariffs or can participate in a global carbon fund or progressive emissions trading.

The assumption to start with a group of more ambitious countries consisting of the richest regions can be motivated based on insights from the literature. Although empirical research finds that the presence of ambitious carbon policies is not positively correlated with levels of income, research shows that it is related with broader indicators of development. Torstad et al. (2020) for example find that the level of ambition in NDCs is positively correlated with the level of democracy, whereas Best and Zhang (2020) conclude that the level of carbon taxes is positively correlated with a measure of climate awareness, control of corruption, and the level of education.

The assumption to start with a carbon club formed by the most developed regions is not crucial for our analysis. As an alternative we could also have started with a different set of countries, based for example on the countries which currently have the highest level of carbon taxes. Crucial for our analysis is the assumption that a relatively small subset of countries takes the initiative for ambitious carbon pricing policies. With this starting point, we explore which policy would be best to convince other regions to join their initiative, while at the same time sharing the burden of introducing carbon pricing policies globally. Obviously, support for carbon pricing in the more ambitious regions is also necessary to come to global carbon pricing. Therefore, we also consider the impact of the different approaches on GDP in the ambitious regions in our analysis.

We employ a recursive dynamic computable general equilibrium (CGE) model, the WTO Global Trade Model (GTM), to analyse the potential of different approaches to confront the challenges of introducing carbon pricing.[5] Section 2 contains a detailed description of the employed model and the construction of the baseline projections until 2030. We start the analysis in Section 3 with a discussion of the need for global carbon pricing to tackle climate change. Carbon pricing policies are needed to keep the world on a path of 1.5°C to 2°C global warming (Section 3.1). We verify that carbon pricing is most efficient at the global level, because emissions will be reduced where it is least costly (Section 3.2). We further illustrate that regional instead of global carbon policies will lead to a demand for adjustment at the border to prevent that energy intensive sectors become uncompetitive in ambitious regions. Such border carbon adjustment (BCA) policies are administratively burdensome and come with the risk of triggering trade conflicts, because the adjustment policies would involve carbon taxes on imports and subsidies on exports.

Next we introduce the two main policy challenges of global carbon pricing in Section 4. We show that global carbon policies have a negative impact on the GDP of most regions in the short to medium run, where the potential benefits of lower emissions are not yet internalized, and that the introduction of carbon pricing in a set of more ambitious regions does not provide incentives for other regions to introduce carbon pricing as well. Next we show that differential carbon pricing mitigates the negative income effects of global carbon pricing only modestly for low-income regions. Hence, such a proposal does not resolve the two challenges of carbon pricing defined in this paper. An equitable distribution of the burden of mitigation policies would require additional policies to insulate the lowest-income regions from the adverse effects of such policies. Finally, global instead of regional carbon pricing and emissions trading change the distribution of losses from carbon pricing policies, but do not insulate lower income regions from the adverse effects.

In Section 5 we then come to the core of our analysis, comparing four sets of climate mitigation policies (carbon club with uniform tariffs, carbon pricing with BCA, global carbon pricing with a global incentive scheme, and emissions trading with a progressive distribution of emission targets) in terms of their potential to tackle the two challenges of global carbon pricing. We project the impact of the four mitigation policies on income, inequality between countries, and social welfare, and analyse the effectiveness of such policies as an incentive mechanism to foster international cooperation.

Our simulations generate the following results. First, a carbon club can be effective in incentivizing non-participants to join a carbon club. However, this approach does not perform well in terms of burden sharing, because welfare in developing countries is negatively affected by the uniform tariffs imposed by the carbon club. Second, the incentives from BCA are not sufficient for non-ambitious countries to introduce carbon pricing in their own economies. The incentives to introduce carbon pricing because of BCA mainly come from the fact that countries can keep the revenues from carbon taxation on their exports. However,our simulations show that these revenues do not provide sufficient incentives to introduce carbon pricing. Third, although the global carbon fund proposal does involve substantial transfers from higher income to lower income regions, it does not provide sufficient incentives to for less-ambitious regions to introduce carbon

[5] We use a variant of the WTO Global Trade Model, extended with energy, electricity and emissions modules following largely the structure of GTAP-POWER.

pricing. Fourth, emissions trading with progressive emission targets does provide incentives for most regions to join a cap-and-trade system. Furthermore, this proposal performs well in terms of burden sharing.

At first sight, one would expect that emissions trading with progressive emissions trading and carbon pricing with a global carbon fund should provide similar incentives to reduce emissions and thus also to join an ambitious carbon club. Under emissions trading reducing emissions leads directly to more revenues for a country, either because less emission rights have to be acquired or more emission rights can be sold. Under a global carbon fund, regions also have an incentive to reduce emissions because they will have to pay less into the carbon fund or receive more from it, in proportion to the reduction in emissions. However, the carbon fund suffers from a coordination problem. If all regions simultaneously decide to reduce emissions the gains are smaller, because the benchmark emission level is also changing. Our simulations indicate that the incentives are much weaker under a global carbon fund and that moreover the costs for the developed countries are higher. The net payments to the carbon fund are much larger than the amount of money spent on buying emission rights.

Hence, our analysis indicates that emissions trading based on progressive emission targets seems best to confront the challenges of introducing global carbon pricing. However, in the literature (for example Cramton et al. (2017)) various objections against global emissions trading have been raised, in particular related to the difficulty to negotiate the introduction of such a policy. We discuss these objections at the end of Section 5.

Our work is related to five strands of literature. First, there is a sizeable literature on the formation of climate coalitions.[6] Most relevant for our paper is the work using computable models. Lessman (2015) evaluate the stability of climate coalitions in five different integrated assessment models. The model outcomes are determined in two stages. In the first stage regions decide to form coalitions with the decision of regions to participate in the coalition based on self-interest (non-cooperative game). In the second stage, regions implement mitigation policies, maximizing the welfare of a coalition. Welfare of policies is determined by the net present value of mitigation costs and benefits in terms of avoided climate damage. One of the main findings is that transfer payments can make stable climate coalitions more feasible. The broader literature on climate cooperation is discussed in Hovi et al. (2015), arguing that, while climate coalitions tend to be relatively small and unstable in most models, there might be a few potential solutions to the coordination problem. For example, countries might introduce complementary policies like cooperation on technology RD, border carbon adjustment measures or deposit-refund systems where a certain amount of currency is deposited by each participant and is forfeited in case of non compliance. Additionally, trust among the members of the coalition and decentralized cooperation seem to be important to enhance stability.

Second, various scholars have explored the role of trade policy in enforcing climate coalitions. Two types of trade policy are proposed in this regard. On the one hand, some scholars evaluate the effectiveness of

[6]The work on climate coalitions fits into a broader literature on the formation of international environmental agreements (IEAs).

border carbon adjustment policies in providing incentives to join a climate club. In Boehringer (2016) the starting point is that a subset of regions (Annex I regions Kyoto protocol) form a carbon club and impose carbon tariffs on regions without carbon pricing. Other regions can decide to introduce carbon taxes as well, retaliate, or do nothing. Boehringer (2016) show with simulations in a CGE model that China and India would introduce carbon pricing as well, whereas the other regions prefer to retaliate.

On the other hand, other scholars explore the effectiveness of uniform tariffs on non-participants to enforce a carbon coalition (Lessman (2009); Nordhaus (2015); Nordhaus (2021)). Nordhaus (2015) shows that the threat of a common external tariff implies that a grand coalition of countries imposing carbon taxes can be sustained as a Nash-equilibrium. Nordhaus shows in simulations with the C-DICE model, that the required external tariff rises in the level of carbon taxes required. For example, a carbon price of $25 per ton of CO2 would require an external tariff of 2%, whereas for a $50 carbon tax a threat of an external tariff of 5% would be needed to sustain a coalition of almost all regions in the world. Importantly, the introduction of a carbon tax of $100 in a broad coalition of countries cannot be achieved in Nordhaus' model with uniform tariff rates of up to 10%. However, Nordhaus (2021) shows in a modified setting with an analysis based on supportable policies in a dynamic model that uniform external tariffs of up to 10% are sufficient to achieve net zero under the assumption of rapid technological change.

Hagen and Schneider (2021) argue that the analysis of external uniform tariffs to sustain climate clubs should include the option for regions to retaliate. They find that the possibility of retaliation can destabilize small coalitions. If an already-large coalition exists, external tariffs can still be effective in achieving a large coalition. However, simulations with a CGE model (GTAP-E) show that the welfare effects can be adverse because of the distortionary effects of the tariffs.

Third, there is an extensive literature analysing the effects of different types of carbon funds and their effectiveness in helping to overcome the collective action problem of introducing global carbon policies. For example, Stoft (2008), Cramton (2010), and Gollier and Tirole (2017) propose a self-financing fund with regions having larger per capita emissions than the global average paying into the fund and regions with below average emissions receiving from the fund.[7] A carbon fund designed in this way also provides incentivizes to introduce carbon policies, since lowering the emissions leads to smaller net payments (higher net benefits) into the carbon fund.

Antimiani et al. model a green carbon fund (GCF) with revenues being a function of GDP per capita, climate change vulnerability and the capacity to react to climate change. The GCF can either take the form of a lump-sum transfer or be used to finance R&D improving energy efficiency or the production renewables. The authors show that a GCF can help to limit the free rider problem in forming a carbon coalition.

A different proposal for a carbon fund solving the free rider problem comes from Gerschbach (2021). They propose to set up an initial fund investing in assets, whose returns are paid out to its members in proportion to the reduction of emissions. They show that a fund of about 0.5% of global GDP can make a

[7]The same set-up for a carbon fund has been proposed by Rajan (2021).

grand coalition feasible in the RICE model.[8]

Fourth, the literature has extensively discussed the differences between price based (carbon tax) and quantity based (cap-and-trade) approaches (Nordhaus (2013); Cramton et al. (2017); Gollier and Tirole (2017)). The various arguments raised in this literature will be further addressed in Section 5 when the feasibility of emission trading is discussed.

Fifth and finally, our work is related to the literature on the impact of carbon pricing on global welfare and inequality between regions. The effects of carbon pricing are discussed for example in Stern and Stiglitz (2017): while its impact on global welfare is potentially positive because it can help to address the climate externality, on the other hand it might entail high costs on low-income countries because the opportunity cost of consumption is relatively high and such countries are at a development stage in which substitution options are not available, they are building their infrastructures and are still dependent on energy-intensive industries. Matoo et al. (2012) project that climate change mitigation policies such as carbon pricing will have a differentiated effect on the manufacturing output and exports of developing countries depending on their carbon intensity: relatively low emission countries like Brazil are projected to experience modest losses, while carbon intensive countries like China and India might be affected more substantially. Moreover, Avetisyan (2018) points out that climate change mitigation measures could induce the transport sector, that accounts for a large share of global emissions, to redirect towards developed countries at the expense of developing countries, which are characterized by less clean technologies. These potential side effects of the international efforts to deal with climate change justify the call for support measures such as climate funds that will be further analysed in our paper.

In light of the voluminious related literature, our work makes three contributions to this literature. First, we provide a comparison of a broad set of approaches to overcome the collective action problem of global climate action employing a dynamic CGE model. Our work adds value by comparing a wide set of policies and by employing a dynamic CGE models. Previous work tends to concentrate on one or two approaches to tackle the climate change problem and tends to employ smaller-scale IAMs. Obviously, a downside of our work is that we do not formally analyze the formation and stability of carbon coalitions. However, this is compensated by comparing a broader set of proposals.

Second, we show that there are important differences in the potential to incentivize regions to join a global carbon coalition between emissions trading and carbon taxation combined with a carbon fund. In particular, we show that a carbon fund with payments based on emission reductions is much less effective because of a coordination problem.

Third, we explore the equity effects of different proposals for global climate action, showing that both BCA and Nordhaus tariffs generate higher inequality between regions than the other approaches.

[8] Kornek et al. (2017) point out a potential adverse effect of a climate fund, drawing parallels with the resource curse. They discuss the likelihood that revenues from global emissions trading could depress economic growth for reasons similar to the resource curse. Mechanisms discussed are the Dutch disease, and the promotion of price volatility and of rent-seeking.

2 Methodology: model and baseline construction

We combine the WTO Global Trade Model with the GTAP-Power model into a recursive dynamic computable general equilibrium (CGE) model featuring both an energy module and a power (electricity) module, as well as greenhouse gas (GHG) emissions. We aggregate data from the GTAP Data Base, Version 10 (2014) to 24 regions and 25 sectors (see Appendix I) and then generate a baseline of the global economy until 2030. We incorporate all the inputs employed in baseline projections with the Global Trade Model (growth of the population, labour force, skills, aggregate productivity growth to target GDP projections from the IMF and OECD, differential productivity growth, and exogenous changes in the savings rate and in trade costs) as described in Bekkers et al. (2022). We complement these changes with changes specific to energy: changes in the energy mix (electrification and share of renewables in electricity), productivity growth of renewables, and changes in energy efficiency. The productivity growth of renewables is based on data from IRENA. Changes in the energy mix are based on data from JRC and GTAP. Finally, changes in energy efficiency are calibrated to generate a baseline close to emissions projected in the Energy Model Forum Study on "Carbon Pricing after Paris" (EMF36) as reported in Böhringer et al. (2021). Projected emissions necessary to stay on the path of 2°C global warming are taken from the same study, which are based in turn on projections by the IEA.

2.1 The model

Our model includes $j = 1, .., J$ countries and $r = 1, .., R$ sectors. A representative consumer buys three categories of goods (private goods, government goods, and savings). Savings are channeled to a global bank allocating savings across the different countries, thus buying investment goods, q_j^{in}, in the different countries. Investment is allocated across countries such that rates of return tend to equalize across countries. In order to produce, firms demand both intermediate inputs and factors of production. The choice between intermediate inputs and value added bundles is modelled as Leontief and the choice between different production factors is constant elasticity of substitution (CES). There are four production factors: land, high-skilled labor, low-skilled labor and a capital-energy composite. Energy is modeled as a nested CES and can be demanded both by households and firms, which generate CO2 emissions when they buy certain energy products (oil, gas, coal, oil products). The model features carbon taxes and quotas defined at the bloc level with a bloc including several regions among which trade in emission allowances is possible. Trade is modeled with Armington preferences and the import price is equal to the export price plus the export tax, the cif-fob margin, and the import tariff.

2.1.1 Demand

A representative consumer in each country j spends her income on quantities of three categories of goods, private goods, q_j^{pr}, government goods, q_j^{go}, and savings, q_j^{sa}, according to a Cobb-Douglas utility function[9]:

$$u_j = \left(q_j^{pr}\right)^{\kappa_j^{pr}} \left(q_j^{go}\right)^{\kappa_j^{go}} \left(q_j^{sa}\right)^{\kappa_j^{sa}} \tag{1}$$

The demand of private goods is non-homothetic, meaning that it is not possible to define a price, while the government and savings demand functions are homothetic. We maximise utility in equation (1) subject to the following implicit budget constraint, with expenditures on category c goods, e_j^c, a function of the quantity of private consumption, q_j^c:

$$\sum_c e_j^c \left(q_j^c\right) = x_j. \tag{2}$$

This leads to the following expression for expenditures, x_j^c, on the three categories of goods, $c \in \{pr, go, sa\}$, as a function of total expenditure (x_j):[10]

$$x_j^c = \kappa^c \left(\frac{\Psi_j^c}{\Psi_j}\right) x_j; c = pr, go, sa \tag{3}$$

where Ψ_j^c is the elasticity of quantity, q_j^c, with respect to expenditure, x_j^c, and Ψ_j is the elasticity of utility, u_j, with respect to total expenditure, x_j. For the other goods –savings (sa) and public goods (go)– $\Psi_j^{go} = \Psi_j^{sa} = 1$, meaning that equation (3) generates the standard expression for Cobb-Douglas expenditure shares. With non-homothetic preferences for private goods the share of spending on private goods is larger than the Cobb-Douglas parameter κ^{pr} if the elasticity of private quantity, q_j^{pr}, with respect to private expenditure, x_j^{pr}, is larger than 1. This gives the consumer an incentive to spend a more than proportional amount on private goods.

Ψ_j^{pr} follows from log differentiating the indirect utility function for private goods defined below in equation (6) below with respect to quantity (q_j^{pr}) and expenditure (x_j^{pr}). This gives the following expression:

$$\Psi_j^{pr} = \frac{1}{\sum\limits_{s=1}^{S} s_{js}^{pr} \eta_{js}} \tag{4}$$

where s_{js}^{pr} is the share of private expenditure spent on good s. Ψ_j follows from maximisation of utility in equation (1):

$$\Psi_j = \sum_c \Psi^c \kappa^c = \Psi^{pr} \kappa^{pr} + \kappa^{go} + \kappa^{sa}. \tag{5}$$

Preferences for private goods across the different sectors are described by the non-homothetic Constant

[9]Savings are included in the static utility function to prevent that a shift away from savings –and thus implicitly from future consumption– towards current consumption would have large welfare effects. The formal underpinning comes from Hanoch (1975) who showed that the expressions for consumption in an inter-temporal setting can also be derived from a static utility maximisation problem with savings in the utility function.

[10]See McDougall (2001) and Bekkers et al. (2018) for a detailed derivation

Distance Elasticity (CDE) implicit expenditure function:

$$\sum_{s=1}^{S} \alpha_{js} \left(q_j^{pr}\right)^{\gamma_{js}\eta_{js}} \left(\frac{p_{js}^{pr}}{x_j^{pr}}\right)^{\gamma_{js}} = 1 \tag{6}$$

where q_{js}^{pr} and p_{js}^{pr} are respectively the quantity and price of private goods in country j and sector s, x_j^{pr} is private expenditure in country j, while α_{js}, γ_{js} and η_{js} are respectively the distribution, substitution and expansion parameters. Private demand, q_{js}^{pr}, as a function of private expenditure, x_j^{pr}, and prices, p_{js}^{pr}, can be derived by log-differentiating equation (6) with respect to p_{js}^{pr} and x_j^{pr} and applying Shepherd's lemma:

$$q_{js}^{pr} = \frac{\alpha_{js} \left(q_j^{pr}\right)^{\gamma_{js}\eta_{js}} \left(\frac{p_{js}^{pr}}{x_j^{pr}}\right)^{\gamma_{js}-1} \gamma_{js}}{\sum\limits_{u=1}^{S} \alpha_{ju} \left(q_j^{pr}\right)^{\gamma_{ju}\eta_{ju}} \left(\frac{p_{ju}^{pr}}{x_j^{pr}}\right)^{\gamma_{ju}} \gamma_{ju}}. \tag{7}$$

Preferences for government goods are Cobb-Douglas, so its quantity q_{js}^{go}, and price index p_j^{g} can be expressed as follows:

$$q_{js}^{go} = pop_j \frac{\beta_{js}^{go}}{p_{js}^{go}} p_j^{go} q_j^{go} \tag{8}$$

$$p_j^{go} = \prod_{s=1}^{S} \left(\frac{p_{js}^{go}}{\beta_{js}^{go}}\right)^{\beta_{js}^{go}} \tag{9}$$

where pop_j is the population in region j and β_{js}^{go} is the Cobb-Douglass parameter of the government demand in region j and sector s.

The total quantity and expenditure for public goods and savings in region j are simply related by the following expression, $q_j^c = \frac{x_j^c}{p_j^c}; c = go, sa$. For private goods we cannot define a price index. Quantity, q_j^{pr}, and expenditure, x_j^{pr}, are implicitly related through the indirect expenditure function in (6).

2.1.2 Production

Input bundles used in production, q_{is}^{ib}, are a Leontief function of factor inputs (a composite of value added and energy inputs), q_{is}^{va}, and intermediate inputs bought by firms in sector s (with superscript fi_s) from sector r, $q_{ir}^{fi_s}$:

$$q_{is}^{ib} = \min\left\{\varpi_{is}^{va} q_{is}^{va}, \varpi_{i1}^{fi_s} q_{i1}^{fi_s}, .., \varpi_{iS}^{fi_s} q_{iS}^{fi_s}\right\} \tag{10}$$

The demand for the value added/energy composite and intermediates are defined as:

$$q_{is}^{va} = \varpi_{is}^{va} q_{is}^{ib} \tag{11}$$

$$q_{ir}^{fi_s} = \varpi_{ir}^{fi_s} q_{is}^{ib} \tag{12}$$

Intermediate input demand by firms from sector s for goods from sector r, $q_{ir}^{fi_s}$, coresponds with the demand by agent $ag = fi_s$, q_{ir}^{ag}, in equation (23).[11]

The price of input bundles, p_{is}^{ib}, is a function of the prices of intermediates, p_{ir}^{fi}, and the price of value added p_{is}^{va}:

$$p_{is}^{ib} = \varpi_{is}^{va} p_{is}^{va} + \sum_{r=1}^{S} \varpi_{irs}^{int} p_{ir}^{fi_s} \tag{13}$$

Demand for the different production factors is CES, implying the following expressions for the price of value added, p_{is}^{va}, and demand for factor inputs (or endowments e), q_{ise}^{end}:

$$p_{is}^{va} = \left[\sum_{e=1}^{E} (\iota_{ise})^{\chi_s} \left(t_{ise}^{end} \omega_{ise} \right)^{1-\chi_s} \right]^{\frac{1}{1-\chi_s}} \tag{14}$$

$$q_{ise}^{end} = \left(\iota_{ise} \frac{c_{is}^{va}}{t_{ise}^{end} \omega_{ise}} \right)^{\chi_s} q_{is}^{va} \tag{15}$$

ω_{ise} and t_{ise}^{end} are respectively the price of and the tax on endowment e, and χ_s is the substitution elasticity between production factors. With this specification there is one substitution elasticity between the different factors of production.[12]

Our model includes four endownments: land, unskilled labor, skilled labor and a capital-energy nest. The structure of the capital-energy nest will be described in the next section.

Capital ca and high and low-skilled labor, hs and ls, are mobile across sectors and its factor price w_{ica} (also the nominal rental rate on capital) is equal between sectors:

$$w_{ise} = w_{ie}; e = ca, ls, hs \tag{16}$$

The supply of capital is described in the subsection 2.1.5. Land (ld) is imperfectly mobile across sectors, and their supply is modelled by the following elasticity of transformation function:

$$q_{ie}^{end,sup} = \left[\sum_{s=1}^{S} \vartheta_{ise} \left(q_{ise}^{end,sup} \right)^{\frac{\mu_e+1}{\mu_e}} \right]^{\frac{\mu_e}{\mu_e+1}} ; e = ld \tag{17}$$

q_{ie}^{end} is the total quantity of immobile factor e and q_{ise}^{end} the quantity used in sector s. The supply of the immobile production factors to the different sectors, q_{ise}^{end}, can be expressed as follows:

$$q_{ise}^{end,sup} = \left(\frac{\omega_{ise}}{\vartheta_{ise} w_{ie}} \right)^{\mu_e} q_{ie}^{end,sup}; e = ld, ls, hs \tag{18}$$

[11] To be able to define demand for all groups of agents ag in the description of international trade we have chosen to work with the somewhat awkward notation for intermediate demand, $q_{ir}^{fi_s}$, with the subscript r indicating the sector from which intermediates are bought and the subscript s in the superscript fi_s indicating the sector buying the intermediates.

[12] Many other CGE-models feature a more nested structure where firms choose for example first between a composite of high-skilled labor and capital on the one hand and low-skilled labor on the other hand in order to model skill-capital complementarity. Or the intermediate energy could be modelled as a composite together with capital.

With the price w_{ie} defined as:

$$q_{ie}^{end,sup} = \left[\sum_{s=1}^{S} \vartheta_{ise}^{\mu_e} \left(\omega_{ise}\right)^{\mu_e+1} \right]^{\frac{1}{\mu_e+1}} ; e = ld \tag{19}$$

So factor price differences across sectors are possible and q_{ise}^{end} moves to the sector where the price w_{ise} is higher.

2.1.3 Energy and emissions

Energy enters both the demand and the production side of the model. As anticipated in the previous subsection, firms' value added includes a capital-energy nest, while consumers directly choose how much energy to purchase within their private goods bundle. In both cases, energy is modeled with a nested CES structure. Agents choose first the breakdown between electricity and non electricity energy; within the non electricity energy nest, the choose between coal and non-coal energy; within the non coal nest, they choose between oil, gas and oil products. On the other hand, within the electricity nest, agents choose between power generation and distribution; within the generation nest, they choose between intermittent and non intermittent energy; within the non intermittent nest, they choose between nuclear, hydroelectric and thermal energy; within the thermal nest, they choose between coal, gas and oil; within the intermittent nest, they choose between solar, wind and other energy sources.

The nesting structure of the energy sector can be represented by a set of CES demand and price index equations with the quantity of energy input f, q_{isf}^{en}, demanded by energy output s and the price index of energy output s, P_{is}^{en}, defined as:

$$q_{isf} = \frac{tw_{isf}^{en}}{twa_{is}^{en}} \frac{1}{a_{isf}^{en}} \left(\frac{p_{isf}^{en}}{a_{isf} P_{is}^{en}} \right)^{-\nu_s} q_{is} \tag{20}$$

$$P_{is}^{p} = \left(\sum_{f} \left(\frac{p_{isf}^{en}}{a_{isf}^{en}} \right)^{1-\nu_s} \right)^{\frac{1}{1-\nu_s}} \tag{21}$$

$\frac{tw_{isf}^{en}}{twa_{is}^{en}}$ is a cost-neutral twist variable satisfying the following expression imposing that changes in twist variables are cost-neutral.[13]

$$\sum_{f} sh_{isf} \left(\widehat{tw_{isf}^{en}} - \widehat{tw_{is}^{en}} \right) \tag{22}$$

a_{isf} is productivity of energy input f, also defined as autonomous energy efficiency improvement (AEEI). ν_s is the substitution elasticity between energy inputs f within the nest s, according to the nesting sequence previously described.

CO2 emissions $CO2_i$ at the regional level emerge when energy inputs coal, oil, oil products, and natural

[13] Variables with a hat indicating percentage changes.

gas are purchased by firms and households. Hence, it is associated both with production and demand. Following McDougall and Golub (2007), we assume that emissions growth is proportional to the growth in usage. A key feature of our model is that each region is assigned an emission quota and regions are grouped in blocs, that are mutually exclusive sets of regions. CO2 emissions must be equal to the quota at the bloc level, but there can be a discrepancy at the regional level, and this gives scope for emission trading among countries in the same bloc.

2.1.4 International Trade

International trade is modelled with Armington preferences in a nested structure. The group of agents ag in country j divides demand within each sector, q_{js}^{ag}, between demand for domestic and imported goods, $q_{js}^{d,ag}$ and $q_{js}^{m,ag}$, according to a CES utility function:

$$q_{js}^{ag} = \left(\left(q_{js}^{d,ag} \right)^{\frac{\rho_s - 1}{\rho_s}} + \left(q_{js}^{m,ag} \right)^{\frac{\rho_s - 1}{\rho_s}} \right)^{\frac{\rho_s}{\rho_s - 1}} \tag{23}$$

Quantities of imported and domestic varieties can be summed across the groups of agents to give total importer and domestic demand, q_{js}^{so} with superscript so the source, $so = d, m$:

$$q_{js}^{so} = \sum_{ag} q_{js}^{so,ag} = \sum_{ag} \left(\frac{ta_{js}^{so,ag} p_{js}^{so}}{p_{js}^{ag}} \right)^{-\rho_s} q_{js}^{ag} \tag{24}$$

$ta_{js}^{so,ag}$ is a group–specific and source-specific tariff, expressed in power terms, so as 1 plus the ad-valorem tariff rate. p_{js}^{ag} and p_{js}^{so} are respectively the prices corresponding with q_{js}^{ag} and q_{js}^{so}. Since q_{js}^{so} is homogeneous across the different agents it does not have a superscript ag.

Import demand, q_{js}^{m}, is in turn distributed across imports from different sourcing countries i, q_{ijs}:[14]

$$q_{js}^{m} = \left(\sum_{i=1}^{J} \left(q_{ijs} \right)^{\frac{\sigma_s - 1}{\sigma_s}} \right)^{\frac{\sigma_s}{\sigma_s - 1}} \tag{25}$$

Import demand from specific source countries i, q_{ijs}, is thus equal to:

$$q_{ijs} = \left(\frac{p_{ijs}}{p_{js}^{m}} \right)^{-\sigma_s} q_{js}^{m} \tag{26}$$

[14]To allow for intra-regional international trade the summation includes country j. Intra-regional international trade is relevant when regions in the model are aggregates of different countries.

p^{ag}_{js}, p^{m}_{js}, and p_{ijs} are respectively the prices corresponding with q^{ag}_{js}, q^{m}_{js}, and q_{ijs}, defined as follows:

$$p^{ag}_{js} = \left(\left(ta^{d,ag}_{js} p^{d}_{js} \right)^{1-\rho_s} + \left(ta^{m,ag}_{js} p^{m}_{js} \right)^{1-\rho_s} \right)^{\frac{1}{1-\rho_s}} \tag{27}$$

$$p^{d}_{js} = tp_{js} b_{js} p^{ib}_{js} \tag{28}$$

$$p^{m}_{js} = \left(\sum_{i=1}^{J} p^{1-\sigma_s}_{ijs} \right)^{\frac{1}{1-\sigma_s}} \tag{29}$$

$$p_{ijs} = ta_{ijs} t_{ijs} p^{cif}_{ijs} = ta_{ijs} t_{ijs} \left(te_{ijs} tp_{is} b_{is} p^{ib}_{is} + \frac{p^{ts}_{ijs}}{a^{ts}_{ijs}} \right) \tag{30}$$

The price of the domestic good is equal to the marginal cost, b_{js}, times the production tax, tp_{is}, times the input bundle price, p^{ib}_{is}. The price of the traded good, p_{ijs}, in equation (30) is equal to the cif-price, p^{cif}_{ijs} times iceberg trade costs, t_{ijs}, times bilateral ad valorem tariffs, ta_{ijs}, both expressed in power terms. The cif-price, p^{cif}_{ijs}, in turn is calculated as marginal cost, b_{is}, times the production tax, tp_{is}, times the price of input bundles in the exporting country, p^{ib}_{is}, times the export subsidy applied to the fob-price, te_{ijs}, plus the price of transport services, p^{ts}_{ijs}, divided by a transport services technology shifter, a^{ts}_{ijs}. Firms spend a fixed quantity share of sales on transport services.

2.1.5 Savings and Investment

The relation between the beginning-of-period capital stock, kb_i, investment, q^{in}_{i}, the end-of-period capital stock, ke_i and capital depreciation, δ_i, is defined as follows:

$$ke_i = (1-\delta)\, kb_i + q^{in}_{i} \tag{31}$$

The beginning-of-period capital stock is used in production, thus giving:

$$q^{end}_{ica} = kb_i \tag{32}$$

Investment goods are like intermediates a Leontief composite of goods used for investment from different industries, q^{in}_{is}:

$$q^{in}_{i} = \min\left\{ \varpi^{in}_{i1s} q^{in}_{i1}, .., \varpi^{in}_{iS} q^{in}_{iS} \right\} \tag{33}$$

Investment demand from different sectors, q^{in}_{is}, and the aggregate price of investment goods, p^{in}_{i}, are thus defined as:

$$q^{in}_{is} = \varpi^{in}_{is} q^{in}_{i} \tag{34}$$

$$p^{in}_{i} = \sum_{s=1}^{S} \varpi^{in}_{is} p^{in}_{is} \tag{35}$$

Total investment demand, q_i^{in}, is determined by the condition that rates of return tend to equalize between countries, modelled by distinguishing between the current and expected rate of return. The current real rate of return on capital, r_i, can be different across countries. It is defined as the rental rate on capital, w_{ica}, divided by the price of investment goods, p_i^{in}, minus the rate of depreciation, δ_i:

$$r_i = \frac{w_{ica}}{p_i^{in}} - \delta_i \tag{36}$$

The expected real rate of return, r^e, instead is equalized across different countries. r^e is proportional to the current rate of return, but is scaled down by a factor proportional to the ratio of the end-of-period to beginning-of-period capital stock, reflecting the presence of capital adjustment costs:[15]

$$r^e = r_i \left(\frac{ke_i}{kb_i} \right)^{-flex} \tag{37}$$

$flex$ is a parameter determining the importance of capital adjustment costs[16].

Total investment, q_{in}, is thus determined by equations (31), (36), and (37), together with the demand for capital in production, as specified in equation (43).

The price of savings in country i is determined by the domestic price of investment and a weighted average of the global price of investment goods:

$$p_i^{sa} = p_i^{in} \sum_{k=1}^{J} \left(p_k^{in} \right)^{\chi_k} \tag{38}$$

χ_k is the value of net investment minus the value of savings in country k divided by the value of global net investment:

$$\chi_k = \frac{p_k^{sa} \left(q_k^{sa} - \delta_k q_{kca}^{end} \right) - p_k^{sa} pop_k q_k^{sa}}{p^{sa} \sum_{j=1}^{K} \left(q_j^{sa} - \delta_j q_{jca}^{end} \right)} \tag{39}$$

To model endogenous capital accumulation, we assume that the beginning- and end-of-period capital stock are identical, $ke_i = kb_i$. This implies that current rates of return, r_i, are equalized across countries according to equation (37).

2.1.6 Tax Revenues

The model includes several taxes: a tax on the use of the endowment, a direct income tax, a production tax, an export tax, an import tax (tariffs) and a carbon tax. We will discuss the tariffs and the carbon tax in this section, as they are the ones we target in our baseline and policy scenarios.

[15] r^e is determined because one of the prices in the model is set as numeraire.

[16] A large value of $flex$ means that additions to the capital stock, corresponding with $ke_i > kb_i$, are costly and thus have a strong negative impact on the expected rate of return. As a result only relatively small flows of capital already lead to equalization of the expected rate of return. With small values of $flex$ instead large changes in the capital stock are required to equalize rates of return.

Source-specific import tax revenues, $t_{js}^{so,ag}$, are determined according to the following equation with $q_{js}^{so,ag}$ defined in (24):

$$tar_{js}^{so,ag} = \left(ta_{js}^{so,ag} - 1\right) p_{js}^{so,ag} q_{js}^{so,ag} \tag{40}$$

where $tar_{js}^{so,ag}$ is the tariff revenue and $ta_{js}^{so,ag}$ is the power on the import tax.

The nominal regional carbon tax revenue, $nctar_j$, depends on the nominal carbon tax rate, $nctax_{b(j)}$, and the regional CO2 emissions, $CO2_j$. Formally:

$$nctar_j = CO2_j \times nctax_{b(j)} \tag{41}$$

where the nominal carbon tax is defined over the bloc $b(j)$. Trade in emission allowances depends on the discrepancy between the regional CO2 emission quota and the actual CO2 emissions: if a country's emissions are higher than its quota, it is a net buyer of emission permits, if its emissions are lower than the quota, it is a net seller. Formally, the net income from emission trading is defined as:

$$nctrad_j = (CO2Q_j - CO2_j) \times nctax_{b(j)} \tag{42}$$

and its value is incorporated into the trade balance. This implies that regional income in region j rises/falls for a net seller/buyer of emission permits.

2.1.7 Market equilibrium

We define an equilibrium as a set of prices and quantities such that demand equals supply in the factor, goods, savings and emission permits market. For capital, land, high and low skilled labor, this implies that:

$$ke_i = \sum_s q_{isca}^{end} \tag{43}$$

$$q_{ie}^{end,sup}; = \sum_s q_{ise}^{end}; e = ld, hs, ls \tag{44}$$

The supply of capital ke_i is determined in subsection 2.1.5 while the supply of the other factors Q_i^l is exogenous.

The product market equilibrium is identified by the following equation:

$$q_{js}^{pr} + q_{js}^{go} = q_{js}^{ib} + \sum_i q_{is}^{ib} \tag{45}$$

meaning that the total (private and public) demand of good s is equal to the domestic supply of good s

plus the imports from the other regions.

The global value of savings is equal to the global value of net investments:

$$\sum_{i=1}^{J} pop_i p_i^{sa} q_i^{sa} = \sum_{i=1}^{J} p_i^{in} \left(q_i^{in} - \delta q_{ica}^{end} \right) \tag{46}$$

Finally, CO2 emissions are equal to their quota at the bloc level:

$$\sum_{i \in b(i)} CO2Q_j = \sum_{i \in b(i)} CO2_j \tag{47}$$

2.2 Baseline construction

To calibrate the model, we need three ingredients: i) data on the global economy in the initial year (2014), ii) values of the behavioral parameters and iii) data on the exogenous shocks that we impose on the model. The first year is calibrated based on the GTAP Power Data Base (Version 10), which contains information on domestic and international trade flows, final demand and value added by factor of production for 141 regions and 76 sectors, which we aggregate to 24 regions and 25 sectors. The GTAP Power Data Base contains disaggregated information on the electricity sector by energy input (Coal, Gas, Oil, Nuclear, Hydro, Solar, Wind and Others) as well as energy sectors (Coal, Oil, Gas and Oil Products). CO2 emissions associated with the use of energy inputs come from the WEO dataset (IEA, 2018).

Behavioral parameters were drawn from the CGE literature, taking the median of the values employed by similar works. Our energy nesting requires four substitution elasticities: between capital and energy; between electricity and non-electricity energy; between coal and non-coal energy; and between crude oil, petroleum products and gas. The substitution elasticity between capital and energy usually ranges between 0 and 1, so we set it to 0.5 as in the DART model (Delzeit et al., 2021); we set the substitution elasticity between electricity and non-electricity to 1 as in the MAGNET model (Woltjer et al., 2014); the substitution elasticity between coal and non-coal energy is set to 0.5 (Cossa et al., 2004) and the substitution elasticity between crude oil, petroleum products and gas, which usually ranges between 0 and 3 in the CGE literature, is set to 1 as in the ADAGE model (Fontagné et al., 2013).

In the power nesting, we have five substitution elasticities: between power and transmission; between intermittent and non-intermittent technologies; between nuclear; thermal and hydroelectric, between intermittent technologies; and between the thermal technologies. We set the substitution elasticity between power and transmission equal to 0: intuitively, a substitution elasticity of zero between power and transmission implies that they are perfect complements and electricity production cannot be increased unless the transmission and distribution network is strengthened too; the elasticity between intermittent and non-intermittent technologies is set to 0.9 (Ross, 2009), the elasticity between nuclear, thermal and hydroelectric to 0.25, the elasticity between the different intermittent technologies to 0.4 (Ross, 2009) and finally the elasticity of substitution between thermal technologies to 2.

Table 1: Macroeconomic shocks

Region	GDP per capita	Population	Unskilled labor	Skilled labor	Savings
Asia LDC	0.35	1.07	-0.78	2.31	10.07
Australia	0.01	1.36	-0.94	0.99	1.86
Brazil	0.43	0.68	-1.23	0.69	1.23
Canada	-0.40	1.01	-1.31	0.57	-0.41
China	4.60	0.14	-1.37	2.21	-5.99
European Union	-0.73	0.26	-2.05	0.04	-0.48
EFTA	-1.41	0.67	-1.05	1.11	-1.15
United Kingdom	-0.23	0.63	-1.25	0.78	1.51
Indonesia	0.64	0.67	-0.26	2.77	2.13
India	2.82	1.07	-1.28	1.53	-0.11
Japan	-0.02	-0.24	-2.03	0.63	-5.96
South Korea	1.88	0.04	-3.42	1.45	-5.22
Latin America	0.52	1.83	1.25	3.89	2.45
Mexico	0.15	1.04	-1.31	1.05	1.47
Middle East	-0.02	1.85	-2.12	0.64	7.73
Other Asian Countries	-0.18	1.92	-0.99	0.54	0.40
Rest of the World	0.93	0.32	-1.77	-0.64	8.39
Russian Federation	0.56	-0.28	-2.20	-1.30	1.94
South-East Asia	-0.03	0.98	-0.96	2.04	1.62
Sub-Saharian Africa LDC	0.18	2.53	1.95	4.78	-0.57
Sub-Saharina Africa Other	-0.53	2.07	0.02	3.06	14.77
Turkey	-0.63	0.73	-1.41	1.32	-0.56
United States	0.10	0.75	-1.15	0.12	-4.16
South Africa	1.93	0.62	0.05	1.43	5.46

Note: The first four columns report average annual percentage changes in the variables of interest (GDP per capita, population, unskilled and skilled labor force) in 2014-2030; the savings rate is reported as simple change in 2014-2030. Data for the 2014-2025 period come from the IMF database, while data for 2026-2030 come from SSP.

Table 1 provides a summary of the main macroeconomic shocks that we impose on the model in order to study the evolution of the global economy in 2014-2030. All the shocks presented in table 1 come from two data sources: we employ IMF projections until 2025 and we complement them with SSP data for 2026-2030; in addition, we target the projected changes in oil, gas and coal prices (see Appendix II) from the IEA database, tariffs and trade costs changes coming from TFA implementation, differential productivity growth by sector and projected changes in the utility function parameters (see Bekkers et al. for a systematic review of these ingredients).

The detailed structure of the energy sector in the Power model allows us to include more detailed and realistic assumptions on energy efficiency and costs of renewable energy over time and to impose realistic targets on renewable and electricity shares.

We employ historical data (2011-2020) of the Levelized Cost of Electricity (LCOE) from IRENA Renewable Energy statistics 2021 to project the productivity growth of renewable energy in 2021-2030. According to the IRENA projections for the future cost reductions, 72% of the cost reduction in solar technology and 82 % of the cost reduction in wind technology should come from productivity growth. Assuming that the cost reduction can be approximated by a linear function, we find that the annual projected productivity growth is 5.97% in solar power and 1.95 % in wind. The productivity of hydro power is projected to stay constant. We calibrate the autonomous energy efficiency growth such that our baseline CO2 emissions in 2030 mimic WEO projections in each region.

Additionally, we target electricity shares in total energy use and renewable (solar and wind) shares in electricity. For renewable energy shares, we target the shares from the JRC Input-Output tables 2014-2030 (see Temursho et al., 2020), while for electricity shares adapt the shocks implied by the JRC I-O tables in order to reach the CO2 emissions implied by WEO in 2030. In practice, our methodology consists in augmenting the demand of firms and households with a cost-neutral demand twist (Dixon and Rimmer, 2002) and shocking it based on the discrepancy between observed shares and the ones implied by our baseline simulation in 2030, including all the baseline ingredients described so far. Additional details on initial and final electricity and intermittent shares as well as energy efficiency growth can be found in Appendix II.

2.3 NDC targets

In our policy scenarios we either target carbon quotas and infer the associated carbon price (i.e. the carbon price that is necessary in order to realize that quota according to our model) or directly target carbon prices. In the first case, we employ as a target three types of Nationally Determined Contributions (NDCs): NDCI targets, based on the unconditional pledges that were submitted to the UNFCCC by the parties of the Paris agreement, NDCU targets, i.e. the updated targets that the parties are willing to pursue conditional on other countries' emission reductions, and NDC2 targets, that were collected by Bohringer et al. (2021) to simulate an aggregate CO2 reduction in line with the 2 °C objective.

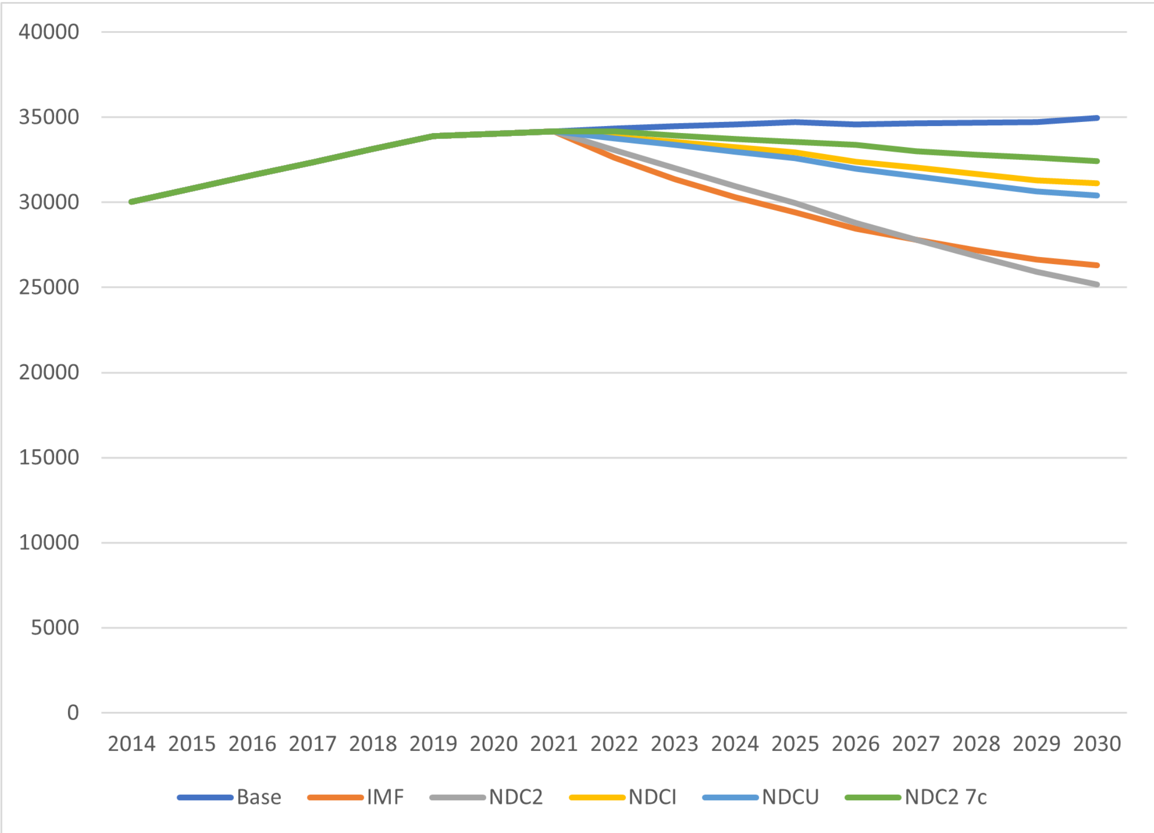
Table 2 reports our baseline projections in 2030 for CO2 emissions by region as well as NDCI, NDCU

Table 2: Baseline and NDC targets

Region	Baseline	NDCI	NDCU	NDC2
Asia LDC	85.88	-3.22	-11.43	33.30
Australia	33.90	-1.89	-1.96	8.59
Brazil	2.05	-17.93	-17.93	-30.70
Canada	-6.05	-17.99	-17.99	-36.30
China	18.20	-6.29	-7.02	-9.03
European Union	-13.55	-19.47	-19.47	-42.50
EFTA	-6.36	-44.63	-44.63	-57.30
United Kingdom	-12.17	-9.36	-9.36	-34.20
Indonesia	76.88	-47.96	-56.75	-36.70
India	98.91	-5.86	-5.86	54.90
Japan	-20.00	-4.36	-4.36	-36.70
South Korea	41.49	-45.52	-45.52	-36.20
Latin America	10.23	-6.42	-10.56	-17.40
Mexico	-2.93	2.96	0.49	-19.30
Middle East	27.37	-4.85	-9.55	-4.05
Other Asian Countries	36.88	-7.16	-7.44	4.26
Rest of the World	2.92	-17.36	-24.17	-37.60
Russian Federation	22.54	-15.89	-16.09	-14.90
South-East Asia	76.17	-10.94	-23.93	11.40
Sub-Saharian Africa LDC	46.42	-4.94	-7.74	10.60
Sub-Saharian Africa Other	47.28	-4.68	-5.46	14.10
Turkey	3.48	-0.86	-0.86	-15.10
United States	-9.72	-13.44	-16.16	-37.30
South Africa	5.33	2.37	-11.75	-23.10

Note: The first column reports the percentage increase in CO_2 between 2014 and 2030 based on WEO. The second, third and fourth columns report NDCI, NDCU and NDC2 CO_2 targets expressed as a percentage change compared to 2030 baseline emissions.

Figure 1: Emission paths until 2030 under different scenarios: NDC targets are insufficient to stay on 2 degrees global warming trajectory



Notes: Baseline emissions (Base) are simulated with WTO Global Trade Model from 2014. IMF displays the emissions under IMF differential carbon price proposal ($25, $50, $75 for respectively low-income, middle-income, and high-income regions). NDC2 displays emissions in trajectory to 2 degrees global warming world. NDCI and NDCU display emissions under initial and updated emission targets from Nationally Determined Contributions (NDCs). NDC2 7c displays emissions if only the seven richest regions (Australia, Canada, EU, EFTA, Great Britain, Japan, USA) adopt the targets prescribed by the NDC2 scenario.

and NDC2 targets expressed as a percentage deviation from the 2030 baseline.

We also employ a price target from the IMF (2021) proposal, which entails carbon prices of 75$, 50$, and 25$ for high-income, upper-middle income, and low and lower-middle income countries respectively.

3 The need for and efficiency and urgency of global carbon pricing

In this section we discuss in turn the need for global climate change mitigation policies to stay on the 2°C global warming path (Section 3.1); the efficiency of global carbon pricing compared to regional carbon pricing (Section 3.2); and the urgency to introduce global carbon pricing to prevent a patchwork of policies with border adjustment mechanisms (Section 3.3).

3.1 Carbon pricing is needed to stay on the path of 2°C global warming

Carbon pricing, including through emission trading schemes (ETS) or carbon taxes, can play an important role in climate change mitigation. Due to the externalities of climate change, voluntary changes of the private sector alone have thus far been insufficient to reach the Paris Agreement targets. Projections suggest that policies such as carbon pricing, regulation and promoting/providing support for green technologies are necessary tools to stay on the path towards 2°C global warming.

Figure 1 displays the projected emissions with NDCI, NDCU and NDC2 targets. NDCI and NDCU pledges respectively imply a 10% and 12% reduction in emissions compared to our baseline, while a 27% reduction is needed in order to stay on the 2°C global warming scenario. Figure 1 also displays the projected emissions under the proposal of a carbon price floor by the IMF. Simulating this proposal with our model shows that it would bring the world onto the path of a 2°C climate change scenario. Finally, we report the emission path if only the seven richest regions (Australia, Canada, EU, EFTA, the UK, Japan and the US) adopt the NDC2 emission targets (NDC2 7c), and we show that it performs relatively poorly compared to the other scenarios.

3.2 Carbon pricing is most efficient at the global level

Carbon pricing would be most efficient in reducing greenhouse gas (GHG) emissions if it were introduced at the global level together with a global emission trading scheme. We compare three different scenarios in figure 2: regional carbon pricing, meaning that the carbon price is determined at the regional level based on emission reduction targets, global carbon pricing, that assumes that the carbon price is determined globally without trade in emission allowances, and emissions trading, assuming that there is a global carbon price and countries trade emission permits in order to reach their regional emission reduction targets[17].

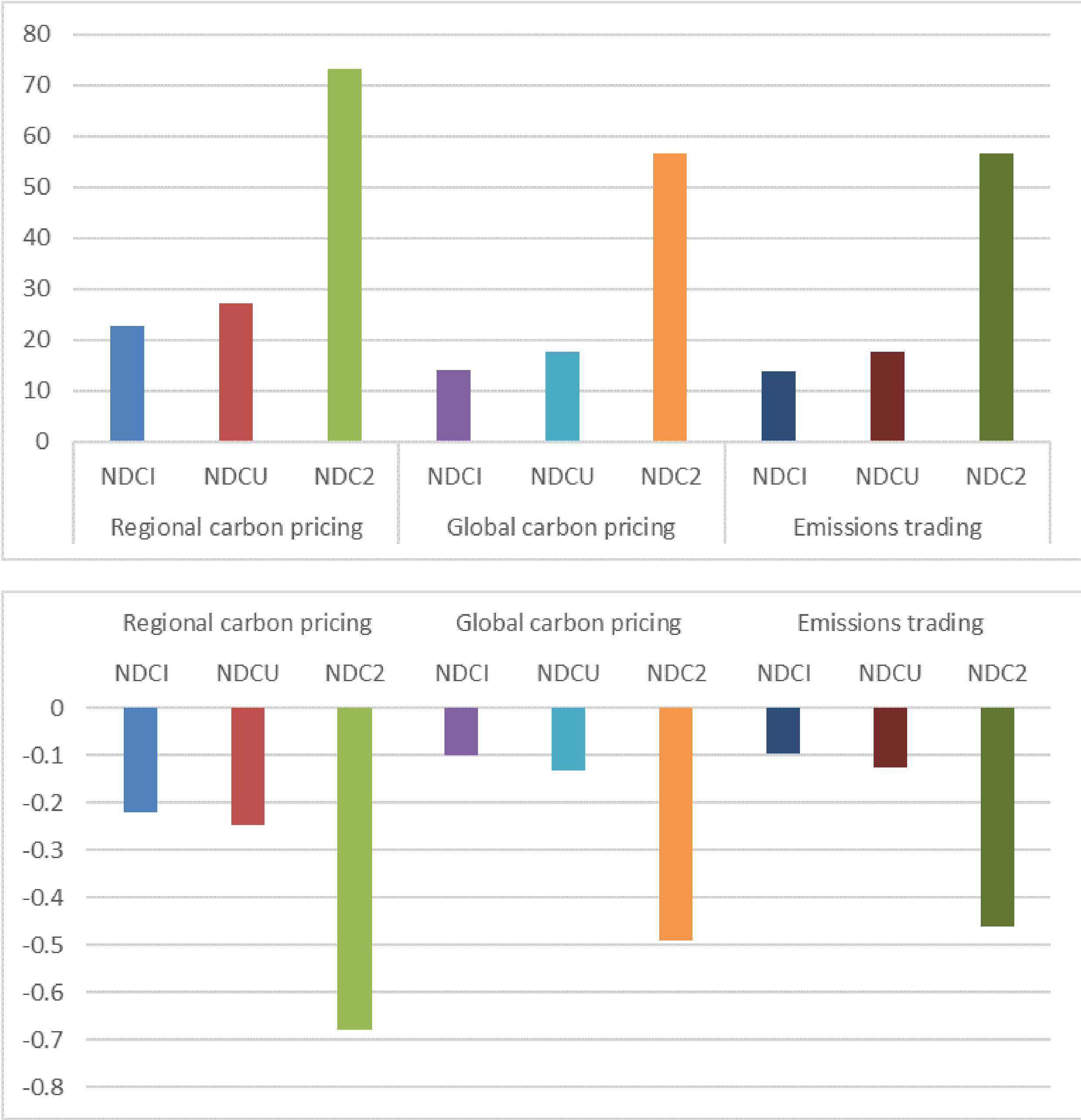
Figure 2 shows that the carbon price required to stay on the path of 2°C global warming is projected to be higher with regional carbon pricing (75$)[18], while it declines when the price is set globally (56.7$) and it is the lowest if emission trading is in place (56.5$).

In order to evaluate the impact of different regimes on aggregate welfare we employ world GDP because there is no straightforward weight to calculate a globally weighted average of real income changes, while we will employ real income at the regional level in section 4. The projected GDP losses of climate change mitigation through carbon pricing are smaller under emission trading (0.46%), slightly increase with global carbon pricing and no emission trading (0.49%) and reach the highest level with regional carbon pricing (0.68%). Comparing the required carbon price to realize NDCI and NDCU leads to the same finding. Global carbon pricing together with emission trading is more efficient than other regimes because it reduces the welfare costs of climate change mitigation, as the reduction in emissions will take place in places where it

[17]The net revenues from the trade in emission allowances are incorporated into the current account balance. We assume that the ratio of the current account balance to real regional income is constant, meaning that an increase in the purchase of emission permits needs to be financed through an increase in exports.
The regional carbon pricing scenarios assume that the carbon prices are determined regionally, based on country-specific reduction targets, and that there is no interregional trade in emission permits. The emission trading scenario assumes that there is one global carbon price and countries are able to trade emission allowances. The global carbon pricing scenario (without emission trading) is implemented by imposing a uniform carbon price in all regions such that the reduction in emissions is the one implied by the NDCI, NDCU and NDC2 scenarios and shutting down emission trading at the same time.

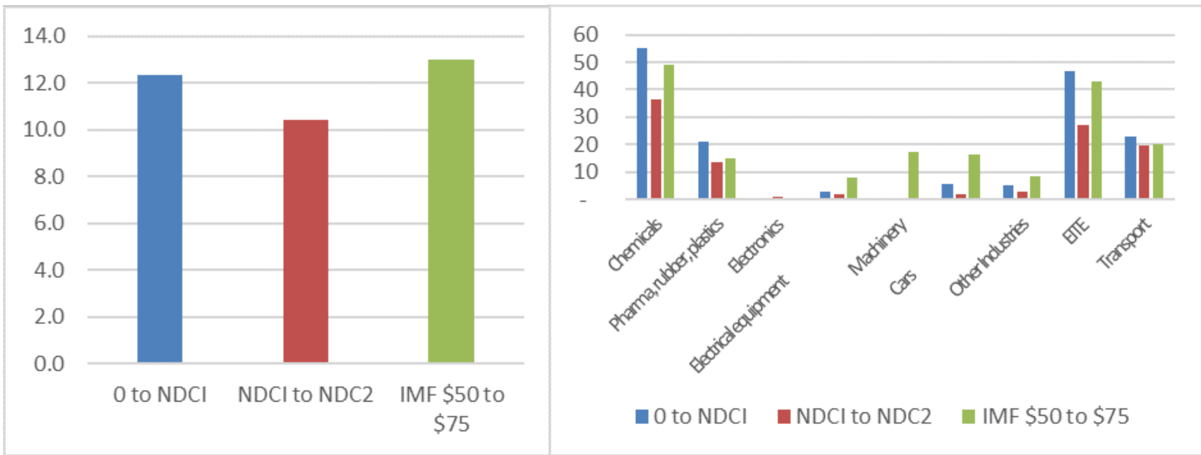
[18]The average global carbon price under the regional pricing regime is computed as the weighted average of the regional carbon prices, where the weights are regional CO2 emissions.

Figure 2: Required carbon price (upper panel) and GDP loss (bottom panel) under regional and global carbon pricing for different emission reduction targets: global carbon pricing with emission trading is more efficient than regional carbon pricing and global carbon pricing without emission trading.



is least costly. This corresponds with bigger emission reductions in regions heavily dependent on coal as a source of energy. Phrased differently, with emissions trading there is more scope for substitution between energy sources and thus less need for an absolute reduction in the use of energy. At the same time, the efficiency gains from emission trading are limited in the aggregate compared with the global carbon pricing scenario: most of the aggregate income gains from the introduction of a global price with international trade in emission allowances would come from the uniformity of the price, not from emission trading itself, which has been the focus of previous models (see for example Bohringer et al., 2021). Section 4.4 will show that emission trading has stronger and heterogenous welfare effects at the regional level.

Figure 3: Aggregate leakage and sectoral leakage under more ambitious carbon policies in a set of regions: Leakage at the sectoral level can be large but at the aggregate level will be limited



Notes: leakage is defined as the increase in emissions in less ambitious regions divided by the reduction in emissions in more ambitious regions. Sectoral leakage rates consider also the indirect emissions from electricity use. Ambitious regions are defined hypothetically based on income levels.

Obviously, in the long run the costs of climate change mitigation have to be compared with the costs of inaction with all the consequences of climate change, such as shifting weather patterns, falling agricultural productivity, rising sea levels and more severe natural disasters. These costs can be large. The Stern Review (2006) for example concluded that the reduction in real income in the long run could be as large as 20%.[19]

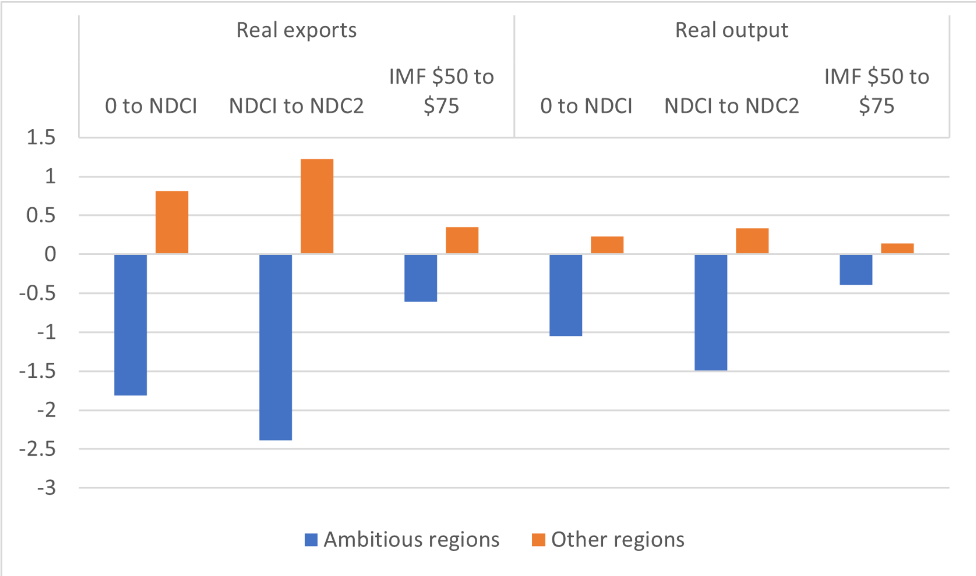
3.3 Differences in carbon prices lead only to limited carbon leakage, but the loss of competitiveness in specific sectors can be substantial.

Some countries might go further in their ambitions to reduce carbon emissions than others which might lead to carbon leakage: rising carbon emissions in less ambitious regions in response to stricter carbon pricing and other climate change mitigation policies in more ambitious regions. Especially emission-intensive production would shift from regions with higher carbon prices to regions with lower carbon prices. Simulations with the Global Trade Model indicate that the extent of carbon leakage is expected to be limited at the country level. To show this, three counterfactual experiments were conducted in which the highest income countries would have more ambitious carbon emission targets than the rest of the world, going respectively from zero reduction targets to NDC reduction targets, from NDCI reductions to NDC2 reductions or from price of $50 to $75[20]. The left panel of Figure 3 shows that the carbon leakage rate is between 10% and 15%. This is in line with findings in the literature.

[19] Dellink et al. (2019) come to more moderate estimates of the losses. They project that the costs of global warming are between 1% and 3.3% reduction in global GDP, with projected losses in Africa and Asia particularly large (up to 8% in India and 6% in Sub Saharan Africa), observing that tipping points such as a shutdown of the Gulf Stream are difficult to model and could have particularly large effects.

[20] In the first experiment a set of high-income countries (Australia, Canada, EU, EFTA, Great Britain, Japan and the USA) is assumed to reduce emissions from no reductions (business as usual) to the NDC target levels with the other countries without targets. In the second experiment the same set of countries is assumed to reduce emissions from the NDC target level to emission reductions to stay on the 2 degrees global warming path (NDC2) with the other countries targeting their NDC objectives. In the third experiment the same set of countries is assumed to set a carbon price of $75 instead of $50 with the other regions setting respectively a carbon price of $25 (low-income regions) and $50 (middle-income regions).

Figure 4: Projected change in real exports and output in emission intensive and trade exposed (EITE) industries in ambitious and other regions: EITE industries display a modest shift from ambitious to other regions



Notes: The figure displays the change in exports and output in the emission intensive and trade exposed (EITE) sectors for three scenarios: 7 ambitious regions (Australia, Canada, EU, EFTA, Great Britain, Japan and the USA) moving from no targets to NDCI, from NDCI to NDC2 and from $50 carbon price to $75 carbon price.

Leakage at the sectoral level is substantially larger[21]. The right panel of Figure 3 displays the extent of carbon leakage in the three counterfactual experiments in a set of selected sectors, showing that a reduction in emissions in the more ambitious regions is to a substantial extent offset by increases in emissions in the same sectors in other regions. Nevertheless, these sectoral leakage rates do not seem to be a reason for concern. From a climate change perspective leakage is only a problem at the national level and not at the sectoral level: to tackle climate change total emissions should be reduced and not necessarily sectoral emissions. The leakage rate at the aggregate level is a weighted average of sectoral leakage rates and although leakage rates are high in some sectors, they are much lower in other sectors[22].

However, uneven carbon pricing (with a subset of countries being more ambitious) is a problem for a different reason: emission intensive trade exposed (EITE) sectors in ambitious regions tend to lose competitiveness because of uneven carbon pricing. To illustrate this, Figure 4 shows the projected changes in real exports (left panel) and output (right panel) in the EITE sectors in the more ambitious regions and the other regions for the three counterfactual experiments.

The figure shows that activity in the EITE sectors is projected to shift modestly from ambitious to other regions. The numbers in the figure suggest that for the entire EITE sector the loss of production (and thus competitiveness) in the ambitious regions is expected to be modest. However, the loss of competitiveness can be more substantial at the more detailed sectoral level (such as in cement and aluminium).

[21]The sectoral leakage rate is defined as the rising emissions in less ambitious regions divided by the falling emissions in more ambitious regions per sector, considering also indirect emissions from electricity use.

[22]In tons of CO2 emissions the largest increase in emissions in less ambitious regions is projected to take place in the transport sector: about half of the increase takes place in the transport sector, indicating that emissions associated with transport (and thus trade) are an important policy issue.

Carbon leakage is defined based on a subset of countries being more ambitious. For example, in the case of the IMF proposal, leakage is defined based on the high-income countries setting a carbon price of \$75 instead of \$50 with respectively low- and middle-income countries sticking to a carbon price of \$25 and \$50. However, carbon prices of $25 and 50$ in these countries will still lead to a reduction of emissions compared to a baseline in which low- and middle-income countries would set no targets. Hence, comparing to a baseline without targets there would be no leakage. This also holds for the losses of competitiveness. Production in EITE sectors is not projected to move substantially from countries setting a carbon price of \$75 to countries setting a carbon price of \$50 when comparing no carbon pricing with the introduction of the IMF proposal[23].

More generally, the results on leakage in the IMF proposal suggest that in proposals for border carbon adjustment mechanisms there is a potential conflict between common but differentiated responsibility under which high-income countries should set more ambitious goals as reflected in the IMF proposal and the objectives of a level playing field under which companies from different regions selling in the same market would be facing the same carbon prices. As shown, the IMF proposal does also lead to carbon leakage and would thus be at odds with the level playing field principle implying BCA.

3.4 BCA can help to limit a loss of competitiveness of emission intensive sectors in countries with ambitious climate policies

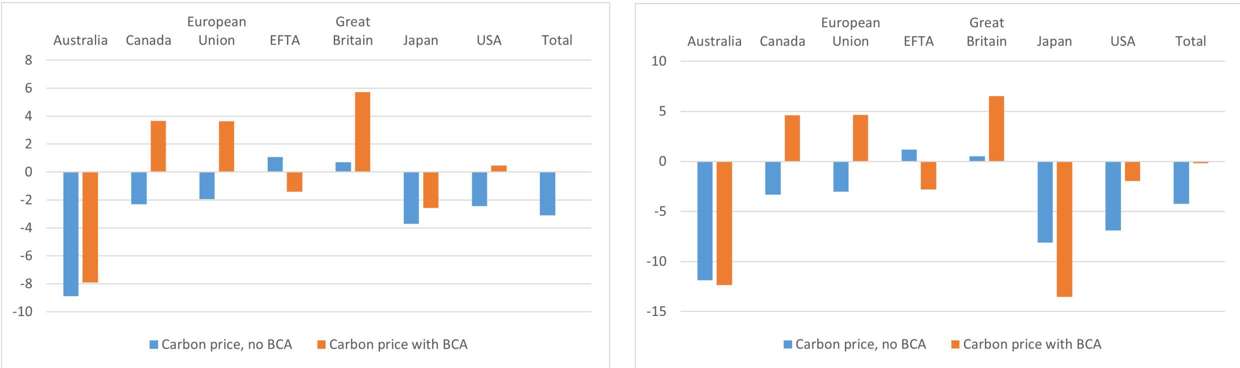
We analyse whether BCA can help ambitious regions to prevent a loss of competitiveness in EITE sectors due to the introduction of carbon pricing. Assuming that a 7 regions coalition (Australia, Canada, EU, EFTA, Great Britain, Japan and the US) introduces carbon pricing and the other regions do not, BCA is modeled as an external tariff on the countries that do not join the carbon pricing coalition based on the carbon content of their production and the level of the carbon tax in the importing countries. Figure 5 shows the change in real value added (net output) and real exports in the EITE sectors of the seven countries introducing a carbon price with and without BCA to achieve the NDC2 target. [24] On average for all seven countries, BCA compensates the costs of introducing the carbon price, bringing both real output and real exports back to the baseline level. However, due to general equilibrium effects, there is substantial heterogeneity between regions. All high-income regions except EFTA and Great Britain experience a loss of value added when introducing the carbon price. If the carbon price is complemented with BCA, value added is projected to increase in four regions, Canada, the EU, Great Britain and the USA. However, Australia and Japan still experience a loss with respect to the baseline without carbon pricing. In EFTA, GE effects seem to dominate the projections: production in EITE sectors would expand in EFTA without BCA and fall with BCA. [25] The impact of BCA on exports is even more heterogeneous because higher tariffs have a

[23] Only the least-developed economies, assumed to set a carbon price of \$25, are projected to see an increase in production in EITE sectors.

[24] The effects for policies to achieve NDCI and IMF carbon taxes are reported in Appendix III.

[25] The reason for this pattern is that carbon pricing under the NDC2 scenario makes EFTA relatively more competitive in EITE sectors thus leading to a shift of production to this region, whereas this shift disappears when BCA is introduced.

Figure 5: Change in value added (left figure) and export value (right figure) in EITE sectors in the NDC2 scenario when the 7-country coalition introduces carbon pricing, both without and with BCA: BCA fosters competitiveness in most countries, but the effect is generally limited



Notes: The left figure shows the projected difference in value added in 2030 in EITE sectors between the scenarios with carbon pricing (with and without BCA) and the baseline without carbon pricing. Both scenarios assume that a uniform carbon price is charged by the seven high income regions, while the other regions do not introduce a carbon price. The right figure presents the same comparison for gross export values. The totals were obtained through a weighted average, where the weight is the value added of EITE sectors by country for the left figure and the aggregate gross exports by country for the right figure.

positive effect on domestic sales but at the same time hamper the demand from non participating countries countries.

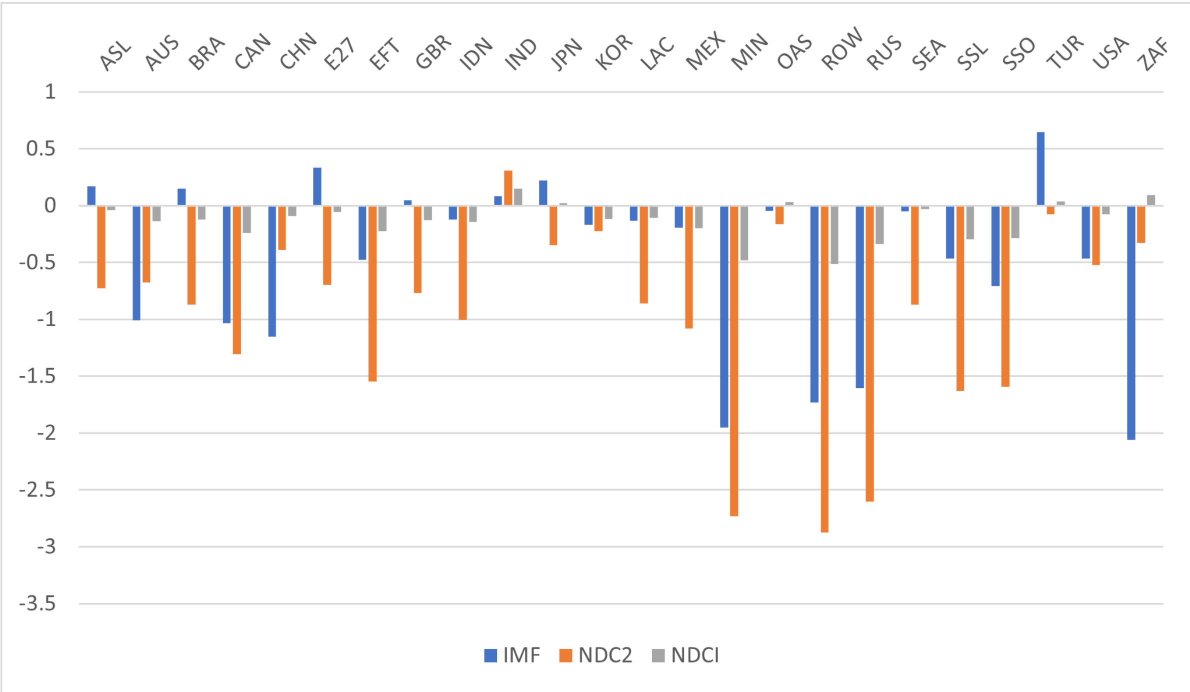
Overall, it seems that the impact of BCA on the competitiveness of EITE sectors is positive, especially when it comes to value added, and this could be particularly relevant to obtain the necessary political support to introduce more ambitious carbon policies in developed countries. However, our simulations also show that if a group of countries introduces BCA, the effects are far from uniform and in some regions BCA will not prevent production losses in EITE sectors.

4 The challenges for global carbon pricing: how to build a global coalition and share the burden of mitigation policies

This section addresses the two main challenges for global carbon pricing: how to build a global coalition and how to share the burden of mitigation policies fairly. Section 4.1 shows that global carbon pricing will affect the economy of most regions negatively. This poses both a challenge in terms of incentives to introduce ambitious carbon policies and in terms of fairness to insulate low-income regions from the adverse effects of climate policies. Section 4.2 shows that regions do not have sufficient incentives to introduce ambitious carbon policies. Section 4.3 shows that differentiation of the global carbon price with richer countries setting a higher price, is insufficient to insulate low-income regions from the adverse effects of climate change mitigation policies. Finally, Section 4.4 explores the effects of emissions trading, showing that if such a policy is introduced in a conventional way it will not insulate low-income regions from the adverse income effects.

Hence, all three approaches, a uniform global carbon price, a differentiated carbon price, and emissions

Figure 6: Changes in real income per region in per cent under different emission targets: energy and EITE exporters are projected to lose most



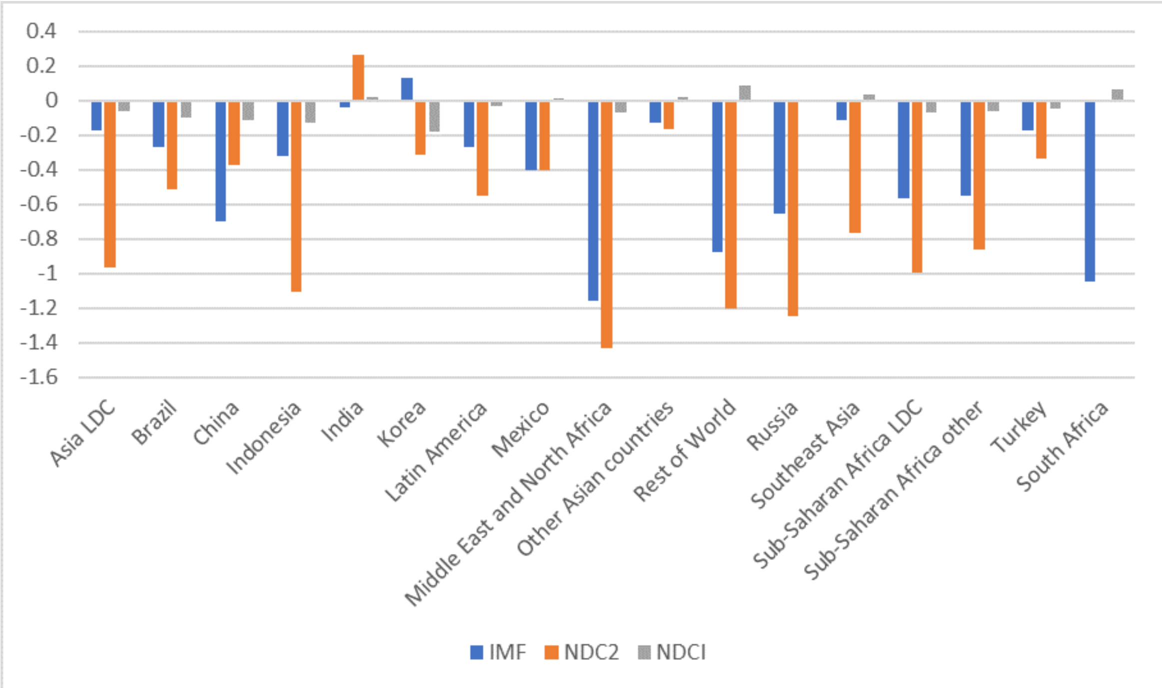
Notes: The figure displays the change in real income (nominal income divided by the aggregate price level) under NDCI, NDC2 (with global carbon pricing and emissions trading) and the IMF proposal.

trading pose challenges because they do not provide sufficient incentives for countries to implement ambitious carbon policies and they do not insulate low-income regions from the adverse effects of carbon mitigation policies.

4.1 Global carbon policies have a negative impact on the income of most regions

Global carbon pricing policies are projected to have a negative income effects in most regions. Figure 6 displays the real income effects for different regions (the definition of the different regions is in Table 1) of global carbon pricing under the NDCI, NDCU, and NDC2 scenarios and the IMF differential carbon price. The figure makes clear that energy exporters and exporters of EITE goods such as Russia (RUS) and Middle East and Northern Africa (MIN) are projected to face the largest reductions in real income. However, with some exceptions in some regions under some scenarios, most regions are projected to face income losses. A fifth scenario is added with IMF carbon taxes only introduced in the seven highest income regions (employed as well in the previous experiments), showing that energy exporters such as RUS and MIN would also see real income reduced if only other countries introduce carbon pricing, although by less. As shown in Figure 1 carbon taxes introduced only in the rich regions will not be sufficient to keep the world on a 2°C global warming path. The global reduction in emissions in the fifth scenario of Figure 6 (IMF only rich) is projected to be 6.3%, whereas in the fourth scenario (IMF) it is 24.8%.

Figure 7: The change in real income developing countries of introducing carbon pricing under different scenarios: most regions would not have an incentive to introduce carbon pricing to avoid BCA under most scenarios.

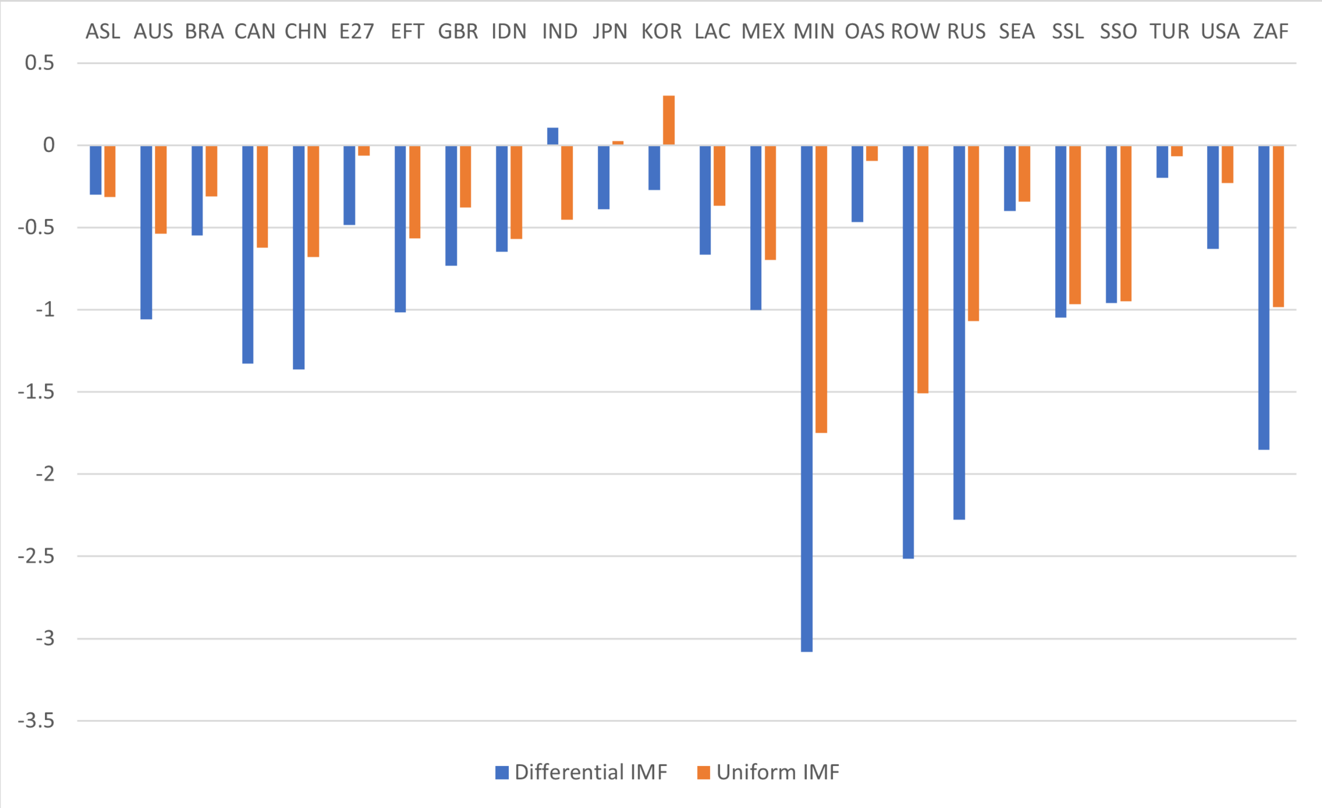


Notes: The figure displays the change in real income in percentage points for developing regions when introducing carbon pricing when also developed countries have a carbon pricing scheme in place under the IMF proposal and targeting emissions reductions corresponding with NDC2 and NDCI.

4.2 Given a coalition of ambitious on climate change mitigation through global carbon pricing policies, other regions do not have sufficient incentives to introduce such policies as well

Both climate change and climate change mitigation suffer from a collective action problem. The emissions of greenhouse gases of a single country contribute to global warming and thus affect all other countries negatively and individual countries have an incentive to wait with mitigation policies for other countries to act and benefit from their efforts. There are various options to tackle the collective action problem. The IMF has proposed to start with a small set of regions (the six largest global emitters), since it would be easier to reach an agreement between a smaller group of countries. According to our projections (see Figure 1), carbon prices of respectively \$25, \$50 and \$75 in these six regions would perform better than NDCs but would not bring the world close to the goal of 2°C global warming. We conclude that if a small group of countries takes the initiative for ambitious carbon pricing policies, other regions will have to follow as well to realise the targets of a reduction in global warming. Therefore, we explore whether other regions have sufficient incentives to introduce carbon pricing if a coalition of ambitious regions start with carbon pricing. The starting point of our analysis is that the support for climate change action is higher in countries with a higher degree of social and economic development (Torstad et al., 2020). Therefore, we assume that the seven developed regions in our simulations decide to introduce carbon pricing. We

Figure 8: Real income effects of differential carbon price and uniform carbon price: losses of most low-income regions are projected to be smaller with differential carbon pricing



Notes: The figure displays the change in real income (nominal income divided by the aggregate price index) under the IMF differential carbon pricing and a uniform carbon price realizing equivalent reductions in global emissions to differential carbon pricing, without trade in emission allowances.

then explore the incentives of the 18 other developing regions to introduce carbon pricing as well. Figure 7 shows the projected real income effect for the developing countries of introducing global carbon pricing (together with emissions trading) compared to a baseline in which only 7 ”ambitious” regions (Australia, Canada, EU, EFTA, UK, Japan and US) introduce carbon pricing. We present the three scenarios explored before (IMF, NDC2 and NDCI). Developing countries could potentially benefit from global carbon pricing with emissions trading because of the possibility to sell emission permits. However, the large majority of the 18 developing countries tends to lose when global carbon pricing is introduced, compared to a scenario where carbon pricing is only introduced in the seven developed economies. This indicates that there is a collective action problem to come to global carbon pricing policies, even if the developed economies decide to introduce such policies. The next section will explore various proposals to tackle this incentive problem.

4.3 Differential carbon pricing mitigates the negative income effects of global carbon pricing only modestly for low-income regions.

The previous section has shown that global carbon pricing affects also low-income regions negatively. There are various proposals to mitigate such adverse effects. One of them is differential carbon pricing, i.e. a carbon pricing regime where low-income countries pay a systematically lower price than high-income countries. We explore whether differential carbon pricing as proposed by the IMF can mitigate the adverse real income effects of global carbon policies for low-income regions. The results are reported in Figure 8.

Comparing the real income effects of differential carbon pricing as proposed by the IMF ($25, $50, and $75 for respectively low-income, middle-income, and high-income regions) with a uniform carbon tax realizing the same aggregate emissions reduction (without emissions trading), we notice that the global carbon price would be $48, meaning that middle and high-income regions would pay a lower price compared to the differentiated scenario, while low-income regions would pay a higher price. Furthermore, Figure 8 shows that the only developing country projected to benefit from differential carbon pricing is India. Instead of facing negative real income effects, its real income effects would turn positive. However, most other regions would face identical or even larger real income losses under differential carbon pricing. Hence, only differentiating the level of carbon prices is insufficient to insulate low-income regions from the adverse effects of carbon pricing.[26]

4.4 Global instead of regional carbon pricing and emissions trading change the distribution of losses from carbon pricing policies, but do not insulate lower income regions from the adverse effects

Emissions trading could reduce the income losses following the introduction of carbon pricing in low-income regions, because it could generate revenues from selling emission rights in such regions. In this section we explore the impact of emissions trading on the distribution of income losses because of carbon pricing in the NDCI and NDC2 scenarios. Additionally, we look at the regional income effects of global carbon pricing in comparison to regional carbon pricing.

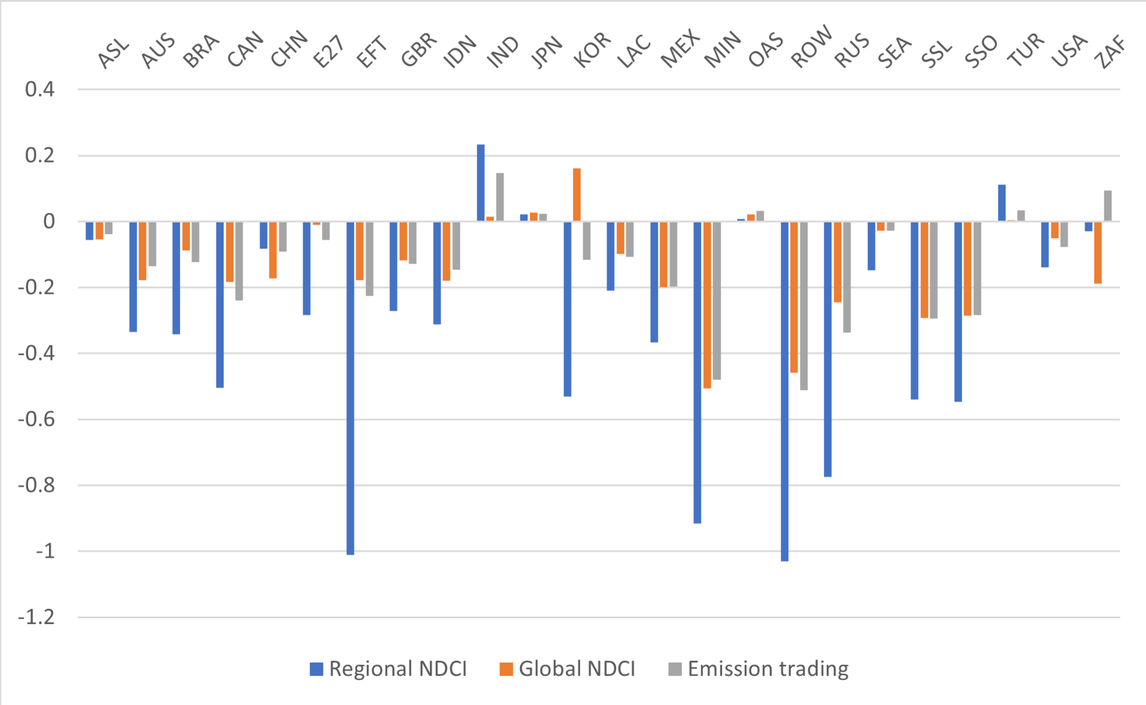
The results are displayed in figures 9 and 10. Developed countries are projected to face a smaller reduction in their real income under the global carbon pricing scenario. The reason is that the global carbon price[27] is lower than the regional prices in developed countries required to reach country-specific NDC targets. On the other hand, China, India and South Africa are projected to experience a larger real income loss in both NDC scenarios with global carbon pricing compared to regional carbon pricing, because for them the global carbon price is higher than the regional carbon price.

The distributional effects between regions change substantially when global carbon pricing is combined with emissions trading. Regions with large abatement potential can reduce emissions below their quota with emissions trading. As a result, they will sell emissions permits and earn a revenue. Other regions will purchase permits to be able to reduce their emissions by less than without emissions trading. Our

[26] Figure 21 in Appendix III compares the uniform carbon pricing scenarios with and without emission trading, showing that there is little difference among them. The experiment reported in figure 21 imposes that each region realizes the same reduction in emissions as in the uniform carbon price scenario without emissions trading. Hence, these emission reductions were already obtained as an endogenous optimal response to a uniform carbon price, so adding emission trading does not change the welfare of households and firms. The comparison looks very different if an exogenous reduction target is set, i.e., a target that is not inferred by the optimization of households and firms (see figures and).

[27] The global carbon price without emissions trading is equal to 56.7 under the NDC2 scenario and to 13.9 under the NDCI scenario. The global carbon price with emissions trading is equal to 56.5 under the NDC2 scenario and to 13.7 under the NDCI scenario.

Figure 9: Real income effects of regional and global carbon pricing, with and without emission trading, under the NDCI scenario.

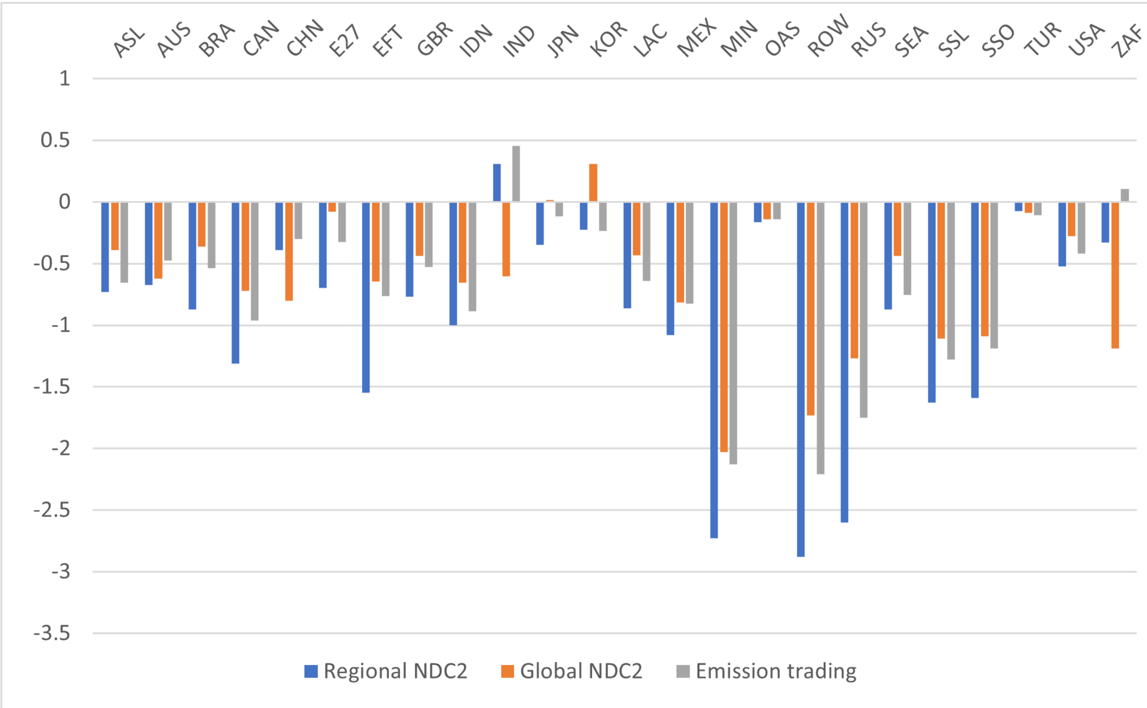


Notes: The figure displays the change in real income (nominal income divided by the aggregate price index) under the NDCI scenario; the first column displays the income effect of regional carbon pricing, the second one reports the impact of a global carbon price realizing the NDCI targets without emission trading and the third column allows for emission trading.

model projects that most of the revenues from the global trade in emission allowances would be captured by China and India since they have a comparative advantage in reducing emissions. China and India have a comparative advantage in reducing emissions both because of the size of their domestic market and because of their energy mix. The importance of these two factors can be explained as follows. In countries with a large domestic market an increase in the price of energy because of carbon pricing will not lead to such a large reduction in sales in comparison to a more open economy. An open economy will face a larger reduction in sales because of carbon pricing, because a larger share of the sales is facing international competition. Concerning the energy mix, the 2014 baseline data indicate that China's and India's emissions from coal represented respectively 76% and 72% of their total CO2 emissions. Since the substitution from coal to other fossil fuel energy sources such as oil and gas comes with large reductions in emissions, there is a large abatement potential in these two countries through the shift to alternative energy sources.

The extent to which other regions will be able to take advantage of emissions trading depends on their scope for emissions abatement, which in turn depends on the emission reduction targets. NDC2 targets are relatively ambitious, meaning that many countries have to purchase emission permits. The revenues of emissions trading are instead concentrated in a few regions (in particular India and China). This means that these regions see their income per capita increase, while other regions experience a loss in income per capita. On the other hand, the revenues from emissions trading are more evenly distributed in the NDCI scenario, as NDCI targets are in general less ambitious and less countries have an incentive to buy emission

Figure 10: Real income effects of regional and global carbon pricing, with and without emission trading, under the NDC2 scenario.



Notes: The figure displays the change in real income (nominal income divided by the aggregate price index) under the NDC2 scenario; the first column displays the income effect of regional carbon pricing, the second one reports the impact of a global carbon price realizing the NDC2 targets without emission trading and the third column allows for emission trading.

allowances in order to mitigate the emission reductions.

The comparison between the effects with and without emissions trading in Africa is also insightful to understand the effects of emissions trading. In Figure 9 (NDCI) the orange bars (global pricing without emissions trading) and the grey bars (global pricing with emissions trading) are very close to each other for Least-developed Sub-Saharan Africa (SSL) and Other Sub-Saharan Africa (SSO). For South Africa (ZAF) instead global carbon pricing has a negative impact without emissions trading and a positive impact with emissions trading. The reason is that South-Africa has a large scope for abatement of emissions, since its production is relatively emissions intensive, i.e., a large share of energy is generated with coal. Hence, with a global carbon price they will abate a lot and with emissions trading they get revenues for it, because they will abate more than their target. Without emissions trading only the negative income effect of the abatement is present. The distribution of gains and losses from emissions trading will obviously change if countries in SSL and SSO are modelled individually, because the scope for abatement is different between countries.

Given that emissions trading is projected to be beneficial only for a small group of developing countries (with large scope for emissions abatement), many low-income regions will be adversely affected by global carbon pricing with emissions trading. Hence, in the next section we discuss different options to insulate low-income regions from such adverse effects and at the same time provide incentives to join more ambitious regions in introducing carbon pricing.

5 Comparing different approaches to overcome the challenges of global carbon pricing

The previous section has introduced the two main challenges for global carbon pricing: (1) overcoming the collective action problem and (2) a fair distribution of the burden of carbon pricing. In this section we analyse four different proposals to address these two challenges: BCA, carbon clubs, a global incentive mechanism, and emissions trading with progressive reduction targets. In Section 5.1 we will explore the effectiveness of these different proposals to tackle the collective action problem and in Section 5.2 we will analyse the distributional effects (between countries) of the different proposals.

We find that the potential of BCA to incentivize non-participating regions to take climate change measures is very limited. A carbon club can be effective to incentivize all regions to introduce ambitious carbon pricing policies but would adversely affect the lowest-income regions and thus not lead to fair burden sharing. A global incentive mechanism seems also to fall short of incentivizing all regions to introduce ambitious carbon pricing policies. Our analysis indicates that global carbon pricing with emissions trading with progressive reduction targets is most effective in both incentivizing all regions to introduce ambitious policies and in a fair distribution of the burden of carbon pricing.

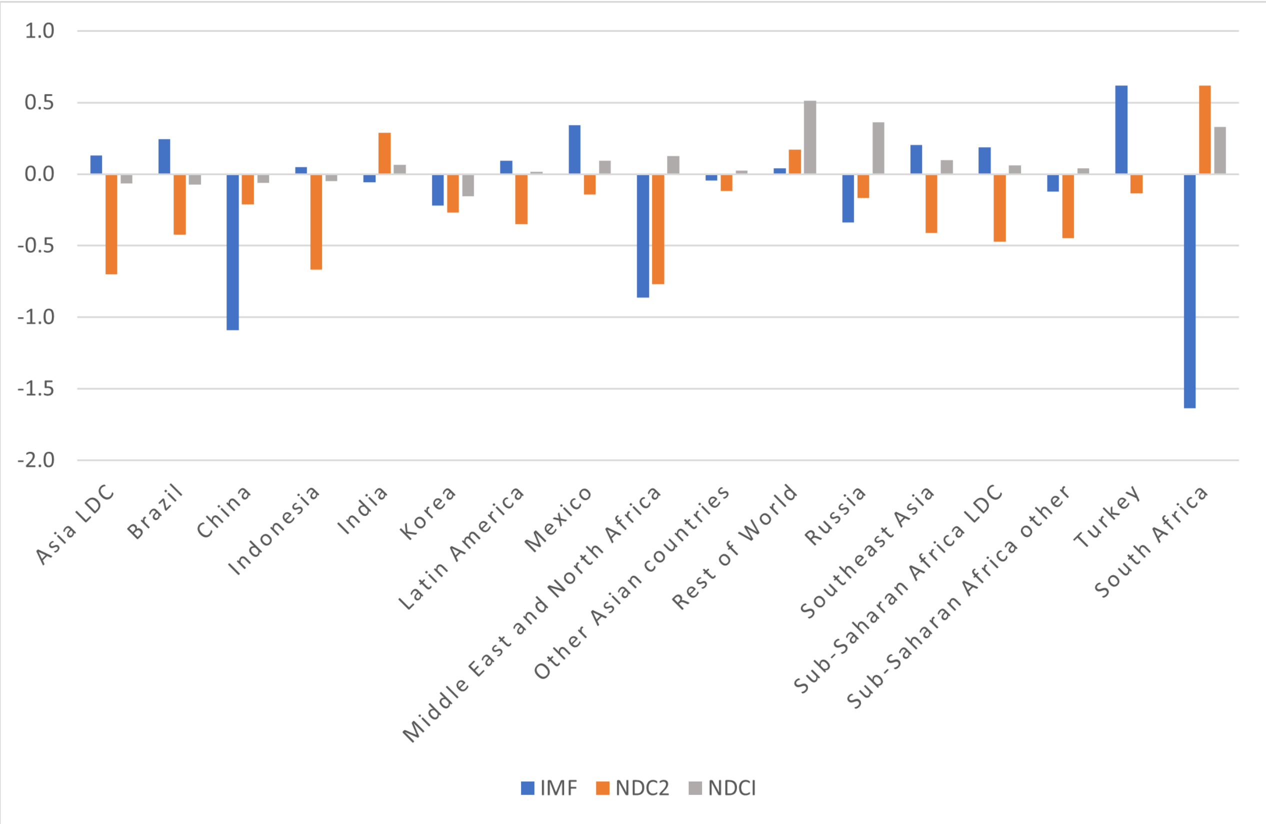
5.1 Overcoming the collective action problem of global carbon pricing

As discussed in Section 4, to tackle global warming it is not sufficient to reduce emissions only in developed economies. If only the seven developed regions in our simulations introduce a carbon price of \$75, the global reduction in emissions would be only 6.3%, whereas emission reductions of 25% are needed to stay on a path of 2°C global warming. However, there is a collective action problem in introducing carbon policies. Countries have an incentive to wait with mitigation policies and benefit from the mitigation policies of other regions. In this section we explore different proposals to incentivize all regions to introduce ambitious carbon pricing policies. The starting point of our analysis is that the support for climate change action is positively correlated with the level of development (see Torstad et al., 2020 and Best and Zhang, 2020). Therefore, we assume that the seven developed regions in our simulations decide to introduce carbon pricing as in section 3.4. We then explore the incentives of the 18 other, developing regions to introduce carbon pricing as well. We discuss in turn BCA, a Nordhaus carbon club, a global incentive mechanism, and emissions trading with progressive reduction targets.

5.1.1 Border Carbon Adjustment (BCA)

BCA could give countries without carbon policies an incentive to introduce carbon pricing to prevent that their firms are faced with foreign (carbon) tariffs when exporting goods embodying carbon emissions. However, the question is whether such tariffs would be sufficient to incentivize countries to introduce domestic carbon policies. With domestic carbon policies producers of energy and emission-intensive goods would be

Figure 11: The change in real income for non-participating regions of introducing carbon pricing and thus avoiding BCA under different scenarios: most regions would not have an incentive to introduce carbon pricing to avoid BCA under most scenarios.

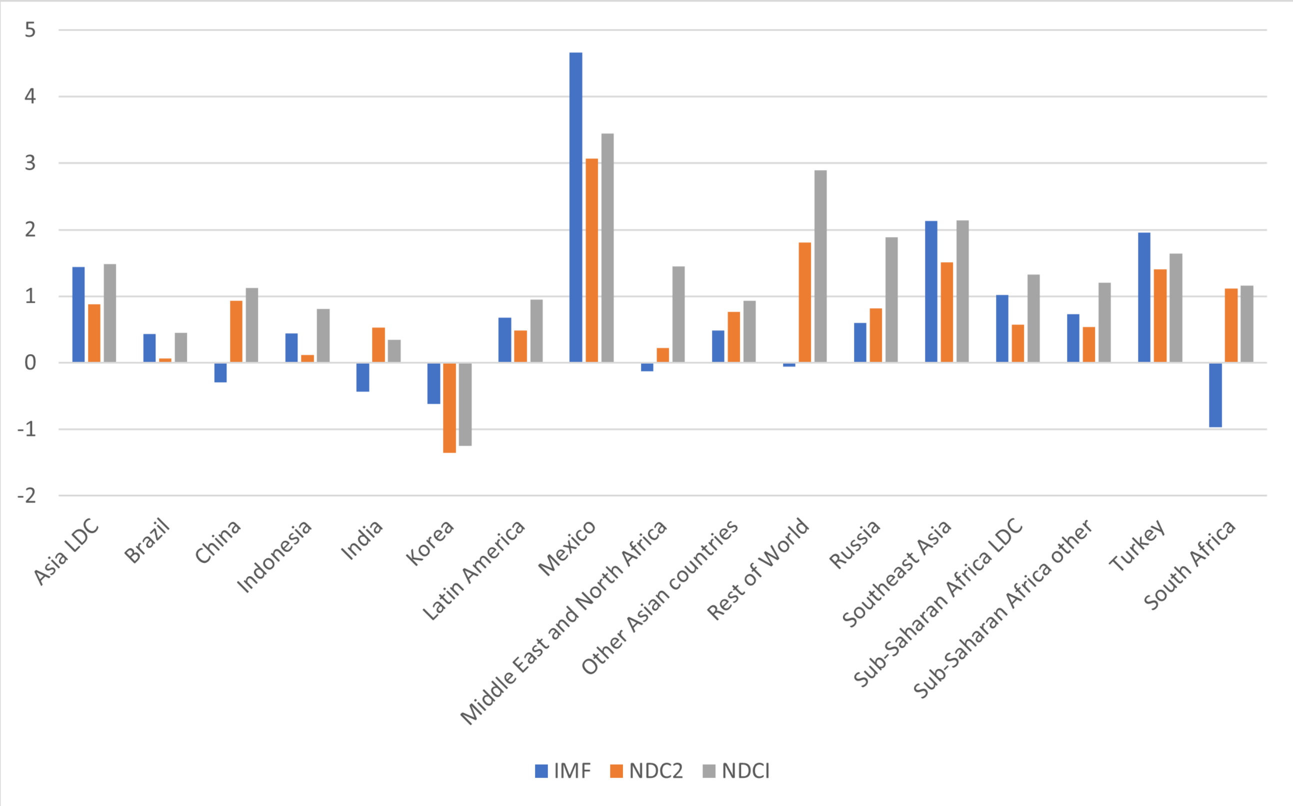


Notes: The figure displays the change in real income in percentage points for non-participating regions when switching from not introducing carbon pricing facing BCA tariffs to introducing carbon pricing and avoiding the tariffs associated with BCA under the IMF proposal and targeting emissions reductions corresponding with NDC2 and NDCI.

affected even more negatively since they would also have to pay carbon taxes on domestic sales. Hence, introducing domestic carbon pricing to avoid BCA is expected to lead to larger losses. The main benefit for a country of introducing domestic policies and thus avoid BCA is that a country can collect the carbon tax revenues itself.

We analyse the incentive effects of BCA assuming, as in section 3.4, that our seven developed regions would introduce carbon pricing and apply BCA (both on the import and export side) on the other regions. Hence, the seven rich regions would impose tariffs on imports from the other regions and provide rebates on exports to these regions, with the rates determined by the carbon price in the rich regions and the emission intensity in the other regions. Figure 11 displays the incentive effects of BCA, showing the change in real income for non-participating regions of moving from no carbon pricing and facing BCA to carbon pricing and avoiding BCA. This exercise is conducted for three changes: from no policies to NDCI, from no policies to NDC2, and from no policies to the IMF differential carbon tax. Under NDCI and NDC2 there would be global carbon pricing with emissions trading and under IMF differential regions would introduce a carbon price of \$75, \$50, or \$25, depending on their level of income. The figure makes clear that most regions under most scenarios would not have an incentive to introduce carbon pricing to avoid BCA.

Figure 12: The change in real income for non-participating regions of joining the carbon club under different scenarios: most regions would have an incentive to join the carbon club.



Notes: The figure displays the change in real income in percentage points for non-participating regions when switching from facing carbon club tariffs to joining the carbon club, avoiding the tariffs and introducing carbon policies corresponding with the indicated scenario under the IMF proposal and targeting emissions reductions corresponding with NDC2 and NDCI.

Two caveats are in place. First, the analysis is based on comparing the scenarios where none of the other countries would introduce carbon pricing and all countries would introduce carbon pricing. The incentive effects could be different when countries decide individually to introduce carbon pricing. Second, there are many options in the design of BCA (sectors included, using carbon content in ambitious or other regions, including export rebates or not) which could have an impact on the incentivizing function of BCA. However, the BCA analysed is relatively comprehensive with most sectors included and adjustment on the export side through export rebates. BCA applied to less sectors is expected to affect less ambitious regions less and so provide even less incentives to introduce more ambitious domestic carbon pricing.

5.1.2 The Nordhaus' carbon club

Nordhaus (2015) has proposed the formation of a climate club with members of the climate club introducing carbon taxes and imposing a uniform tariff on non-participants to incentivize them to join the club. Such a proposal would be an administratively less cumbersome alternative for BCA and could provide sharper incentives to introduce carbon policies for non-members of the climate club. Nordhaus shows that global cooperation would be a sustainable equilibrium with such a uniform carbon tax[28].

[28] More formally, Nordhaus shows that global cooperation would constitutes a (Nash) equilibrium in such a case, i.e. none of the regions would have an incentive to deviate from joining the carbon club, because of the threat of facing uniform tariffs

We analyse the Nordhaus proposal assuming that the seven developed regions in our database form a climate club and impose a 2% uniform tariff on the imports of all goods from non-club members. Figure 12 displays the projected change in real income in the non-participating regions if they would decide to join the carbon club, introduce carbon taxes, and thus avoid the carbon club tariffs[29]. As for BCA we compare the real income effects with global carbon pricing (with emissions trading) with the climate club (with carbon pricing only in the climate club and a uniform tariff for non-members). Figure 12 shows that most regions would gain by joining the climate club under most scenarios. Interestingly, the largest non-participating regions, i.e., China and India, would be better off if they did not join the carbon club in some scenarios. The reason is that large regions with more market power would suffer relatively smaller terms of trade losses because of the climate club tariffs.

5.1.3 Global Carbon Incentive mechanism

As an alternative to tackle the coordination problem in climate change mitigation, Cramton et al. (2017) proposed that countries emitting more than a certain cut off (e.g., more than the global average of around five tons per capita) would pay to a global incentive fund and those below the cut off would receive a commensurate payout[30]. This proposal, also discussed by Rajan (2021) and known as "Global Carbon Incentive" (GCI from now on) mechanism, entails that each country's net income from the global carbon fund would be given by the difference between the country's per capita CO2 emissions and the global average per capita emissions, multiplied by population and a global price for carbon emissions. Countries whose emissions per capita are higher than the world average would have an incentive to reduce their emissions in order to reduce their transfers to the fund, while countries whose emissions per capita are lower than the world average would have an incentive to reduce them in order to increase their revenues. The fund would be self-financing: the net-income from the fund is equal to zero in the aggregate. It can be formally shown that the mechanism would be equivalent to collecting the revenues from the carbon incentive scheme into a global pool and redistributing them to each country based on their share of the global population (see Appendix V for a formal derivation).

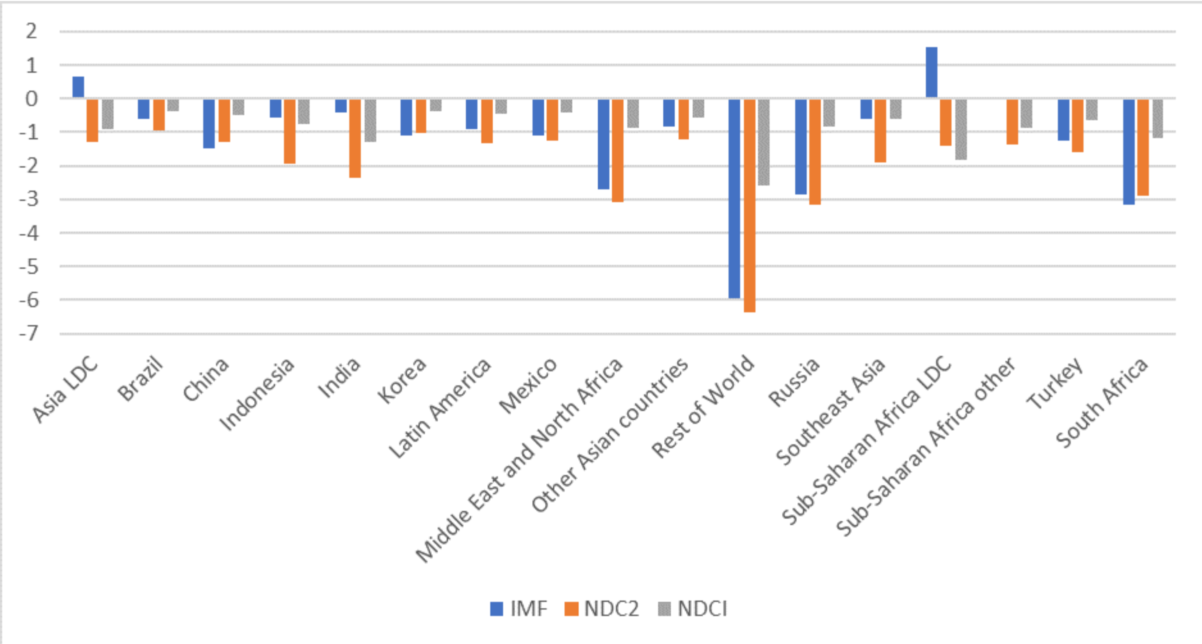
In order to evaluate the GCI as an incentive mechanism, we assume that the global carbon incentive is equal to the global carbon price, implying that the global revenues from carbon pricing are entirely redistributed between regions. Assuming that the fund is in place and at the same time the seven richest regions introduce carbon pricing, Figure 13 shows the change in real income when the other regions introduce carbon pricing as well. Therefore, the figure compares the real income effects under global carbon pricing (with NDCI and NDC2 targets or IMF pricing) in all regions combined with GCI with the real income effects

from the other regions in case they do not participate in the carbon club.

[29]In the calculations all countries are assumed to join simultaneously. Hence, the calculations are not intended to formally show whether joining the club for all regions is a Nash equilibrium, since this would require showing welfare increasing in each of the regions if they join individually.

[30]The impact on the within-country distribution is not covered in this note. A range of policy measures have been proposed such as transfers directed to the poor, reimbursing firms through transfers or tax cuts, or transparency of revenue use for green spending to establish trust about effectiveness of carbon pricing. See for example World Bank (2019).

Figure 13: The change in real income for non-participating regions of introducing a carbon price under different scenarios with the global carbon incentive scheme in place: most regions do not have an incentive to introduce carbon pricing.



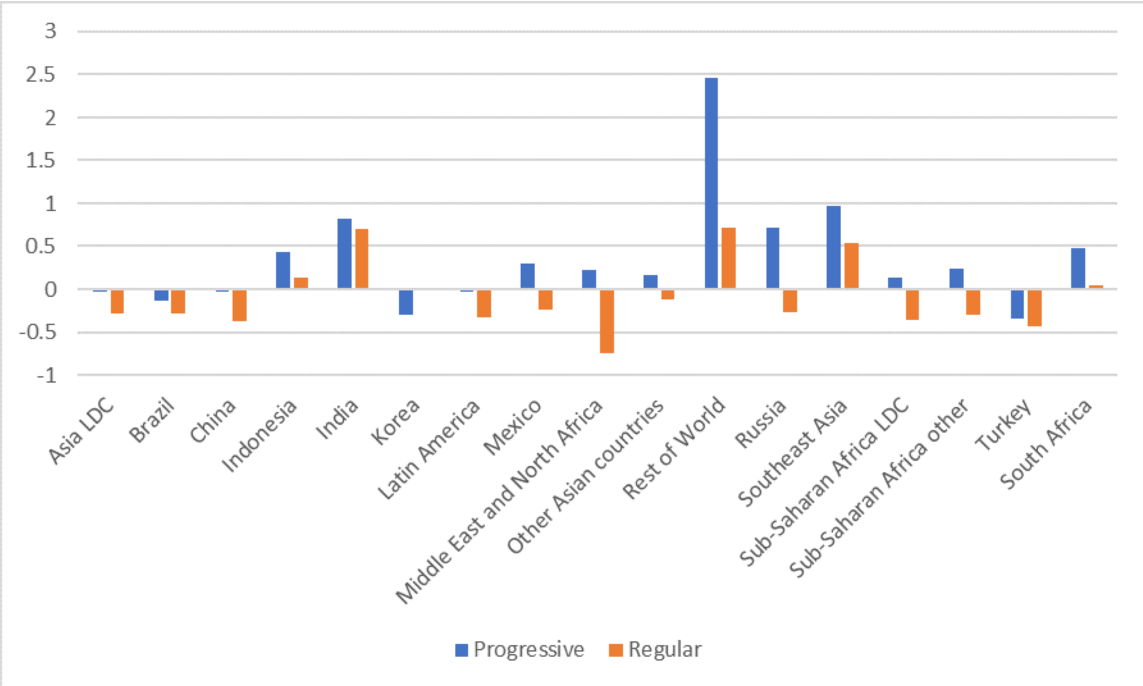
Notes: The figure displays the change in real income in percentage points for non-participating regions when switching from no carbon pricing to global carbon pricing, increasing their net revenues from the global carbon fund.

if only 7 regions are introducing carbon pricing with GCI in place. When coupled with GCI, carbon pricing generates a positive income effect for regions reducing emissions because of increased net revenues from the global incentive fund. However, this incentive does not seem to be strong enough for most developing countries to make it beneficial to introduce carbon pricing. According to Figure 13, most regions would experience a loss in real income after introducing carbon pricing. Only the lowest income regions (Asia LDC and Sub-Saharan Africa LDC) would see their income increase with IMF carbon pricing. As a consequence, the GCI proposal is not projected to have a strong impact as an incentive tool.

5.1.4 Emissions trading with progressive reduction targets

Finally, a combination of emission trading and progressive reduction targets could incentivize developing countries to introduce carbon pricing. If the reduction targets of developed countries are more ambitious than the ones of developing countries, firms in developed countries have an incentive to buy emission allowances from developing countries in order to overcome their domestic CO2 quotas. If this is the case, developing countries can increase their real income through emissions trading. Figure 14 compares the real income of developing countries with emission trading and carbon pricing with the alternative scenario where developing countries do not introduce carbon pricing and are not trading emissions rights. We consider two different sets of targets, regular and progressive. In the "regular" scenario, low-income countries have an emission target of 1.29 per cent per year, middle-income countries by 2.68 per cent and high-income countries by 4.4 per cent. The "progressive" scenario is more demanding for developed countries. They

Figure 14: The change in real income for non-participating regions of introducing a carbon price under different scenarios with emission trading: most regions do have an incentive to introduce carbon pricing under the progressive scenario.

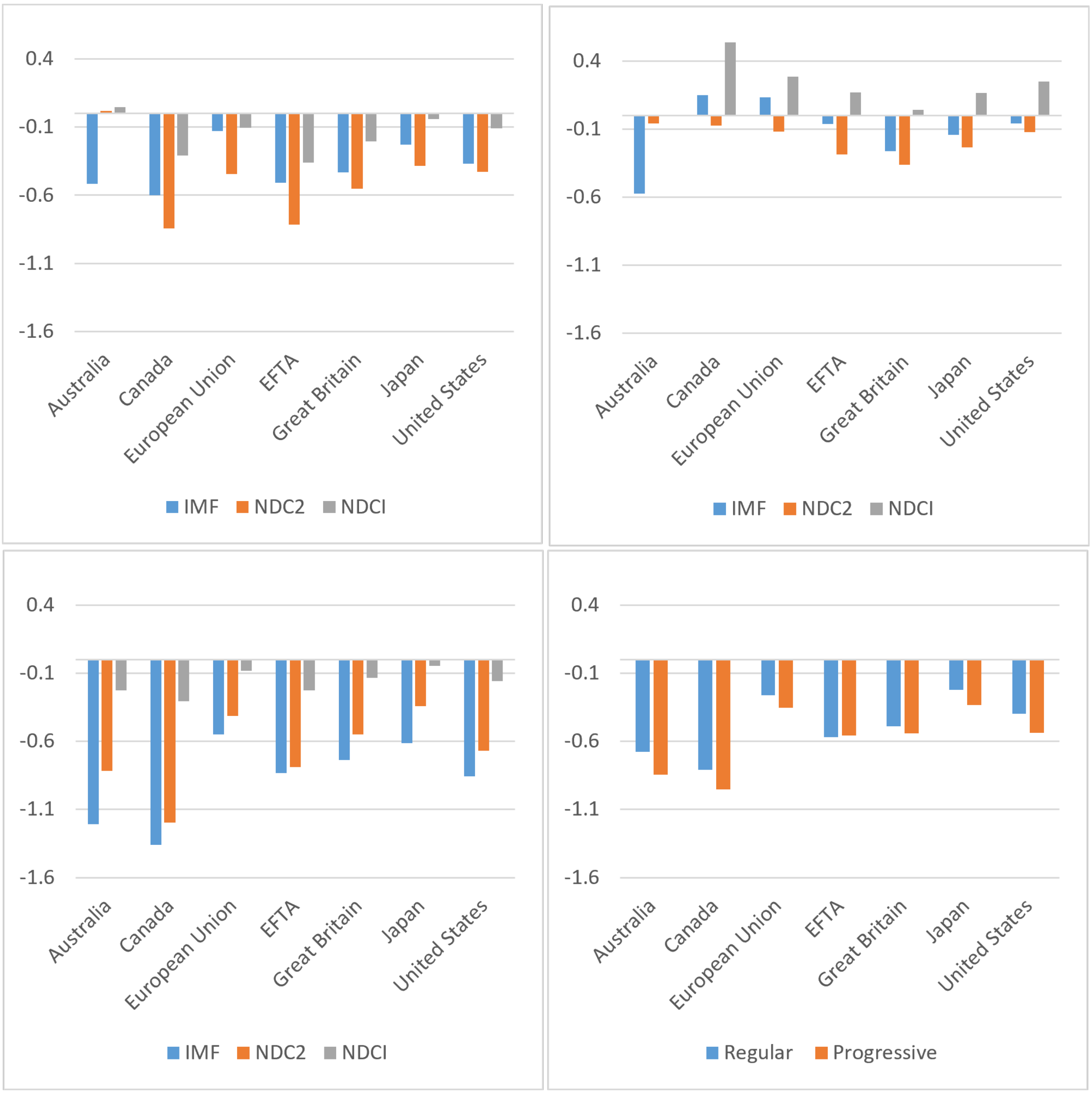


Notes: The figure displays the change in real income in percentage points for non-participating regions when switching from no carbon pricing to global carbon pricing, obtaining revenue from emission trading.

would have to reduce their emissions by 7 per cent per year, while the targets of low and middle-income countries are 1.5 and 0.5 percent per year. Both scenarios lead to the same aggregate reduction in emissions as the NDC2, but the distribution of the reduction targets is different.

Figure 14 shows that only four countries (India, Indonesia, Rest of the World and South-East Asia) would have an incentive to introduce carbon pricing under the regular scenario, while almost all developing countries are better off with carbon pricing under the progressive scenario. As a consequence, progressive emission trading seems to outperform both GCI and BCA as an incentive mechanism. Moreover, progressive emission trading is projected to be less expensive than the GCI fund: net buyers of emission permits are projected to spend on average 15.88 US$ billion per year, while net donors of the fund associated with the GCI mechanism are projected to spend 54.23 US$ billion per year in the NDC2 scenario. Since the global reduction in emissions is the same, it means that the GCI mechanism is less efficient than our emission trading scenario. The reason for the lower efficiency of the GCI mechanism could be that the global incentive fund suffers from a coordination failure problem: the incentive to introduce a carbon price comes from the benefits of lowering emissions per capita compared to the global average. However, the global average is reduced if all countries introduce carbon pricing, so, even if the amount of resources devoted to the fund is relatively high, the benefits of introducing carbon pricing are limited if many other countries do the same. Emission trading, on the other hand, is based on the idea that emissions should be reduced wherever it is more efficient to do so. Hence, there is no scope for strategic interaction making emission reductions less

Figure 15: The change in the real income of developed countries when introducing carbon pricing together with complementary measures (clockwise, BCA, Nordhaus, emission trading and GCI)



Notes: The figure displays the change in real income in percentage points for developing regions when introducing the global incentive scheme together with various global carbon pricing regimes (IMF, NDC2, NDCI) together with support measures: BCA (upper-left), Nordhaus (upper-right), emission trading (bottom-right) and GCI (botto-left). Emission trading with regular and progressive targets assumes that the aggregate reduction in emissions is equal to the one implied by the NDC2 scenario.

beneficial (see also Appendix V).

5.2 Analysing the burden of carbon pricing: income and inequality effects

Common but differentiated responsibility has been an important principle in talks about climate change (UNFCCC, 1992), since rich countries historically are responsible for most of the greenhouse gas emissions. Hence, it is important that the burden of carbon pricing is shared in such a way that low-income regions are largely insulated from its adverse income effects. However, the different proposals could also differ in terms of efficiency, as measured by their impact on global GDP.

Before comparing the different proposals in terms of their impact on equity and efficiency at the global level, we first assess the impact of the different policy measures on the developed economies introducing them. Figure 15 shows that the real income effect of carbon pricing complemented by BCA, Nordhaus, emission trading with progressive targets and the GCI mechanism on the set of seven ambitious regions differ substantially. GCI is projected to be on average the most costly measure in terms of GDP losses in the rich countries, even if emission trading is more costly for a number of regions. On the other hand, Nordhaus' carbon club proposal is projected to have a weakly negative or even positive impact on the welfare of developed countries in most scenarios. This result, together with the competitiveness effects of BCA discussed in section 3.4, underlines the fact that using external tariffs to tackle the climate change common pool problem might be tempting for developed economies, even if additional costs should be considered, such as the risk of retaliation.

In order to systematically assess the impact of the different policies on social welfare from a global perspective, this section analyses them in terms of both their efficiency and distributional effects on different regions. We combine the analysis of the distributional and efficiency effects of the different proposals by exploring the impact on a measure of social welfare.

To do so, we define a social welfare function over the distribution of GDP per capita among countries. We employ a widely accepted social welfare function introduced by Sen (1974):

$$SW = Y(1 - I)$$

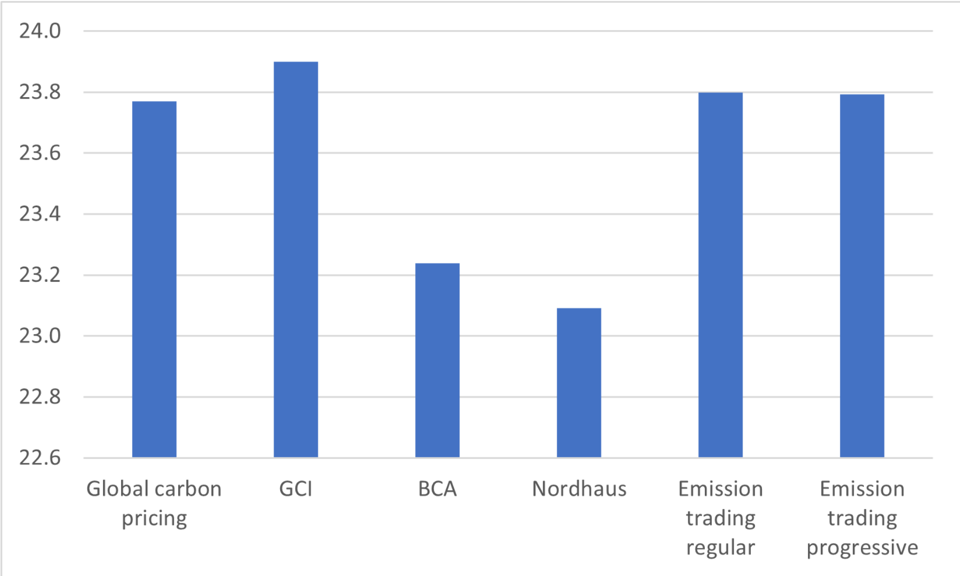
Where SW is global social welfare, Y is average global GDP per capita and I is Atkinson's index of inequality[31] (between regions). This social welfare function is attractive because it is increasing in average income and decreasing in income inequality . Since Atkinson's index of inequality ranges between 0 (perfect equality) and 1 (perfect inequality), social welfare ranges between 0 (perfect inequality) and average global GDP per capita (perfect equality).

Figures 16 and 17 display the two components of social welfare, i.e. average GDP per capita and Atkinson's inequality index, among different scenarios, while Figure 18 reports Sen's measure of social welfare. Each figure reports the global carbon pricing scenario without additional measures as well as carbon pricing complemented with the GCI scheme, BCA, Nordhaus climate club and progressive/regular emission trading. We focus on the NDC2 scenario because the progressive and regular emission trading scenarios were built such that the aggregate emission reduction is equal to the one implied by NDC2 carbon pricing, so the different policy measures are comparable. Moreover, the NDC2 scenario is policy relevant because of the urgency of climate action and the insufficiency of the NDC pledges to realize a 2 °C global warming path.

Figure 16 shows that BCA and the Nordhaus carbon club lead to a much lower global average GDP

[31] See Francois and Rojas-Romagosa (2004) for a micro-foundation of this social welfare function. Their analysis leads to the same result as Sen's (1974) when the utility function of the policy-maker displays constant relative risk aversion and the aversion to inequality is set to be equal to 2, as we do throughout this note.

Figure 16: Global average GDP per capita under simple carbon pricing and carbon pricing combined with different climate mitigation policies in the NDC2 scenario (Rajan's incentive scheme, BCA, Nordhaus climate club, Emission trading)



Notes: The average GDP per capita is expressed in US$ thousands

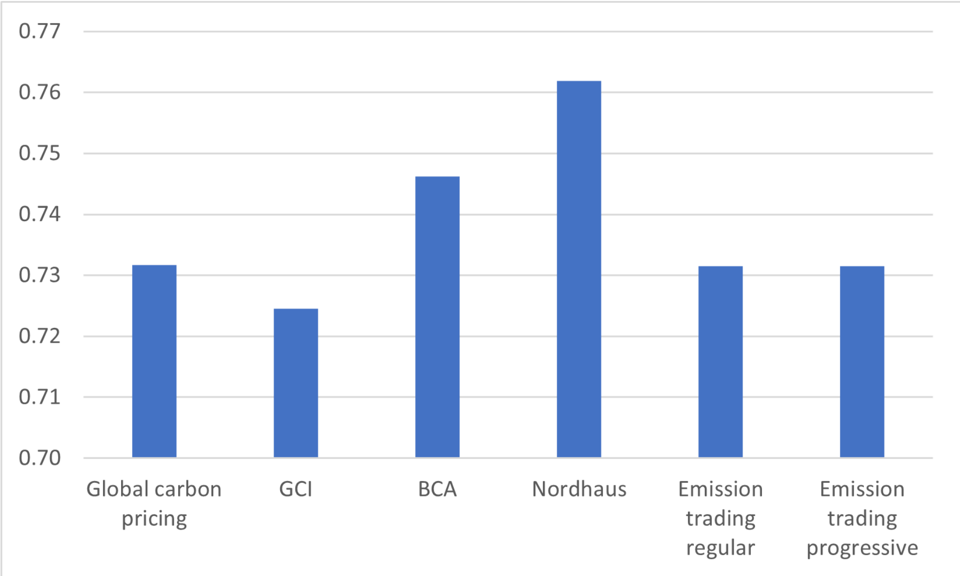
per capita than global carbon pricing, GCI and emission trading. The reason is that higher tariffs have a distortionary effect and thus hamper economic growth. The differences between global carbon pricing, GCI and progressive emissions trading in terms of global real GDP are small. The GCI mechanism is projected to outperform global carbon pricing, while regular and progressive emission trading both induce a higher average income than the global carbon pricing scenario, but not as high as GCI[32].

Figure 17 reports the Atkinson's index of income inequality (based on GDP per capita), showing that BCA and Nordhaus imply a higher degree of inequality as they impose higher tariffs towards lower income countries. Furthermore, the figure indicates that GCI leads to the lowest inequality between regions, followed by emission trading, meaning that it is the most effective proposal in terms of sharing the burden of climate change mitigation.

The findings that BCA and Nordhaus are outperformed by other proposals both in terms of efficiency (average income effects) and equity (distribution effects) imply that our model projects that there is not a trade-off between efficiency (a higher income) and equity (a lower income dispersion): policies that foster international cooperation like global carbon pricing, emissions trading and incentive funds are projected to work better in both dimensions. This is captured by Sen's synthetic measure of global welfare in Figure 18, which shows that social welfare is much lower under BCA and Nordhaus than under the other policies. Welfare is maximized by the GCI mechanism, although the differences with progressive emissions trading

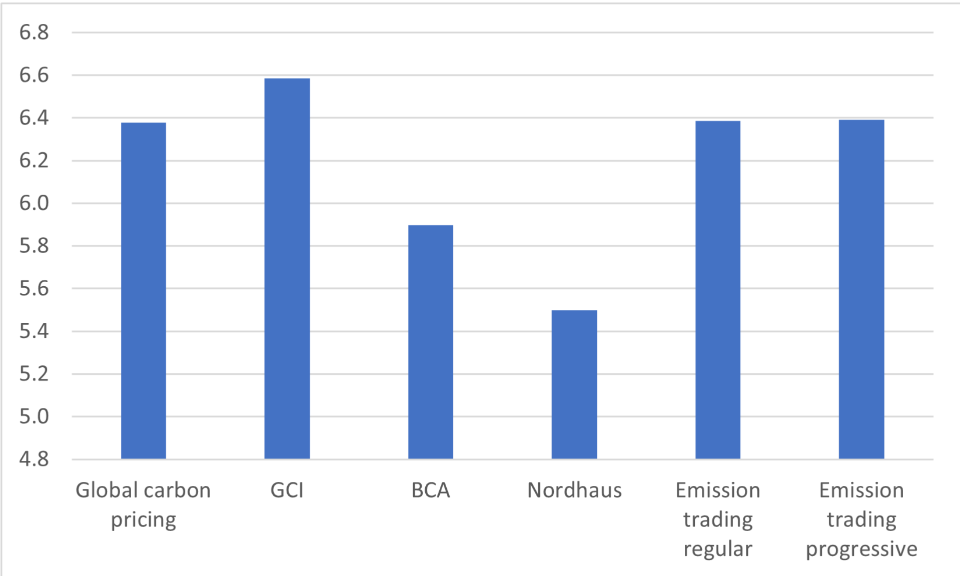
[32] See Table 8 in Appendix IV for a summary of the global emission reductions under the NDC2 scenario and table 9 for the implied carbon prices under the different policy scenarios. The implied global carbon prices in the BCA, Nordhaus and GCI scenarios are very similar since the reduction targets are the same, while the implied carbon price with progressive emission trading is lower because emission reductions are more skewed towards developed countries and countries with a high emission abatement potential (like the Middle East, Russia and India) have lower emission reduction targets, which increases the supply of emission allowances and ultimately reduces the price.

Figure 17: Atkinson's index of inequality at the global level under simple carbon pricing and carbon pricing combined with different climate mitigation policies in the NDC2 scenario (Rajan's incentive scheme, BCA, Nordhaus climate club, Emission trading)



Notes: Atkinson's index of inequality is computed based on GDP per capita by country and assuming a coefficient of inequality aversion equal to 2. A higher value of the index implies higher inequality

Figure 18: Global level of social welfare under simple carbon pricing and carbon pricing combined with different climate mitigation policies in the NDC2 scenario (Rajan's incentive scheme, BCA, Nordhaus climate club, Emission trading)



Notes: The value of social welfare is given by the product of the average GDP per capita and the reciprocal of the global inequality index.

are small.

Three points should be kept in mind when interpreting these results. First, our measure of global inequality is about inequality across countries, based on GDP per capita data, but is silent regarding the impact of different policies on income inequality within countries.

Second, the results in Figure 18 can be interpreted as a measure of social welfare only if we assume that there is a global social planner whose preferences have a very restrictive functional form[33]. In reality, each country evaluates the desirability of the different policy measures based on its own welfare assessment, and the choice of the global policy setting depends on the strategic interaction between different agents that pursue their own interests. The adoption of policies that are sub-optimal at the aggregate level, like BCA and Nordhaus carbon clubs, can be optimal at the regional level depending on their welfare effects on specific constituencies and sectors.

Third, the Nordhaus scenario reports income, inequality and social welfare under the assumption that the countries within the coalition punish the countries outside the coalition and that countries outside the coalition do not introduce carbon pricing, because, if they did, they would not be subject to Nordhaus' tariffs. Figure 12 shows that, if real income is the criterion of interest for policy makers, most countries outside the carbon club would have an incentive to join the club if Nordhaus' proposal is implemented, meaning that Nordhaus could lead to a scenario that is close to global carbon pricing in terms of welfare. On the other hand, the response of countries outside the club to the introduction of a tariff punishment could be more complex than that: for example, they could threaten to retaliate increasing their own tariffs on the imports from the carbon club coalition. In that case, the creation of a carbon club might trigger a trade war and further decrease social welfare. In practice, the ultimate welfare effect of Nordhaus' carbon club is strictly dependent on the assumptions on the behavior of non participating regions, that might lead either to a good equilibrium (global carbon pricing) or a bad one (trade war between coalitions of countries).

5.3 Discussion on proposals to tackle collective action under fair burden sharing

Our analysis has shown that the potential of BCA and GCI to incentivize regions to introduce ambitious carbon policies is limited, while both the Nordhaus climate club and a combination of emissions trading and progressive reduction targets are projected to be effective. However, the Nordhaus proposal does not score well in terms of insulating low-income regions from adverse effects. More generally, BCA and Nordhaus do not score well in terms of both of equity and efficiency: social welfare is lower under these proposals than the other three proposals. Hence, when it comes to these two proposals in comparison to the other three proposals, there is no trade-off between equity and efficiency. The inequality between regions is lowest under GCI, whereas income effects are similar between GCI, global carbon pricing, and progressive emissions trading.

Although GCI scores best in terms of inequality and thus fair burden sharing, progressive emissions trading seems the preferred policy, because GCI is not providing sufficient incentives to less ambitious low-

[33] As argued in Mas-Colell, Whinston and Green (1995), social welfare functions are often necessary because the concept of efficiency eliminates the outcomes that are not on the so-called "Pareto-fronteer" , but does not provide a criterion to choose between equilibria that display a similar degree of efficiency. According to Mas-Colell, Whinston and Green (1995), social welfare functions must satisfy some specific requirements: non-paternalism (only the welfare of the individual countries matters), Paretian property (aggregate welfare is increasing in individual utility), symmetry (the order of the countries does not matter) and concavity (social welfare is decreasing in inequality). There is not a universal agreement on the specific functional form of the social welfare function, that can range from purely utilitarian (only the sum of the individual countries' utilities matters) to Rawlsian (only the welfare of the lowest-income country matters).

income regions to introduce carbon pricing policies, which is necessary to tackle climate change. The realism of progressive emissions trading depends on the extent to which a few regions are willing to pay a higher price in order to boost the international cooperation on emission reduction. However, the analysis has shown that the costs of progressive emissions trading are relatively limited: the net buyers of emission permits would spend about 16 US$ billion per year, which is a smaller amount than the targeted expenditures on the green climate fund (100 US$ billion per year).

Although our simulation results suggest that emissions trading with progressive emissions trading have most potential to tackle the challenges of global climate action, various objections have been raised against emissions trading. In particular, Cramton et al. (2017) and Cooper (2017) present four main arguments against a global cap-and-trade system compared to global carbon pricing. First, quantity based approaches (cap-and-trade) generate large uncertainty for participating countries making them reluctant to agree in negotiations. The authors give the example of China which turned out to grow much stronger between 1990 and 2020 than expected and so would have to reduce emissions much more drastically than initially expected. Obviously, this argument can also be reversed. A certain level of carbon prices would be insufficient to limit emissions corresponding for example with a 1.5C global warming trajectory. Furthermore, the target of net zero (by 2050 or later for some countries) is currently discussed in the global policy community, a target that is less dependent on potentially uncertain growth rates.

Second, Cramton et al. (2017) argue that negotiations on emission targets are complicated if first a global target is negotiated and then country-level emission targets. If one country does more in such a setting, i.e. sets more ambitious emission targets, other countries will do less. Therefore, each country has an incentive to free-ride on the efforts of other regions. However, such problems would also occur in negotiations about redistribution through a carbon fund. And if burden sharing is considered important, global carbon pricing cannot be introduced without redistribution through a carbon fund. Related is the argument that emissions trading serves a dual goal, tackling climate change and sharing the burden of doing so. Cramton et al. (2017) claim that this makes negotiations less transparent and therefore more complicated. However, this dual objective of emissions trading can also be seen as an advantage, since only one policy has to be agreed (emissions trading) instead of two (carbon pricing and a carbon fund). Moreover, Gollier and Tirole (2017), while acknowledging the potential difficulties of negotiating a cap-and-trade system, stress that cap-and-trade might be easier to enforce than carbon pricing. While the monitoring of CO2 emissions by country is in principle doable through a relatively simple accounting mechanism, monitoring carbon pricing policies could be difficult to enforce because countries might introduce opaque transfer programs in order to undo the negative effects of carbon pricing and more importantly carbon pricing could be implicitly implemented though non price policies (green subsidies, infrastructural investments and so on) whose price equivalent is not straightforward to compute.

Third, there are two arguments against global emissions trading related to the difficulties to introduce national emissions trading. Cramton et al. (2017) contend that in practice agreeing on emission targets and emission trading between countries does not necessarily mean that countries have to introduce carbon pricing or emissions trading domestically. Furthermore, Cooper (2017) argues that the introduction of emissions trading is complicated in countries with a weak institutional environment. The fact that emission rights constitute a potentially large value implies a risk of rent-seeking and unfair distribution of the emission. However, our analysis is focused on the usefulness of emissions trading between regions and does not necessarily require the introduction of domestic emission trading. A discussion of the efficiency of emission trading is beyond the scope of this paper.

Finally, an important caveat of the analysis on tackling the collective action problem is that we assume that governments are interested in real income (welfare). However, the question is whether governments use national welfare as their objective. Energy and emission-intensive sectors might have a large influence on government policies and from their perspective it could be better for example to accept a uniform tariff in the Nordhaus proposal compared to the introduction of stricter national carbon policies.

6 Concluding remarks

In this paper we employ a dynamic CGE model integrating the features of the WTO Global Trade Model with a detailed energy nesting (both for firms and households' demand), CO2 emissions and carbon pricing in order to explore some of the main questions related to the economic impacts of climate change mitigation policies. Our baseline includes a set of shocks that project the evolution of the global economy in 2014-2030, such as GDP per capita growth, population, labor force, savings, trade costs, differential productivity by sector, shifts in preferences and energy prices (oil, gas and coal). We also include energy ingredients in order to project technical improvements that might be relevant for climate change mitigation policies: we target electricity and renewable shares from JRC I-O tables, projected productivity growth of solar and wind from IRENA, autonomous energy efficiency increases. Our policy scenarios include both emission targets implied by different nationally determined contributions (NDCI, NDCU or NDC2) and price targets (IMF price floor)

Climate policy induces a well known common pool problem, as the benefits of climate change mitigation are global, but the costs are regional, making a binding global commitment complicated to reach (Gollier and Tirole, 2017). At the same time, climate action is urgent in order to bring global CO2 emissions closer to the 2°C degrees path: according to the IEA (2021), without further policy action, the temperature on the planet could increase by 2.7°C in 2100.

Current NDC commitments are not sufficient to bring global emissions on the 2°C path: according to our projections, NDCI and NDCU pledges respectively imply a 10% and 12% reduction in emissions compared to our baseline by 2030, while a 27% reduction would be needed to reach the 2°C objective. The IMF differential carbon pricing proposal is projected to get relatively close to this target, but at the same time it does not seem to insulate low income countries from the negative economic effects of climate change mitigation according to our projections.

In line with the previous literature (Bohringer et al., 2021), we find that carbon pricing, either in the form of a price target or an emission target, is an effective tool to reduce CO2 emissions, and that it would be most efficient if it were introduced globally together with an international emission trading scheme. For example, we project that the (average) carbon price required to stay on the path of 2°C global warming is equal to 75 US$ per tonne of CO2 with regional targets, while it would be equal to 56.5 US$ under a global carbon pricing scheme with emission trading. Global coordination minimizes the level of the carbon price and the consequent global GDP loss. Additionally, global coordination might be useful in order to avoid the costs of unilateral trade policy measures: while the extent of carbon leakage is projected to be limited, carbon pricing is projected to have a substantial impact on the competitiveness of EITE sectors in developed countries. As a consequence, some countries might be tempted to introduce BCA in order to protect their domestic industries in the absence of internationally coordinated action.

Building a global carbon pricing coalition is not an easy task, as the costs of climate change mitigation are immediate and local while its benefits are global and diluted over time (Gollier and Tirole, 2017). Our scenarios start from the assumption that a group of developed countries (Australia, Canada, EU, EFTA, UK, Japan and USA) takes the initiative for ambitious carbon pricing policies and has to convince other regions to join their carbon club. In our model, carbon pricing *per se* has a negative impact on the economy, so complementary measures are needed in order to incentivize developing countries to join the carbon club[34].

We analyse four sets of complementary policies. Border Carbon Adjustment (BCA), meaning that countries impose an import tariff based on the importing country's carbon price and the exporting country's emission intensity; Nordhaus' carbon club, meaning that countries impose a uniform import tariff of 2% on non participating regions; a Global Carbon Incentive mechanism, i.e. a global carbon fund where the global revenues from carbon pricing are redistributed towards countries whose average emissions per capita are lower than the average; and finally emission trading with progressive emission reduction targets, where low income countries can gain from emission abatement by selling emission allowances. We analyse these policies both in terms of incentive compatibility (i.e. the extent to which they facilitate the creation of a global carbon coalition) and in terms of fairness (i.e. to which extent they promote global welfare and reduce inequality between countries). We can draw at least three main conclusions.

First, BCA does not provide sufficient incentives to introduce carbon pricing, whereas a carbon club imposing uniform tariffs on non-participating members does. At the same time, both measures perform poorly in terms of burden sharing and lead to a decrease in global welfare compared to the plain global carbon pricing scenario. However, the ultimate impact of policies involving tariff increases depends on the behavior of the regions outside the carbon coalition: they could either decide to join the club in order to avoid the tariffs or threaten to increase their own external tariffs in order to negotiate better conditions.

[34]The negative impact of carbon pricing might be overestimated in our setting because we do not take into account the long-run costs of climate inaction. However, our analysis mainly focuses on the short to medium run (the simulations range from 2014 to 2030), whereas the benefits of climate change mitigation come over the longer run

Second, according to our simulations, differential carbon pricing seems insufficient to implement the principle of differentiated responsibility, since also the lower income regions introducing a lower carbon tax would suffer substantial income losses. Hence, such a proposal would have to be accompanied by some type of international support to insulate the low income regions from the adverse effects of carbon pricing.

Third, our projections suggest that progressive emissions trading provides sufficient incentives to join a carbon club for most regions, whereas the burden of carbon pricing is shared fairly in comparison to other proposals. On the other hand, global carbon taxation together with redistribution of the revenues through a global carbon fund is projected to do so only for a small group of regions. The reason is that the GCI proposal expresses the net revenues from the carbon fund as a function of the difference between regional emissions per capita and global emissions per capita, which is a moving target and tends to shrink the net revenues from the fund for all regions when simultaneously decreasing their emissions. In other words, this type of self-financing climate fund induces a mechanism broadly comparable to a coordination failure. As discussed in Section 5.3, various objections have been raised in the literature against global emissions trading related to the difficulties to introduce such a system, emphasizing instead the benefits of a global carbon tax. Therefore, there could be important advantages to the introduction of a global carbon tax together with a carbon fund. Given our findings that emissions trading would be less costly and provide better incentives for the participation of developing countries and arguments in the literature about the practical difficulty to introduce global emissions trading, we call for further research on the design of a carbon fund which does not suffer from coordination failures and can thus provide more incentives to join a global carbon coalition.

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Appendix I: sector and region classification

Table 3: Sector and region names and acronyms

Region acronym	Region name	Sector acronym	Sector
ASL	Asia LDC	Agriculture	Agriculture
AUS	Australia	Coal	Coal
BRA	Brazil	Oil	Oil
CAN	Canada	Gas	Gas
CHN	China	Oil_Pcts	Oil products
E27	European Union 27	Chm	Chemicals
EFT	EFTA	Prp	Pharmaceuticals
GBR	Great Britain	Ele	Electronic equipment
IDN	Indonesia	Ome	Machinery and equipment nec
IND	India	Mvh	Motorvehicles
JPN	Japan	Otn	Transport equipment nec
KOR	Korea	Oth_Ind	Other industries
LAC	Latin America	En_Int_Ind	Energy intensive industries
MEX	Mexico	TnD	Electricity transmission
MIN	Middle East and North Africa	NuclearE	Nuclear electricity
OAS	Other Asian countries	Ome	Machinery and equipment nec
ROW	Rest of World	Eeq	Electrical equipment
RUS	Russia	CoalE	Coal power
SEA	Southeast Asia	GasE	Gas power
SSL	Sub-Saharan Africa LDC	WindE	Wind power
SSO	Sub-Saharan Africa other	HydroE	Hydro power
TUR	Turkey	OilE	Oil power
USA	United States	OthE	Other power
ZAF	South Africa	Services	Services
		Transport	Transport

Appendix II: Additional baseline ingredients

Table 4: Projected energy price changes

Region	Oil	Coal	Gas
Asia LDC	-0.10	-1.56	-0.64
Australia	-0.10	-1.56	-0.64
Brazil	-0.10	-1.56	-0.64
Canada	-0.10	-1.56	-0.64
China	-0.10	-1.96	0.25
European Union	-0.10	-1.03	-0.20
EFTA	-0.10	-1.56	-0.64
United Kingdom	-0.10	-1.03	-0.20
Indonesia	-0.10	-1.56	-0.64
India	-0.10	-1.56	-0.64
Japan	-0.10	-1.75	-1.63
South Korea	-0.10	-1.56	-0.64
Latin America	-0.10	-1.56	-0.64
Mexico	-0.10	-1.56	-0.64
Middle East	-0.10	-1.56	-0.64
Other Asian Countries	-0.10	-1.56	-0.64
Rest of the World	-0.10	-1.56	-0.64
Russian Federation	-0.10	-1.56	-0.64
South-East Asia	-0.10	-1.56	-0.64
Sub-Saharian Africa LDC	-0.10	-1.56	-0.64
Sub-Saharina Africa Other	-0.10	-1.56	-0.64
Turkey	-0.10	-1.56	-0.64
United States	-0.10	-1.19	-0.48
South Africa	-0.10	-1.56	-0.64

Note: Oil, Coal and Gas average annual price growth rate in 2014-2030 from IEA.

Table 5: Productivity and income elasticities by sector

Sector	Diff. Productivity	Utility shock
Agriculture	4.9509	-0.0048
Coal	0.0000	-0.0017
Oil	0.0000	-0.0017
Gas	-1.7459	-0.0017
Oil products	6.2602	-0.0017
Chemicals	4.0023	-0.0002
Pharmaceuticals	2.9721	-0.0003
Electronic equipment	2.7355	-0.0005
Electrical equipment	2.5769	-0.0009
Machinery nec	2.4290	-0.0002
Motorvehicles	2.6974	-0.0004
Transport equipment nec	2.2090	0.0000
Other industries	2.6721	-0.0025
Energy intensive industries	2.6940	0.0001
Eletricity transmission	-1.9301	-0.0017
Nuclear power	-4.2000	-0.0017
Coal power	-3.5431	-0.0017
Gas power	-4.5958	-0.0017
Wind power	-6.1273	-0.0017
Hydro power	-8.9615	-0.0017
Oil power	-1.9639	-0.0017
Other power	-5.0056	-0.0017
Solar power	-9.3347	-0.0017
Services	-0.8695	-0.0011
Transport	0.0000	-0.0011

Note: Differential productivity growth rates by sector are inferred by EU-KLEMS data. Details on the shock to the non homothetic utility function can be found in Bekkers et al. (2022)

Table 6: Power shares of firms and households

Region	Initial share	Final share	Initial share	Final share
	Firms		Households	
Asia LDC	0.301	0.344	0.553	0.581
Australia	0.279	0.317	0.432	0.538
Brazil	0.251	0.368	0.365	0.495
Canada	0.186	0.288	0.344	0.431
China	0.269	0.481	0.394	0.572
European Union	0.246	0.467	0.429	0.539
EFTA	0.231	0.672	0.444	0.612
United Kingdom	0.231	0.592	0.320	0.495
Indonesia	0.094	0.194	0.240	0.408
India	0.261	0.341	0.303	0.576
Japan	0.258	0.438	0.443	0.492
South Korea	0.175	0.305	0.292	0.486
Latin America	0.166	0.256	0.376	0.404
Mexico	0.182	0.236	0.226	0.326
Middle East	0.142	0.211	0.458	0.478
Other Asian Countries	0.262	0.413	0.540	0.584
Rest of the World	0.292	0.448	0.534	0.582
Russian Federation	0.198	0.237	0.430	0.628
South-East Asia	0.152	0.216	0.410	0.482
Sub-Saharian Africa LDC	0.256	0.387	0.411	0.435
Sub-Saharian Africa Other	0.178	0.323	0.331	0.391
Turkey	0.239	0.374	0.324	0.486
United States	0.199	0.443	0.379	0.410
South Africa	0.216	0.275	0.237	0.389

Note: Initial and final share of power in total energy consumption of firms and households, adapted such that our baseline CO_2 emissions in 2030 match WEO projections in all regions.

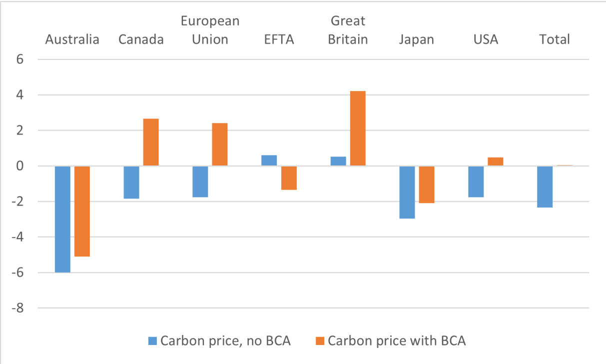
Table 7: Intermittent shares and autonomous energy efficiency improvements

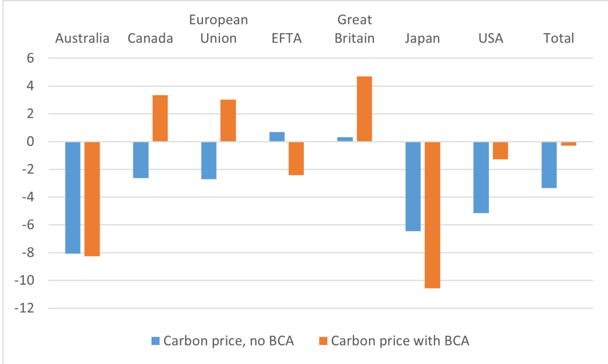
Region	Initial int. share	Final int. share	AEEI
Asia LDC	0.007	0.042	1.500
Australia	0.112	0.128	0.000
Brazil	0.042	0.055	8.000
Canada	0.043	0.135	2.710
China	0.032	0.062	3.500
European Union	0.135	0.108	6.000
EFTA	0.021	0.006	5.000
United Kingdom	0.197	0.191	10.000
Indonesia	0.000	0.000	3.050
India	0.041	0.080	1.000
Japan	0.034	0.082	3.200
South Korea	0.016	0.011	0.500
Latin America	0.013	0.031	5.000
Mexico	0.009	0.017	5.000
Middle East	0.006	0.071	5.000
Other Asian Countries	0.015	0.023	0.500
Rest of the World	0.006	0.009	4.000
Russian Federation	0.000	0.000	2.000
South-East Asia	0.009	0.007	0.000
Sub-Saharian Africa LDC	0.003	0.026	7.160
Sub-Saharian Africa Other	0.001	0.001	3.300
Turkey	0.021	0.019	5.000
United States	0.060	0.098	4.000
South Africa	0.010	0.050	1.000

Note: Columns 2 and 3 report the initial and final share of intermittent power (wind and solar) in total electricity consumption from JRC. Column 4 reports the annual energy efficiency improvement by region, adapted such that our baseline CO2 emissions in 2030 match WEO projections in all regions.

Appendix III: additional simulation results

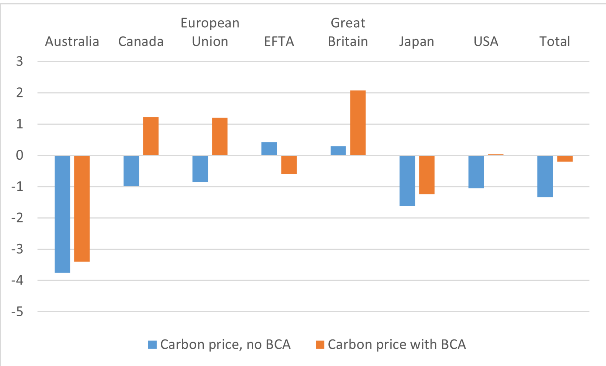
Figure 19: Change in value added (left figure) and export value (right figure) in EITE sectors in the IMF scenario when the 7-country coalition introduces carbon pricing, both without and with BCA: BCA fosters competitiveness in most countries, but the effect is generally limited

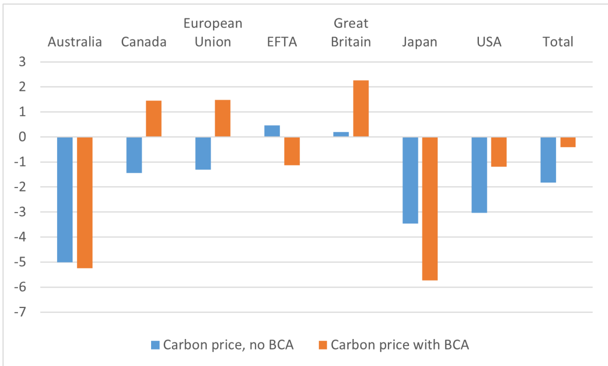




Notes: The left figure shows the projected difference in value added in 2030 in EITE sectors between the scenarios with carbon pricing (with and without BCA) and the baseline without carbon pricing. Both scenarios assume that a uniform carbon price is charged by the seven high income regions, while the other regions do not introduce a carbon price. The right figure presents the same comparison for gross export values.

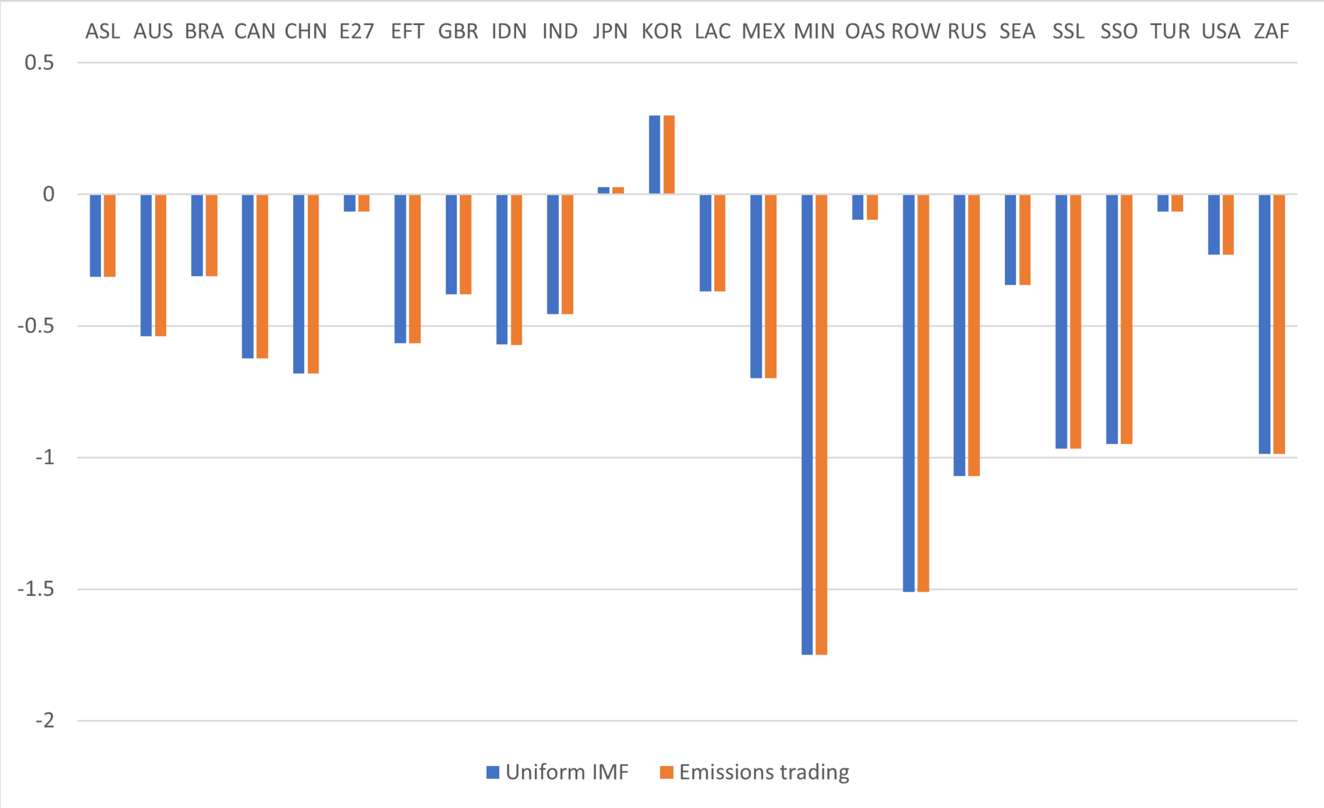
Figure 20: Change in value added (left figure) and export value (right figure) in EITE sectors in the NDCI scenario when the 7-country coalition introduces carbon pricing, both without and with BCA: BCA fosters competitiveness in most countries, but the effect is generally limited





Notes: The left figure shows the projected difference in value added in 2030 in EITE sectors between the scenarios with carbon pricing (with and without BCA) and the baseline without carbon pricing. Both scenarios assume that a uniform carbon price is charged by the seven high income regions, while the other regions do not introduce a carbon price. The right figure presents the same comparison for gross export values.

Figure 21: Real income effects of uniform carbon pricing, with and without emission trading: the effect of emission trading is projected to be small when targeting the price



Notes: The figure displays the change in real income (nominal income divided by the aggregate price index) under the IMF uniform carbon price realizing equivalent reductions in global emissions to differential carbon pricing, with and without trading in emission allowances.

Appendix IV: global emission reductions and carbon prices under different scenarios

Table 8: Global emission reduction under different scenarios

	All	Only ambitious
NDCI	10.13	3.41
NDCU	12.33	3.66
NDC2	27.12	7.15
IMF	24.8	5.84
Regular emission trading	27.12	12.26
Progressive emission trading	27.12	17.66

Note: Global emission reduction under different scenarios (NDCI, NDCU, NDC2, IMF and regular/progressive emission trading) if all countries participate to the reduction effort or only the 7 ambitious regions participate

Table 9: Carbon price under different scenarios

	All	Only ambitious
BCA	56.47	104.33
Nordhaus	56.47	96.38
GCI	57.44	96.58
Regular emission trading	42.95	121.52
Progressive emission trading	38.27	242.79

Note: Carbon price implied by different policies (BCA, Nordhaus, GCI and regular/progressive emission trading) with NDC2 global reduction targets, if all countries participate to the reduction effort or only the 7 ambitious regions participate

Appendix V: equivalence between the global carbon incentive scheme and redistribution based on population shares

The Global Carbon Incentive fund is structured such that each region's net income from the global carbon fund is given by the difference between region j per capita CO2 emissions and the global average per capita emissions, multiplied by population and the nominal carbon tax[35].

Define the average CO2 emissions per capita as:

$$CO2av = \frac{\sum_r CO2_r}{\sum_r pop_r} \tag{48}$$

We can write the net income flows implied by the GCI mechanism as:

$$CO2net_r = nctax \times [CO2av \times pop_r - CO2_r] \tag{49}$$

Where the first element of the equation, i.e. $nctax \times CO2av \times pop_r$, represents the revenue from the global fund, while $nctax \times CO2_r$ represents the payment to the fund.

It is trivial to show that the sum of the revenue streams is equal to the sum of the payments, i.e.:

$$\sum_r nctax \times CO2av \times pop_r = \sum_r nctax \times CO2_r \tag{50}$$

We will call the aggregate figure CO2totrev and the regional revenue $CO2rev_r$. The strategy we followed in order to implement the rule for redistribution was to express $CO2rev_r$ as a share of CO2totrev. Such share is defined as follows:

$$shp(r) = \frac{CO2rev_r}{CO2totrev} = \frac{nctax \times CO2av \times pop_r}{\sum_r nctax \times CO2av \times pop_r} \tag{51}$$

Since both the carbon price and the average CO2 emissions are defined as the global level, the expression is equivalent to:

$$shp(r) = \frac{pop_r}{\sum_r pop_r} \tag{52}$$

In practice, the GCI mechanism is equivalent to collecting the carbon tax into a global pool and redistributing the revenues to each country as a proportion of population. There is one simplifying assumption throughout this derivation: we implicitly assume that the global carbon tax is equivalent to the global carbon incentive, while in principle they could differ (Rajan (2021) proposes 10 US$ per tonne of CO2, which is lower than our global carbon price). In that case, only a fraction of the revenues from carbon pricing are allocated to the global fund, so the impact of redistribution is expected to be lower.

[35] Actually, the GCI price might be different from the global carbon tax. This will be discussed at the end of the section

How large is the incentive provided by the global fund?

The global fund we just described is conceived as an incentive mechanism: if the fund is in place, countries whose emissions per capita are above the global average have an incentive to reduce emissions in order to devote less resources to the fund, while countries whose emissions per capita are below the global average have an incentive to do that in order to increase their revenues. But how high-powered is this incentive mechanism?

A useful comparison is emission trading. Under emission trading, countries have an incentive to reduce their emissions because in that way they can sell emission allowances. Under global carbon pricing, if they reduce their emissions by one tonne of CO2, their additional revenue is equal to the nominal carbon price, i.e. $nctax$. The global incentive fund is different, because the positive effect due to the increase in the net revenues from the fund is weakened by the reduction in the average CO2 emissions per capita (in other words, reducing emissions also moves the threshold that defines the net revenues from the fund). In order to assess the magnitude of these two effects, it is useful to start from equation 49. Using the definition in equation 48, we can re-write the net revenues as:

$$CO2net_r = nctax \times pop_r \times [\frac{\sum_s CO2_s}{\sum_s pop_s} - \frac{CO2_r}{pop_r}] \tag{53}$$

The impact on net revenues of decreasing CO2 emissions by one tonne equals -1 multiplied by the derivative of $CO2net_r$ with respect to $CO2_r$, i.e.:

$$-\frac{dCO2net_r}{dCO2_r} = nctax \times (1 - shp_r) \tag{54}$$

Where shp_r was defined as the share of world population of country r. If the country is relatively small (i.e. shp_r tends to 0), the expression is equal to $nctax$, i.e. the incentive effect of GCI is analogous to emission trading. On the other hand, if the country is relatively large the effect becomes smaller, because the reduction in emissions reduces average emissions per capita proportionally to the population share.

It is also interesting to look at the impact of a reduction in emissions in a third country on the net revenues of country r. Formally,

$$-\frac{dCO2net_r}{dCO2Q_s} = -nctax \times shp_r \tag{55}$$

Meaning that a reduction in CO2 emissions in country s always have a negative impact on the revenues of country r. Intuitively, the total amount of resources allocated to the fund is equal to the carbon price multiplied by the emission quantity expressed in tonnes of CO2, so an emission reduction of one tonne of CO2 reduces the value of the fund by the value of the carbon price. The impact on country r is proportional to its population share because the resources are distributed to the countries depending on their population shares.

This result suggests that, if all countries simultaneously reduce emissions, the gains from emission reduction could be weak. As an example, assume that all countries reduce emissions by 50%. The net revenues of each country would be equal to:

$$CO2net_r = 0.5 \times nctax \times pop_r \times [\frac{\sum_s CO2Q_s}{\sum_s POPR_s} - \frac{CO2_r}{pop_r}] \quad (56)$$

i.e. one half of the initial net revenues. Countries with emissions per capita that are higher than the global average are still better off, because they devote to the fund one half of the resources that they allocated initially [36], while countries whose emissions per capita are lower than the average are worse off, because they receive one half of the initial resources. In order to obtain the same financial benefits that they enjoyed initially, they should further reduce their emissions.

Since reducing emissions is costly and the increase in the net revenues from the fund might be limited, countries might not have a strong incentive to reduce their emissions under the global incentive mechanism, which is what we find in our simulations. On the other hand, purely Walrasian frameworks such as global emission trading (possibly associated with progressive reduction targets) might be more effective in providing incentives to reduce emissions because the benefit is always determined by the carbon price and there is no scope for strategic interaction[37].

[36] Nevertheless, their increase in income is lower than in the hypothetical scenario where the other countries did not decrease their emissions. In that case, their net revenues from the fund would have been equal to:

$$nctax \times pop_r \times [\frac{\sum_{s \neq r} CO2Q_s + 0.5 \times CO2_r}{\sum_s pop_s} - \frac{0.5 \times CO2_r}{pop_r}]$$

[37] Actually, even with emission trading the utility of each country depends on the choices of the others. Since the market for emissions is Walrasian, an increase in the supply of allowances reduces the carbon price and hence might weaken the incentive to reduce emissions. Our simulations suggest that this effect is not dominant for most countries.