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How to Boost Countries' Climate Ambitions: Turning Gains from Emissions Trading into Gains for Climate

Abstract

The Nationally Determined Contributions (NDCs) under the Paris Agreement fall short of the abatement needed to reach the 2°C target. Emissions trading could be a "costless" means to reduce the ambition gap if countries used their gains from trade for additional abatement. However, this requires cooperative behavior. We show that with emissions trading, countries' non-cooperative choices of emissions reduction contributions can lead to even more abatement, provided that these contributions may not be lower than initial NDCs. Intuitively, countries with high climate damages raise their contributions if they can meet them partly through abatement in countries with low abatement costs.

JEL-Codes: H230, Q540, Q560, Q580, C720.

Keywords: Paris Agreement, emissions trading, NDCs, game theory.

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1 Introduction

Under the Paris Agreement, individual countries are required to submit Nationally Determined Contributions (NDCs) that specify the emissions reductions they intend to achieve. From an economic perspective, these NDCs reveal countries' willingness to pay for the protection of the climate system. However, the current NDCs fall substantially short of the emissions reductions needed to limit global warming to at least 2°C, which is the common target of United Nations member states. A natural idea to raise countries' ambition level for a given willingness to pay is to exploit the costs savings from emissions trading, which to date is operated only via few fragmented cap-and-trade systems such as the EU ETS (World Bank, 2022). Article 6.2 of the Paris Agreement allows for the "use of internationally transferred mitigation outcomes [ITMOs] towards nationally determined contributions" and, thus, has the power to unlock this potential.

After a long stalemate, an Article 6 rule book was finally agreed at the COP 26 climate negotiations in Glasgow in 2021, so that the conditions for comprehensive international emissions trading are now in place. This was not the case when countries submitted their original NDCs and the first round of revisions until October 2021. Hence, we suggest that they chose these NDCs under the presumption that abatement has to be implemented through domestic action.[1] Furthermore, as countries are essentially free to set their NDCs, economic theory suggests that NDCs as voluntary commitments mainly codify individually rational Nash behavior. In the literature, this argument has not only been made for the Paris Agreement (Barrett, 2016; Dimitrov et al., 2019), but even for the Kyoto Protocol that comes substantially closer to a top-down cooperative agreement (Böhringer, 2002; Böhringer & Vogt, 2004).

In this paper, we show how gains from emissions trading can turn into gains for climate, i.e., more emissions abatement than delivered with the original NDCs. This can put international climate action back on track to still reach the 2°C target. Our theoretical analysis and numerical simulations based on data from the 36$^{\text{th}}$ Energy

[1]Note that there is only one NDC for the EU as a geopolitical region so that trading under the EU ETS is consistent with the assumption of domestic abatement.

Modeling Forum study (EMF36, Böhringer et al., 2021), evaluate four archetypical scenarios of future climate policy which differ in assumptions on the scope of emissions trading and the strategic behavior of countries. The original NDCs to be achieved via domestic action constitute our reference scenario (referred to as scenario *notrade*) where countries act in a non-cooperative manner. Our second scenario (referred to as scenario *trade*) analyzes the case where countries maintain their abatement targets of scenario *notrade* and simply reap the cost savings from emissions trading — in this case, countries do not make any strategic update of their initial NDCs.

In a third scenario (referred to as scenario *gains*) we assume that countries "donate" all cost savings from trading in a cooperative effort to ramp up their original NDCs. Hence, the country-specific costs remain the same as with the original targets and, thus, do not exceed the willingness to pay that countries have already revealed. Yet, as our numerical simulations based on empirical data show, overall abatement increases by about 70% compared to scenarios *notrade* and *trade*. While this idea of turning gains from emissions trading into gains for the climate has a lot of appeal, its fundamental problem is the lack of incentive compatibility. Unfortunately, after three decades of arduous climate negotiations there are good reasons to be skeptical about the willingness of countries to forgo self-interest for the sake of cooperation.

Reflecting this sobering assessment, our fourth scenario (referred to as scenario *strategic*) is based on non-cooperative behavior. Surprisingly, we find that emissions trading may still be very effective in strengthening countries NDCs – to an extent that even exceeds the abatement level of the cooperative scenario *gains*, leading to an increase of overall abatement by nearly 120% compared to scenarios *notrade* and *trade*. More specifically, scenario *strategic* assumes that countries choose their emissions reduction targets under trading as mutual best-response strategies, subject to the constraint that each country's abatement target must not be lower than its emissions reductions in scenario *notrade*, i.e., than its NDC abatement level. Subsequently, countries can exploit where-flexibility by trading emissions reductions, i.e., ITMOs in the terminology of the Paris Agreement. This ties in to the current state of climate negotiations, where countries have already submitted their NDCs and are now revising them as the rules of Article 6 have been set to allow trading of emissions reductions. NDCs are revised every five years and it is mandatory that their ambition has to increase (United Nations Framework Convention on Climate Change [UNFCCC], 2022). The constraint also reflects that, according to Article 6, the use of ITMOs in the implementation of NDCs shall "allow for higher ambition in their mitigation [...] actions". Hence it appears realistic that the existing NDCs constitute a political and legal lower bound for countries' emissions reduction contributions once an emissions trading system has been established.

The striking policy-relevant insight from our analysis is that the non-cooperative choices of tradable emissions reduction targets subject to the NDC constraint in scenario *strategic* can induce countries to abate even more emissions than would be the case if countries were to cooperatively invest all cost savings from emissions trading in additional emissions reductions as in scenario *gains*. Our theoretical analysis helps to understand the reasoning behind. The key mechanism was first mentioned by Helm (2003): With emissions trading, the costs of an additional abatement unit are not determined by a country's domestic abatement cost function, but by the common price of emissions allowances. This incentivizes a country with high environmental ambitions to strengthen its emissions reduction contribution under emissions trading as it can exploit cheap abatement options in countries with lower ambitions. The cooperative scenario *gains* fails to fully tap this potential to turn gains from emissions trading into gains for climate. A priori, however, there is a countervailing effect since other countries have an incentive to choose lower abatement targets under emissions trading in order to sell an excessive amount of emissions reductions, often termed "hot air" in the literature. Importantly, the Paris Agreement prescribes that revised and updated NDCs must be more ambitious than existing ones (UNFCCC, 2022), thereby avoiding the pitfall of "hot air". From this perspective, the "pledge and review" approach of the Paris Agreement and the original failure to provide the rules for emissions trading turn out to be an unexpected opportunity for attaining the 2° C target without relying too much on countries' willingness — or political ability — to act beyond their national self-interest.

Our contribution to the literature is twofold. First, we extend the theoretical analysis by Helm (2003) with the treatment of initial NDCs as a lower bound constraint for countries' non-cooperative choices of tradable emissions reduction targets. Second, to ascertain the policy relevance of our theoretical findings, we complement our theoretical analysis with numerical simulations based on a meta-analysis where we use data input from nine modeling teams from the 36$^{\text{th}}$ Energy Modeling Forum study (EMF36, Böhringer et al., 2021). Drawing upon the NDCs under the Paris Agreement and data on regional marginal abatement costs from EMF36, our quantitative results suggest that emissions trading with the NDC constraint more than doubles the global emissions reductions as compared to the purely domestic abatement in scenario *notrade,* thereby putting international climate action on track with the 2°C target.

The remainder of our paper is organized as follows. Section 2 provides a brief literature review. Section 3 presents the theoretical analysis of future climate policy regimes under the Paris Agreement that differ in assumptions on emissions trading and strategic behavior. Section 4 discusses quantitative results from our simulation analysis based on empirical data. Section 5 concludes, and the Appendix contains all proofs.

2 Literature review

Emissions trading in the context of the Paris Agreement has been analyzed by several scholars who mainly performed numerical simulations to estimate potential cost savings from where-flexibility (e.g., Böhringer et al., 2021; Edmonds et al., 2021; Fujimori et al., 2016; Hof et al., 2017; Li & Duan, 2020; Rose et al., 2018) or identified environmental integrity risks (e.g., La Hoz Theuer et al., 2019; Michaelowa et al., 2019; Müller & Michaelowa, 2019; Schneider & La Hoz Theuer, 2019). However, little attention has been paid so far to the issue how the cost savings from emissions trading could possibly translate into a higher ambition level for emissions abatement. A few authors have taken up the idea to use these cost savings one-to-one for financing additional abatement efforts such that countries remain effectively at the economic burden associated with purely domestic implementation of their NDCs (Edmonds et al., 2021; Piris-Cabezas et al., 2018, 2019). Yet, this idea lacks economic appeal as it is not based on strategic interaction of self-interested economic parties. Helm (2003) studied non-cooperative choices of tradable emissions allowances and showed that the efficiency gains from emissions trading need not translate into higher abatement due to the choice of a higher allowance number by environmentally less concerned countries. Carbone et al. (2009) extended this by allowing the formation of trading coalitions that can block the participation of those countries that would opt for very high allowance allocations. Other authors analyzed the strategic allowance allocation between countries subject to an exogenous constraint, which imposes a limit on global aggregate emissions (e.g., Bahn & Haurie, 2008; Haurie et al., 2006; Morgan & Prieur, 2013). Yu et al. (2017) also analyzed a strategic carbon market with an exogenous constraint on regional allowances specified as a certain percentage of business-as-usual emissions. By contrast, we derive the constraint on countries' allowance choices from the current status of climate negotiations.

A related strand of literature addresses the question whether the pledge-and-review mechanism applied within the Paris Agreement can help to increase global abatement (e.g. Barrett & Dannenberg, 2016; Cramton et al., 2017; Jacquet & Jamieson, 2016). Gollier and Tirole (2017) call the pledge-and-review mechanism inadequate and claim it creates incentives for countries to free ride and "green wash" their climate ambitions. Harstadt (2023a, 2023b), on the other hand, holds a more positive view and finds that pledge-and-review may lead to a larger number of participants in a climate agreement and an increase in welfare. Our analysis points out a different advantage of the pledge-and-review approach as the initial pledges constitute a lower bound when countries review them after an emissions trading system has been established.

3 Theoretical analysis

We investigate four archetypical climate policy regimes — *notrade, trade, gains* and *strategic* – which differ in assumptions on the scope of emissions trading and the strategic behavior of countries as summarized in Table 1. Note that we refer to emissions reduction pledges as "Emissions Reduction Contributions" (ERCs),

Table 1: Climate policy regimes

	Trading of emissions reductions	Strategic choice of emissions reduction contributions (ERCs)	Climate policy context
notrade	no	yes (non-cooperative)	Reference scenario where countries choose initial ERCs to be fulfilled by purely domestic abatement
trade	yes	no	Countries reap cost savings from trading their initial ERCs (global emissions abatement remains at the *notrade* level)
gains	yes	yes (cooperative)	Countries spend all cost savings from trading emissions reductions on raising their ERCs in a cost-neutral manner
strategic	yes	yes (non-cooperative)	Each country determines its ERC strategically subject to the constraint that it must not fall below the initial *notrade* abatement level

which takes up the wording "Nationally Determined Contributions" (NDCs), but is more specific about the form of contributions that we analyze, namely emissions reductions. This also allows us to reserve the term "NDCs" for the actual NDCs submitted until October 2021.

We use index $i \in \{1,...,I\}$ to refer to the individual countries. Countries' emissions reductions $a_i = E_{i0} - e_i$ are given as the difference by which emissions e_i are reduced below the business-as-usual emissions level E_{i0} that would prevail without any mitigation measures. Abatement costs are represented by increasing and strictly convex functions $c_i(a_i)$. Abatement is beneficial as it reduces climate damages, which we represent by concave benefit functions $b_i(a)$ where $a = \sum_{i=1}^{I} a_i$ is the overall (global) abatement level. We assume that countries' ranking in terms of their individual marginal benefits of abatement is the same for all global abatement levels.

Assumption 1. *For any two overall abatement levels a', a'', and any two countries i, j: $b'_i(a') > b'_j(a') \Longleftrightarrow b'_i(a'') > b'_j(a'')$.*

This assumption is consistent with empirical estimates for damages of climate change

(Ricke et al., 2018; Tol, 2019) and obviously holds for linear benefit functions that are widely adopted in the literature. We now determine the solution for the four climate policy scenarios to examine how international emissions trading can foster overall emissions abatement.

3.1 Scenario *notrade*

In scenario *notrade*, each country chooses the level of its non-tradable ERC, i.e., domestic abatement, to maximize national welfare:[2]
[3]

$$\max_{a_i} \; b_i(a) - c_i(a_i). \tag{1}$$

Nash equilibrium abatement levels, $a_1^N, \ldots, a_I^N$, satisfy the familiar first-order conditions that marginal costs and benefits of abatement are equalized:

$$c_i'(a_i^N) = b_i'(a^N), \qquad i = 1, \ldots, I. \tag{2}$$

Emissions reductions in scenario *notrade* are inefficient for two reasons. Countries ignore the benefits of their abatement for other countries, and abatement is not done cost-effectively because marginal abatement costs differ across (non-symmetric) countries. The next two scenarios address the second issue.

3.2 Scenario *trade*

In scenario *trade*, each country maintains the ERC as in scenario *notrade*, but emissions reductions are now tradable across countries. Hence $\omega_i^T = a_i^N$, where ω_i^T de-

[2]One may criticize that the assumption that ERCs and NDCs mainly codify individually rational Nash behavior neglects any role of the tedious and ongoing international negotiation process that has led to the Paris Agreement and probably influenced countries' NDCs. At the same time, benefits of abatement need not be restricted to purely egoistic motives but may also capture other aspects such as how countries account for benefits of abatement in other countries of the world, possibly as a result of international climate negotiations. In this interpretation, the NDC levels that countries have actually chosen reveal their preferences over emissions abatement.

[3]Note that this and all further optimization problems are concave so that the first-order conditions are sufficient for optimality.

notes the ERC of country i in scenario *trade*. Note that the expression $a_i = E_{i0} - e_i$ implies a one-to-one correspondence between abatement and emissions. Therefore, trading of emissions reductions and trading of the implied emissions lead to the same abatement and emissions levels — with associated marginal costs that are the same except for the reversed sign. In our analysis, we consider trade in emissions reductions — respectively ITMOs in the terminology of the Paris Agreement — as this simplifies the notation and better corresponds to the idea of NDCs that specify emissions reduction targets as well as ITMOs that can be traded under Article 6.2.[4]

Each country i chooses its abatement level a_i so as to minimize the costs of abatement $c_i(a_i)$ and the implied expenses on the market for emissions reductions $p(\omega_i - a_i)$ where the latter are negative for sellers of emissions reductions, i.e., countries that abates more than their ERCs would require ($a_i > \omega_i$):

$$\min_{a_i} c_i(a_i) + p(\omega)(\omega_i - a_i). \tag{3}$$

The first-order condition together with the market clearing condition determine after-trade equilibrium abatement $a_i^*(\omega)$ and the price $p^*(\omega)$ at which emissions reductions are traded as functions of the given overall abatement level $\omega = \sum_{i=1}^{I} \omega_i$:

$$c_i'(a_i) - p^*(\omega) = 0, \; i = 1, ...I \tag{4}$$

$$\sum_{i=1}^{I} a_i(p^*(\omega)) - \omega = 0. \tag{5}$$

By construction, overall abatement and the implied benefits are the same in both scenarios *trade* and *notrade*. Hence, for each country the welfare gains of scenario *trade* over *notrade* result only from the cost savings from where-flexibility and are given by

[4] Note that the Kyoto Protocol used a different terminology by explicitly mentioning the international trading of emissions allowances, called "Assigned Amount Units" (AAUs) while Article 6 of the Paris Agreement focuses on the trading of emissions reductions, called "Internationally Transferred Mitigation Outcomes" (ITMOs). Arguably, this reflects that — at least for non-economists — the idea of paying other countries for emissions reductions appears less controversial than giving countries the right to emit greenhouse gases and allowing them to earn revenues from the sale of these pollution rights.

$$c_i(a_i^N) - c_i(a_i^*(\omega^T)) - p^*(\omega^T)(\omega_i^T - a_i^*(\omega^T)) \geq 0,\ i = 1,...,I. \qquad (6)$$

Note that the sign of the expression follows from the fact that each country could always choose $a_i^*(\omega^T) = \omega_i^T$ and, thus, only participates in trading of emissions reductions if this is beneficial.

3.3 Scenario *gains*

In scenario *gains*, countries cooperatively agree to use the costs savings from trading of emissions reductions for additional abatement efforts. Such a "gains for climate" agreement has some fairness appeal because all countries benefit from the higher abatement while having the same costs as in scenario *notrade*. Disputes on uneven efficiency gains from trading (Böhringer & Helm, 2008) are thus avoided and governments can serve requests for more ambitious climate action without additional cost burdens for domestic citizens.

Specifically, we assume that the countries choose their ERCs in scenario *gains*, denoted ω_i^G, such that after trading of emissions reductions each country has the same costs as in scenario *notrade*:

$$c_i(a_i^N) = c_i(a_i^*(\omega^G)) + p^*(\omega^G)(\omega_i^G - a_i^*(\omega^G)),\ \ i = 1,...,I, \qquad (7)$$

where the price $p^*(\omega^G)$ at which emissions reductions are traded and the after trade abatement $a_i^*(\omega^G)$ follow from the first-order conditions (4) and (5) for $\omega = \omega^G$.[5] Obviously, each country has a higher welfare than in scenario *notrade* as its costs are the same, but the overall abatement level and associated benefits are higher. However, the solution is neither efficient, nor is it strategically stable because the resulting ERCs constitute no best-response to each other. The latter issue is addressed in our fourth scenario *strategic.*

[5]Formally, Eqs. (4), (5), and (7) constitutes a system of $2I+1$ equations that determines $p^*(\omega^G)$ as well as ω_i^G and $a_i^*(\omega^G)$ for $i = 1,...,I$ as a function of the exogenous abatement levels a_i^N under *notrade*.

3.4 Scenario *strategic*

The preceding scenarios *trade* and *gains* both took Nash equilibrium abatement levels $a_1^N, \dots, a_I^N$ — interpreted as countries' non-tradable ERCs — as exogenously given and then analyzed the implications if countries (*i*) reap the gains from where-flexibility by international trade of emissions reductions (scenario *trade*) or (*ii*) cooperatively agree to devote all efficiency gains from trade to higher abatement efforts (scenario *gains*). Our final scenario, called *strategic,* adopts the idea from scenario *gains* that cost reductions from where-flexibility can induce more abatement, but as in scenario *trade* countries interact non-cooperatively. Specifically, as in Helm (2003) we assume that countries choose their level of ERCs non-cooperatively. However, we add the constraint that these ERCs must not fall below the Nash equilibrium abatement levels in scenario *notrade* in which abatement is more costly due to the missing where-flexibility. As mentioned above, this ties in with the situation of climate negotiations where countries have already submitted NDCs and are now asked to ratch them up as emissions reductions become tradable.

We model this as a three-stage game where countries first decide whether to establish a system for the trading of emissions reductions, then choose their ERCs, and subsequently trade emissions reductions on a competitive market. As usual, the game is solved by backward induction. We first analyze the trading of emissions reductions for a given overall level of ERCs, ω^S (superscript S denotes scenario *strategic*). This has already been considered in Subsection 3.2 and led to the first-order conditions (4) and (5) that determine the price of emissions reductions $p^*(\omega^S)$ and after-trade abatement $a_i^*(\omega^S)$. To analyze how these values change in ω^S, we differentiate Eq. (4) with respect to p and Eq. (5) with respect to ω, yielding

$$c_i''(a_i)a_i'(p^*) - 1 = 0, \;\; i = 1, ...I, \tag{8}$$

$$\sum_{i=1}^{I} a_i'(p^*)p'(\omega) - 1 = 0, \tag{9}$$

so that upon substitution

$$p^{*'}(\omega) = \frac{1}{\sum_{i=1}^{I} a_i'(p^*)} = \frac{1}{\sum_{i=1}^{I} \frac{1}{c_i''(a_i)}} > 0. \tag{10}$$

Similarly, differentiation of Eq. (4) with respect to ω yields $c_i''(a_i)a_i'(\omega) - p^{*'}(\omega) = 0$ so that after substitution for $p^{*'}(\omega)$ from Eq. (10) we obtain

$$a_i'(\omega) = \frac{p^{*'}(\omega)}{c_i''(a_i)} = \frac{1}{\sum_{j=1}^{I} \frac{c_i''(a_i)}{c_j''(a_j)}} \in (0,1). \tag{11}$$

Intuitively, if countries choose to abate more (higher ω), the price of emissions reductions and abatement of each country both increase.

This is anticipated in the second stage of the game, where each country i chooses its ERC, thereby accounting for environmental benefits, abatement costs, payments on the market for emissions reductions, and the NDC constraint that ERCs must not fall below abatement levels in scenario *notrade*:

$$\max_{\omega_i} b_i(\omega) - c_i(a_i^*(\omega)) - p^*(\omega)(\omega_i - a_i^*(\omega)) \;\; s.t. \quad \omega_i - a_i^N \geq 0, \tag{12}$$

where we have used $a^* = \omega$ from Eq. (5). Differentiation of the corresponding Lagrangian and using $p^*(\omega) = c_i'(a_i^*(\omega))$ to simplify the expression yields the Karush-Kuhn-Tucker conditions for $i = 1, \ldots I$ (μ_i is the Lagrangian multiplier):

$$b_i'(\omega) - p^*(\omega) - p^{*'}(\omega)(\omega_i - a_i^*(\omega)) + \mu_i = 0, \tag{13}$$

$$\omega_i - a_i^N \geq 0, \quad \mu_i \geq 0, \;\; \mu_i \left(\omega_i - a_i^N\right) = 0. \tag{14}$$

Intuitively, a marginal increase in ERCs has the following effect: (*i*) it increases abatement and the associated benefits (the term $b_i'(\omega)$), (*ii*) has direct costs equal to the price at which emissions reductions are traded (the term $p^*(\omega)$), and (*iii*) raises the price of emissions reductions, which is costly for a country that abates less than the level of ERC to which it has committed; and vice versa (the term $p^{*'}(\omega)(\omega_i - a_i^*(\omega))$). To this the shadow price μ_i of the NDC constraint is added.

In the remainder of this Section, we derive some properties of the solution that arises from the above Karush-Kuhn-Tucker conditions, examine the effects of the NDC constraint on abatement, and compare the environmental effectiveness of scenarios *gains* and *strategic*. Starting with the first point, the following classification of countries turns out to be useful.

Definition 1. Let r denote the country that has the highest marginal benefits of abatement of all sellers of emissions reductions. We refer to countries with $b_i'(\omega) \leq b_r'(\omega)$ as **low-benefit-of-abatement countries** and to countries with $b_i'(\omega) > b_r'(\omega)$ as **high-benefit-of-abatement countries**.

From that we can derive Proposition 1, which indicates that whether a country acts as a buyer or seller of emissions reductions depends on its benefit of abatement function.

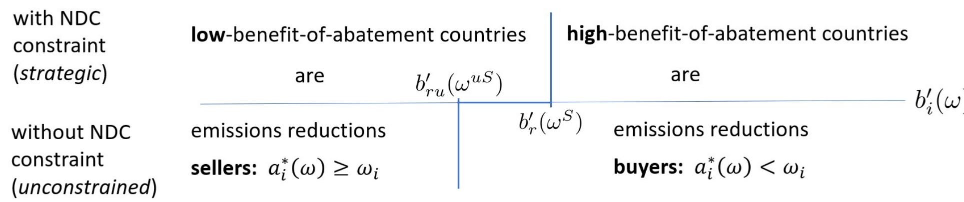
Proposition 1. *High-benefit-of-abatement countries are buyers of emissions reductions, i.e., they choose ERCs that exceed their level of domestic abatement ($\omega_i > a_i^*(\omega)$). Low-benefit-of-abatement countries are sellers of emissions reductions, i.e., they abate more than their ERCs require ($\omega_i \leq a_i^*(\omega)$).*[6]

Without trading, countries choose abatement such that their marginal costs and benefits of abatement are equalized (see Eq. 2). Therefore, high-benefit-of-abatement countries have higher marginal abatement costs than low-benefit-of-abatement countries. Trading opens the possibility to implement emissions reductions in other countries, which — for a given overall abatement level — reduces the marginal costs of abatement for high-benefit-of-abatement countries. Therefore, with trading they are willing to accept higher ERCs. The reverse argument applies for low-benefit-of-abatement countries. In Figure 1, the upper bold vertical line at $b_r'(\omega^S)$ that separates sellers and buyers illustrates this result of scenario *strategic*.

We now analyze how the NDC constraint affects abatement and countries' incentives to sell or buy emissions reductions. Obviously, a country for which the constraint binds will have to choose a more ambitious ERC than it would have done

[6]Thus, without loss of generality we refer to the unlikely boundary case of a country that has $\omega_i = a_i^*(\omega)$ as a seller.

Figure 1: Classification of buyers and sellers of emissions reductions



otherwise. However, it is well know that such a unilateral increase of an abatement target risks to trigger lower abatement by other countries. As Hoel (1991) has shown, total emissions may even be higher when one country reduces its emissions unilaterally. In our setting, such free riding is limited by the fact that the NDC constraint applies for all countries. Moreover, trading ensures that marginal abatement costs are equalized across countries so that each of them contributes to the additional overall abatement. Altogether, we obtain the following result.

Proposition 2. *Let superscript uS index the* unconstrained *solution that would obtain in the absence of the NDC constraint, and suppose that there is at least one country for which the NDC constraint binds. Then, compared to the* unconstrained *solution, each country abates more ($a_i^*(\omega^S) > a_i^*(\omega^{uS})\ \forall\ i \in I$) so that also overall abatement is higher ($\omega^S > \omega^{uS}$) and the equilibrium price at which emissions reductions are traded rises ($p^*(\omega^S) > p^*(\omega^{uS})$).*

From Proposition 1 and Definition 1, there exists a country r such that a country i is a seller of emissions reductions if and only if $b_i'(a^S) \leq b_r'(a^S)$. In the following, we refer to r as the "critical" country in the constrained solution, i.e., in our scenario *strategic* with the NDC constraint. We denote the “critical” country in the *unconstrained* solution by ru. As Proposition 2 indicates, a binding constraint leads to a higher price of emissions reductions compared to the *unconstrained* solution. This has implications for the set of buyers and sellers. On the one hand, a higher price makes buying emissions reductions less and selling more attractive; suggesting that there are more sellers in the constrained solution. On the other hand, in the *unconstrained* solution countries with low benefits of abatement tend to choose less ERCs ω_i, so as to later sell their abatement services to other countries. In the *con-*

strained solution this is limited by the constraint $\omega_i \geq a_i^N$, suggesting that there are less sellers. Hence, there are two opposing effects, but one tends to predominate.

Proposition 3. *Consider a situation where the NDC constraint matters, i.e., it binds for at least one country. If marginal benefits of abatement are constant — an assumption that we make in the numerical simulations — then in scenario* strategic *more countries are sellers of emissions reductions than in the* unconstrained *solution.*

Figure 1 illustrates the proposition, where the bold vertical lines separate sellers and buyers for the two cases with the NDC constraint (upper part) and without it (lower part). To understand the intuition for the proposition, remember that with trading the marginal costs of increasing abatement by one unit is given by the common price, $p^*(\omega)$, and, thus, are the same for all countries. Intuitively, countries whose marginal benefits of an additional abatement unit, $b_i'(\omega)$, exceed that price will take on greater ERCs, but implement some of them by buying emissions reductions from other countries. We know that in scenario *strategic* overall abatement is larger than in the *unconstrained* solution. At the margin, this increases the costs of an additional ERC unit and (weakly) reduces the benefits. Hence the benefit/cost ratio worsens and less countries accept ERCs that exceed the level of abatement which they implement after trading. Accordingly, there are less buyers of emissions reductions in scenario *strategic*.

In the first stage of the game, the countries decide whether they consent to establishing a trading system with the condition that each country's ERC must satisfy the NDC constraint $\omega_i \geq a_i^N$. In this scenario *strategic,* it is a feasible action for each country to choose the same ERC level as in the fallback-scenario *notrade* and to not participate in trading. Countries that do so would have the same abatement costs as in scenario *notrade*, but would still have a (weakly) higher welfare because the constraint $\omega_i \geq a_i^N$ for all i implies that environmental benefits are (weakly) larger in scenario *strategic*, i.e., $b_i(\omega^S) \geq b_i(a^N)$.

Hence all countries have a (weakly) larger welfare in scenario *strategic*, and strictly so unless all countries choose $\omega_i = a_i^N$. Moreover, in this case there would be gains from trading unless all countries are symmetric. Welfare maximizing countries will always exploit these gains. Moreover, trading affects the costs of abatement and, thus, countries' ERCs. By construction, these must satisfy $\omega_i \geq a_i^N$ so that only adjustments that increase the level of ERCs are feasible. Intuitively, the cost reductions from trading will lead countries to take on higher abatement targets. We summarize these results in the following proposition.

Proposition 4. *Unless all countries are identical (so that there would be no gains from trading), countries will unanimously agree on a system of tradable emissions reductions that are subject to the NDC constraint $\omega_i \geq a_i^N$. Moreover, the overall level of abatement in this scenario* strategic *is strictly larger than in scenario* notrade, i.e., $\omega^S > a^N$.

3.5 Comparison of scenarios *strategic* and *gains*

The result that abatement in scenario *notrade* is lower than in the scenarios *strategic* and *gains* is evident. This is not the case for the comparison of scenarios *strategic* and *gains.* As discussed at the beginning of Section 3, *gains* takes the ERCs of scenario *notrade* as given, but assumes cooperative behavior in that countries agree to devote all efficiency gains from trading to finance higher emissions reductions. Scenario *strategic* is based on non-cooperative behavior, but takes into account that the costs savings from trading may lead countries to choose more ambitious ERCs in the first place. A priori, it is unclear which of the two effects dominates.

In both scenarios, *strategic* and *gains*, emissions are reduced cost-effectively (marginal abatement costs are equalized) so that higher overall abatement implies higher overall abatement costs. Therefore,

$$a^S \gtreqqless a^G \Longleftrightarrow \sum_{i=1}^{I} c_i(a_i^*(\omega^S)) \gtreqqless \sum_{i=1}^{I} c_i(a_i^*(\omega^G)) = \sum_{i=1}^{I} c_i(a_i^N), \tag{15}$$

where the equality follows from the fact that, by construction, overall abatement costs in scenarios *gains* and *notrade* are the same. Let $c_i(\omega_i^S)$ denote a country's marginal abatement costs if it did not trade (i.e., $c_i(\omega_i^S) := c_i(a_i)$ for $a_i = \omega_i^S$). Adding $\sum_{i=1}^{I} c_i(\omega_i^S)$ on both sides of the right-hand side equivalence in (15) and rearranging yields an expression that fosters intuition:

$$a^S \gtreqless a^G \Longleftrightarrow \sum_{i=1}^{I} c_i(\omega_i^S) - \sum_{i=1}^{I} c_i(a_i^N) \gtreqless \sum_{i=1}^{I} c_i(\omega_i^S) - \sum_{i=1}^{I} c_i(a_i^*(\omega^S)). \quad (16)$$

Due to the NDC constraint in scenario *strategic*, $\omega_i \geq a_i^N \forall i$, , the sum on the left-hand side is positive. Both its terms give abatement costs without trading so that the difference represents countries' higher ambitions in scenario *strategic* compared to scenario *notrade*. If this exceeds the cost savings from emissions trading in scenario *strategic* — the terms on the right-hand side— then countries reduce more emissions in *strategic* than in *gains*.

Intuitively, the size of the two effects depends on countries' specific benefit and abatement cost functions. To make this explicit, we use a well-known result for Taylor polynomials (see, e.g., Simon, Blume, et al., 1994, p. 828), according to which there exists a point x_i between a_i^N and $a_i^*(\omega^S)$ such that

$$c_i(a_i^*(\omega^S)) - c_i(a_i^N) = b_i'(a^N)\left[a_i^*(\omega^S) - a_i^N\right] + 0.5c_i''(x_i)\left[a_i^*(\omega^S) - a_i^N\right]^2, \quad (17)$$

where we have used $b_i'(a^N) = c_i'(a_i^N)$ from Eq. (2).[7] The last term is strictly positive for all countries (by convexity of the abatement cost functions). Moreover, it follows immediately from $\omega^S > a^N$ that $\sum_{i=1}^{I}\left(a_i^*(\omega^S) - a_i^N\right) > 0$. Hence, if all countries had the same benefit functions, summation of the right-hand side of Eq. (17) over all countries would yield a strictly positive term so that $a^S > a^G$ from (15).

The general case of heterogeneous benefit functions can be further examined by using

$$a_i^*(\omega^S) - a_i^N = \frac{p(\omega^S) - b_i'(a^N)}{0.5\left[c_i''(x_i) + c_i''(y_i)\right]}, \quad (18)$$

where y_i is another point between a_i^N and $a_i^*(\omega^S)$, and the equation follows from the above result for Taylor polynomials (see Proof of Proposition 5). In particular, we obtain the following result.

Proposition 5. *A country abates more in scenario* strategic *than in scenario* no trade *($a_i^*(\omega^S) > a_i^N$), if and only if $b_i'(a^N) < p(\omega^S)$ — i.e., if its marginal benefits in*

[7] Upon rearranging it is straightforward to see that Eq. (17) is simply the Taylor approximation of c_i of order 1 at a_i^N,where $0.5c_i''(x_i)\left[a_i^*(\omega^S) - a_i^N\right]^2$ is the remainder term.

scenario notrade *are comparatively low. Moreover,*

$$a^S \gtreqless a^G \Longleftrightarrow \sum_{i=1}^{I} \left(b_i'(a^N) \left[\frac{p(\omega^S) - b_i'(a^N)}{0.5\left[c_i''(x_i) + c_i''(y_i)\right]} \right] + 0.5 c_i''(x_i) \left[\frac{p(\omega^S) - b_i'(a^N)}{0.5\left[c_i''(x_i) + c_i''(y_i)\right]} \right]^2 \right) \gtreqless 0, \tag{19}$$

where $x_i, y_i \in [a_i^N, a_i^*(\omega^S)]$.

The last term in Eq. (19) is strictly positive. However, the first term has a negative sign for countries with marginal benefits, $b_i'(a^N)$, above $p(\omega^S)$, which is combined with a weight $b_i'(a^N)$ that is larger for those countries for which the term $p(\omega^S) - b_i'(a^N)$ is negative. Hence the overall effect is ambiguous.

To understand the main determinants, let us consider the widely used quadratic cost function, for which the second derivative is a constant that we denote by c_i''. Using this to simplify expression (19), multiplying out the terms and rearranging yields

$$a^S \gtreqless a^G \Longleftrightarrow \sum_{i=1}^{I} \left(\frac{b_i'(a^N)}{c_i''} \left[p(\omega^S) - b_i'(a^N) \right] + 0.5 \left[p(\omega^S) - b_i'(a^N) \right]^2 \right) \gtreqless 0. \tag{20}$$

Remember that after accounting for payments from trading emissions reductions, countries' compliance costs in scenario *gains* are the same as in the reference scenario *notrade*. This purely cost-based approach limits the additional emissions reductions that result from trading. In scenario *strategic,* by contrast, countries with high marginal benefits of abatement boost their ERCs because they can use the potential for cheap emissions reductions in countries that — due their low marginal benefits of abatement — have only low emissions reductions and abatement costs in the reference scenario *notrade.* Intuitively, this potential is particularly large if the marginal abatement costs of these countries rise only modestly in additional abatement. Formally, this corresponds with a low value of c_i'' for countries with $b_i'(a^N) < p(\omega^S)$, as Eq. (20) reflects. Consistent with these elaborations, the following numerical simulations will show that it are especially China and India with their relatively flat marginal abatement cost functions that drive the superior performance of scenario *strategic.*

By contrast, the countries with a high valuation for abatement ($b_i'(a^N) > p(\omega^S)$)

will even have lower abatement costs in *strategic* as compared to *gains* and *notrade* — just as the first statement in Proposition 5 suggests. The reason is that their resources are better invested in financing emissions reductions in low abatement cost countries, which scenario *strategic* allows them to do.

4 Numerical analysis

In order to ascertain the relevance of our analytical findings for climate policy design in the aftermath of the Paris Agreement, we perform numerical simulations based on empirical data. We first describe the parametrization of our analytical framework. We then discuss the simulation results. Finally, we present sensitivity analysis to check the robustness of our key insights. Note that all central case simulation results can be replicated using the data from Table 2 as well as Tables 7 and 6 in Appendix B showing business-as-usual emissions in 2030 and marginal abatement cost coefficients across all models and regions.[8]

4.1 Data and parametrization

The numerical model translates one-by-one the logic of the theoretical model while using empirical data to parametrize (i) business-as-usual (BaU) emissions, (ii) NDCs for emissions reductions, and (iii) marginal abatement cost curves for geopolitical regions[9]. The data for parametrization stems from the 36$^{\text{th}}$ Energy Modeling Forum study on "Carbon Pricing After Paris" (EMF36, Böhringer et al., 2021). EMF36 brought together international expert modeling groups to assess the economic impacts of implementing NDCs in 14 geopolitical regions by 2030 as the policy-relevant target year. Our analysis builds on data from nine modeling groups[10] that

[8] The numerical model is programmed in GAMS (Generalized Algebraic Modeling System) and the code for the numerical model is available from the authors upon request.

[9] In the numerical analysis, we use the term "regions" instead of "countries" because the data refers to 14 geopolitical regions. Furthermore, note that we treat these regions as "domestic" entities so that emissions trading *within* these regions, such as under the EU ETS, is then consistent with the assumption of purely domestic abatement in scenario *notrade*.

[10] Table 4 in Appendix B shows the institutions and experts involved.

Table 2: BaU CO_2 emissions and NDCs

Region		2030 BaU CO_2 emissions (mean)	NDC emissions reductions
		Mt	% from BaU
global		31834.6	10.3
Africa	(AFR)	1233.5	1.8
Australia & New Zealand	(ANZ)	447.2	4.7
Brazil	(BRA)	456.8	18.9
Canada	(CAN)	553.1	21.8
China	(CHN)	8172.9	5
Europe	(EUR)	3821.4	24.9
India	(IND)	3070.4	5
Japan	(JPN)	922.5	8.1
South Korea	(KOR)	590.5	33.4
Middle East	(MEA)	2153.5	2.1
Other Americas	(OAM)	1318.9	6
Other Asia	(OAS)	3037.1	12.2
Russia	(RUS)	1418.7	1.1
United States	(USA)	4638.1	15.6

Source: EMF36 (Böhringer et al., 2021). The country coverage of the regions can be found in Table 5 in Appendix B.

commonly adopted projections from the International Energy Outlook (IEO) (EIA, 2017) on regional BaU development of GDP and fossil fuel demands. Table 2 states the BaU CO_2 emissions from fossil fuel combustion in 2030 as the mean value across the nine modeling groups together with the regional NDCs in terms of CO_2 emissions reduction targets from BaU levels. EMF36 considers only CO_2 emissions from the combustion of fossil fuels being the main source of anthropogenic greenhouse gas emissions. Since various regions stated their NDC targets for all greenhouse gas emissions, these NDCs had to be converted into reduction targets for CO_2 emissions from fossil fuel combustion.[11]

The modeling groups also provided data on how incremental CO_2 emissions pricing leads to regional emissions abatement in their respective macroeconomic models accounting for different abatement options: CO_2 emissions abatement can take

[11] Appendix A.2 in the EMF36 summary article (EMF36, Böhringer et al., 2021) provides a detailed description of how the NDCs were derived for the 14 EMF regions.

place by fuel switching (i.e., interfuel substitution), energy efficiency improvements (i.e., substituting capital for energy in more energy-efficient appliances), or energy savings (i.e., a scale reduction of production and final demand activities). More specifically, each group ran its model over a sequence of hypothetical tax scenarios with region-specific CO_2 taxes from \$0 to \$200 per ton of CO_2 in incremental steps of \$1. At each CO_2 price, the models quantified the induced regional emissions reductions. We use this information to derive regional marginal abatement cost curves for each of the nine EMF36 models based on a least-square fit to polynomial functions of third degree:

$$c_i'(a_i) = k_{1i}a_i + k_{2i}a_i^2 + k_{3i}a_i^3, \tag{21}$$

where k_{1i}, k_{2i}, k_{3i} denote the coefficients for region i.

The fitted coefficients for the nine modeling groups are provided in Table 7 in Appendix B. Figure 2a visualizes the average marginal abatement cost curves across the nine models which reveal substantial variations in the ease of CO_2 emissions substitution across regions due to cross-country differences in average CO_2 intensity, fuel mixes of CO_2-based energy carriers (oil, coal, gas), initial energy price levels, or pre-existing emissions regulations.

EMF36 does not provide any explicit monetary estimates for climate damages from CO_2 emissions. Such estimates – often referred to as the social costs of carbon – are still subject to larger uncertainties (Rennert et al., 2022) and reflect the policy preferences of individual countries only to a limited extent. Therefore, similar to deriving consumers' preferences from their consumption decisions (Samuelson, 1948; Varian, 1982), we take the regions' NDCs in Table 2 as their revealed preferences for reducing CO_2 emissions. Specifically, remember that we interpreted the NDCs as the solution of the scenario *notrade.* Together with the marginal abatement cost functions from the EMF36 models, Eq. (2) then gives a point estimate of marginal benefits at this solution. Moreover, we adopt the widely used assumption that damage costs, respectively benefits from abatement, are linear in emissions.[12]

[12]Golosov et al. (2014, p. 78) state that "Linearity is arguably not too extreme a simplification, since the composition of a concave S-to-temperature mapping with a convex temperature-to-damage

4.2 Simulation results

The simulation results are based on a meta-analysis, where we parametrize the numerical model with data input from nine EMF36 modeling teams. For each of our four policy scenarios we thus obtain nine sets of results for the target year 2030 that we can present in descriptive statistics. For the sake of compactness and readability, the exposition of results is focused on mean values, but we also use Box-Whisker plots to visualize the distribution of selected results by means of the median, the mean, the first and third quartile as well as whiskers within 1.5 times the interquartile range (i.e. 1.5 the distance between the upper and lower quartile).

Figure 2a provides information on the average marginal abatement cost curves across the nine EMF36 models. The substantial differences across regions reflect their varying ease of CO_2 emissions substitution via fuel switching, energy efficiency improvements, and energy savings as captured by the slope (convexity) of regional marginal abatement cost curves.

Figure 2b depicts the equilibrium values of marginal abatement costs in scenario *notrade,* where regions implement their individual NDCs through domestic abatement only. Marginal abatement costs in scenario *notrade* vary substantially across regions, which reflects the differences in marginal benefits of abatement as revealed by the NDCs under the Paris Agreement.[13] In particular, mean CO_2 prices in scenario *notrade* range from about 2\$/tCO_2 for Russia (Russia stands out for a very modest NDC and cheap abatement options) to about 140\$/tCO_2 for Europe and South Korea (both regions stand out for ambitious NDCs together with rather costly domestic abatement options). The global mean amounts to 43\$/tCO_2.

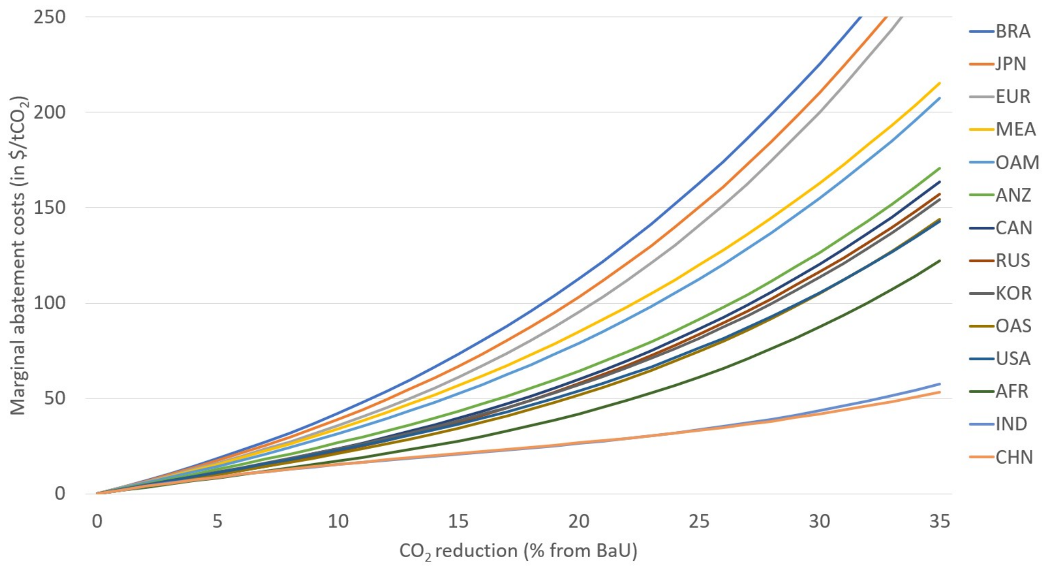
The large spread in CO_2 prices in scenario *notrade* indicates the potential for substantial cost savings by equalizing marginal abatement costs via emissions trading. We now show how this can be used to increase global emissions abatement in an incentive compatible manner well beyond the initial NDC targets, which is our most policy-relevant finding. Figure 3 shows the range of global CO_2 emissions reductions for our four climate policy scenarios as Box-Whisker plots across the nine

function may be close to linear" (see also Finus et al., 2006).

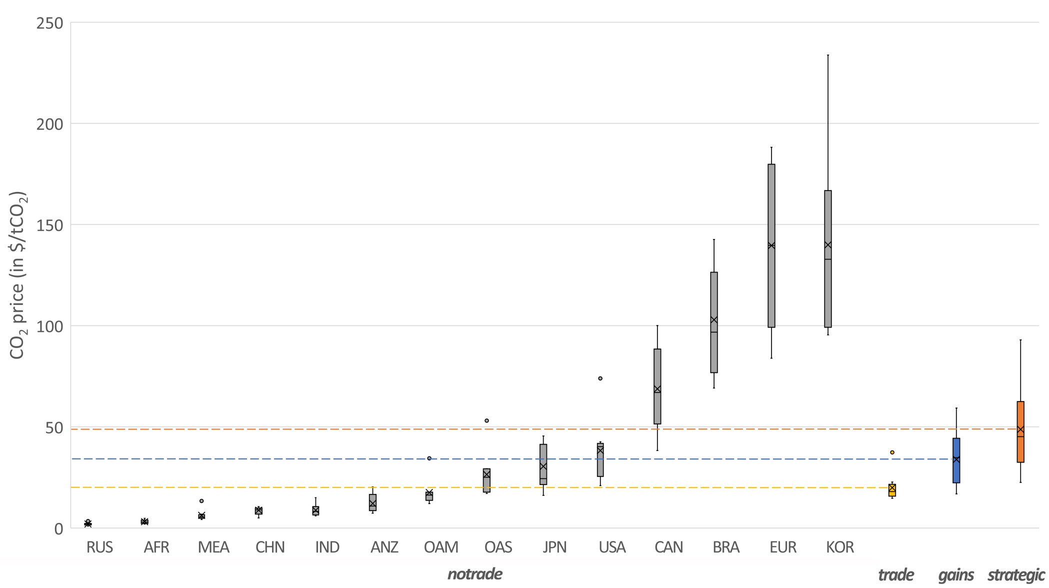
[13]Remember that from Eq. (2), the regions' NDCs equalize marginal benefits and costs of abatement.

Figure 2: Average marginal abatement cost curves and regional and global CO_2 prices

(a) Average marginal abatement cost curves across the nine EMF36 models

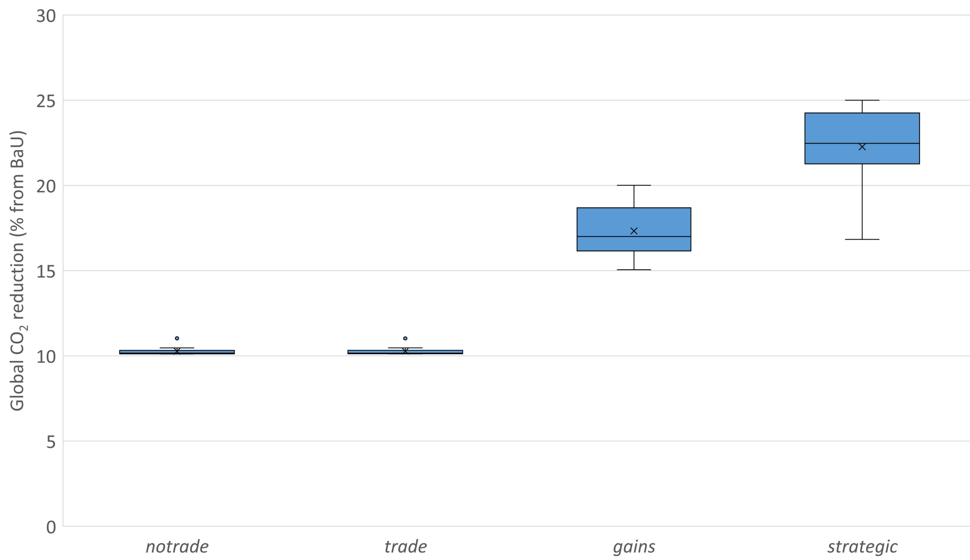


(b) Regional and global CO_2 prices



Note: Box–Whisker plot shows the median (line), mean (cross), first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range. Dots indicate outliers. For region keys see Table 2.

Figure 3: Global CO_2 emissions reduction



Note: Box–Whisker plot shows the median (line), mean (cross), first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range. Dots indicate outliers.

different model parametrizations.

In our reference scenario *notrade* that maps the regions' NDCs, the mean global reduction as compared to BaU is 10.3%. By definition, we obtain the same reduction in scenario *trade* where regions participate in emissions trading but do not adjust their abatement targets. Scenario *gains* indicates that if regions spent all their cost savings from emissions trading on additional abatement, the mean global emissions reduction increases from 10.3% to 17.3% (compared to BaU). The fundamental caveat with scenario *gains*, however, is that it is not incentive compatible because additional emissions reductions do not follow from the individual cost-benefit calculus but are simply imposed exogenously.

This conceptual limitation does not apply to scenario *strategic* where regions balance marginal costs and benefits of tradable emissions reductions in their own best interest, while taking initial NDCs as a lower bound for their ambition level. Remarkably, this setting results in a mean global emissions reduction of 22.3% compared to BaU, which is even higher than the outcome in scenario *gains* that requires cooperative behavior. It more than doubles the initial NDC pledges and brings re-

Table 3: Key determinants for emissions reductions in scenario *strategic*

Region	$b'_i(a^N)$	$p(\omega^S) - b'_i(a^N)$	$0.5\,[c''_i(x_i) + c''_i(y_i)]$	overall
	$/tCO$_2$	$/tCO$_2$	$/tCO$_2$	$/tCO$_2$
AFR	3.09	45.65	0.18	5,637
ANZ	12.14	36.60	0.69	1,577
BRA	102.90	-54.17	1.49	-2,713
CAN	68.78	-20.05	0.82	-1,433
CHN	8.80	39.94	0.02	67,983
EUR	139.62	-90.89	0.19	-41,666
IND	8.82	39.92	0.05	19,649
JPN	30.44	18.29	0.54	1,310
KOR	139.95	-91.21	0.97	-8,385
MEA	6.23	42.50	0.17	6,610
OAM	17.55	31.19	0.30	3,300
OAS	26.45	22.29	0.11	7,944
RUS	1.97	46.77	0.20	5,205
USA	38.29	10.44	0.07	6,323
all				71,340

For region keys see Table 2. For the context of the terms see Eq. (19) in Proposition 5.

duction efforts by 2030 within the range of emissions cuts considered necessary to meet the 2°C target.[14]

The main reasons for this have already been mentioned in the discussion of Eq. (19) in Proposition 5. Remember that the individual term of each region under the summation sign is positive if its abatement costs in scenario *strategic* exceed those in *notrade*, and *strategic* leads to more overall abatement than *gains* if the sum of these terms is positive.[15]

The row "all" in the last column of Table 3, which sums up the ("overall") value of the individual terms under the summation sign, shows that this is indeed the case. Moreover, the individual overall terms of the regions show that this result is mainly driven by the substantially higher abatement costs that China and — to a lesser

[14]Mean global 2030 CO_2 emissions in scenario *strategic* are lower than the respective mean CO_2 emissions from energy use in the various 2°C pathway scenarios of the integrated assessment models provided by IIASA's AR6 Scenarios Database (Byers et al., 2022).

[15]Note that *overall* abatement costs of scenarios *notrade* and *gains* are the same as revenues and expenses from trading of emissions reductions cancel in the aggregate.

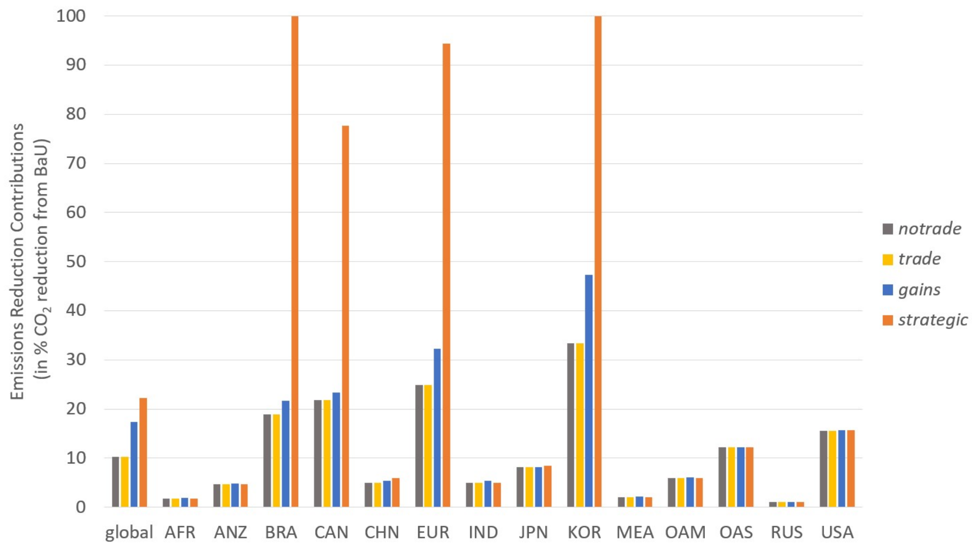
extent — India accept in scenario *strategic* compared to scenario *notrade*. This is because their revenues from selling emissions reductions make them overall better off. By contrast, the four regions with marginal benefits of abatement that exceed the equilibrium price of emissions reductions of 48.74 \$/tCO_2 in scenario *strategic* (Brazil, Canada, Europe and South Korea; see 2nd and 3rd column), have even lower abatement costs in scenario *strategic* as compared to *notrade*.

This reflects that marginal benefits and marginal costs of abatement of China and India in the reference scenario *notrade* are less than one tenth of those in Europe and South Korea (see 2nd column). Moreover, the marginal abatement costs of China and India increase only modestly in additional abatement. This is indicated by the very low values for $0.5\,[c_i''(x_i)+c_i''(y_i)]$ in the 4th column of Table 3, which is consistent with the relatively flat shape of the marginal abatement cost functions of China and India in Figure 2a. In scenario *strategic*, regions with high marginal benefits of abatement anticipate this potential for cheap emissions reductions in other regions and, thus, choose substantially higher ERCs than in *notrade* (their current NDCs) and any of the other scenarios (see Figure 4).

The regions that implement the additional emissions reductions also benefit as they receive the equilibrium price on the trading market for each unit of abatement above their own ERCs. For that reason, they would actually prefer to lower their own ERCs as they could then sell even more emissions reductions. Indeed, without the NDC constraint, regions with low marginal benefits of abatement (Russia, Africa, Middle East, India, China, Australia and New Zealand) would choose ERCs which are substantially lower than their NDC abatement levels and sometimes even below their BaU emissions, triggering "hot air". Hence global abatement would decline drastically to only 8.7% compared to BaU, even lower than in scenario *notrade* (10.3%).[16] However, the provisions in the Paris Agreement that revised NDCs must be more ambitious than existing ones, which we implement via the NDC constraint in Eq. (12), serve as a safeguard. In contrast, the cooperative scenario *gains* does use the cost savings from emissions trading to finance additional abatement, but it makes only insufficient use of regions' willingness to raise their ERCs if they can

[16]Further details regarding the ERCs and CO_2 reduction values without the NDC constraint are provided in Appendix C.

Figure 4: Emissions Reduction Contributions (ERCs) across regions



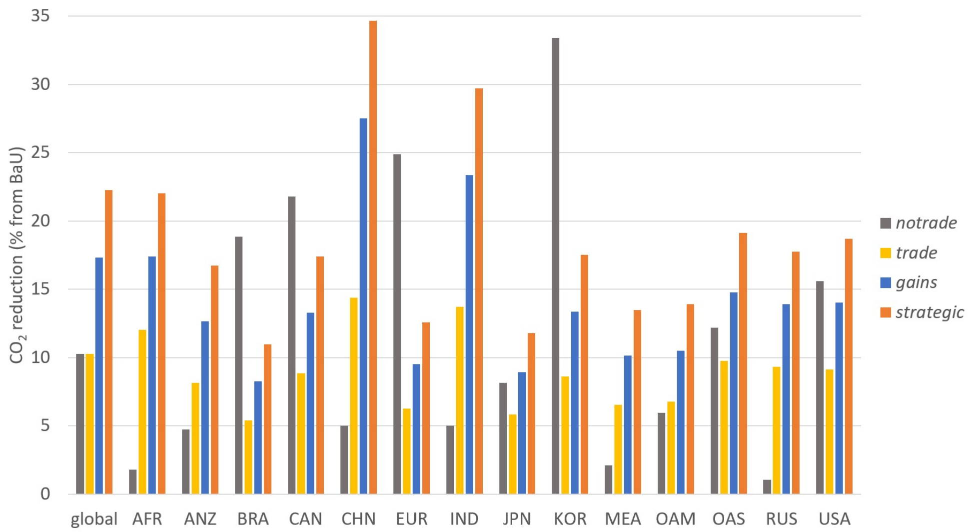
Mean values across models. For region keys see Table 2.

implement them at comparatively low costs in other regions. This is also reflected in Figure 4, where the ERCs of the regions with the highest valuation for abatement (Brazil, Canada, Europe and South Korea) increase only modestly when we move from scenario *notrade* to *gains*.

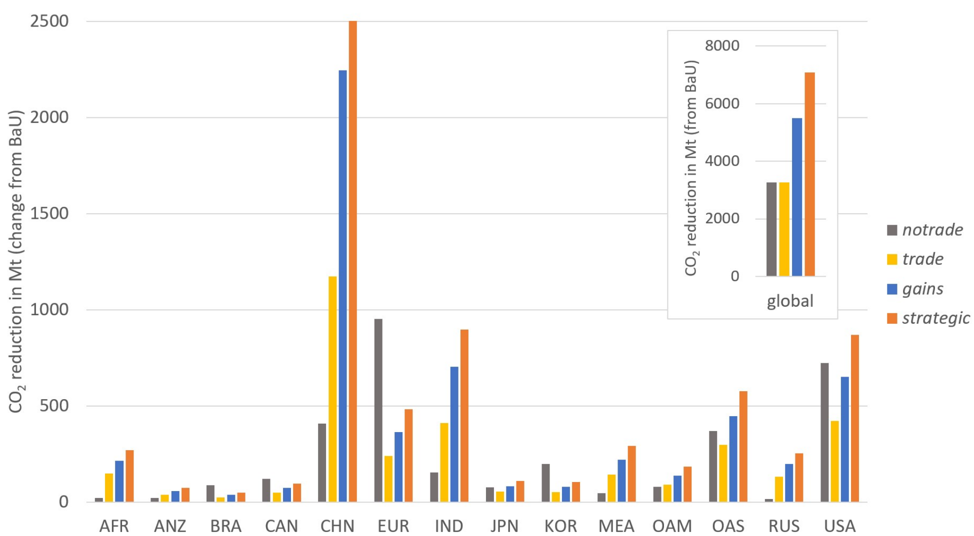
Figure 5 displays the mean values for regional emissions reductions from BaU levels both in terms of percentage changes (Figure 5a) as well as in terms of absolute values, i.e. Mt CO_2 (Figure 5b). For scenario *notrade* the regional emissions reductions equal the initial NDCs as provided in Table 2. By design, the abatement effect of moving from *notrade* to *trade* is zero at the global level, but very different across regions, depending on their positions as sellers or buyers and the extent of trading. Regions such as South Korea, Europe, and Brazil whose marginal abatement costs under *notrade* are above the global CO_2 price become buyers of emissions reductions (see Figure 2b), while regions such as China, Russia, and India whose marginal abatement costs under *notrade* are below the global CO_2 price become sellers of emissions reductions. By contrast, the regional increase in abatement from *trade* to *gains* and then to *strategic* is similar across regions, which reflects that it is driven by the rising CO_2 price that is the same for all regions. Moreover,

Figure 5: Regional CO_2 emissions reductions

(a) CO_2 reduction (in % from BaU)



(b) CO_2 reduction (in Mt)



Mean values across models. For region keys see Table 2.

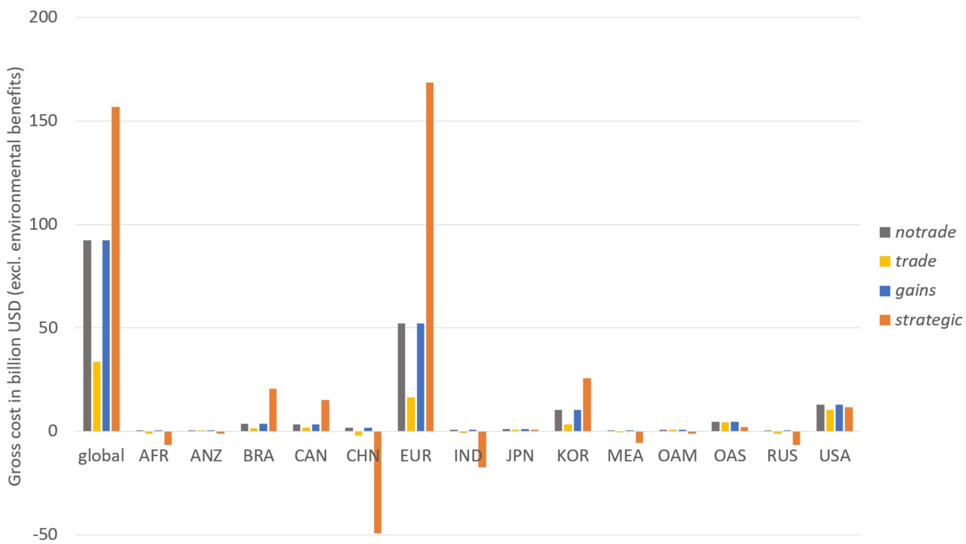
remember that from Proposition 1 there is a critical region such that in scenario *strategic* all regions with lower marginal benefits are sellers of emissions reductions and vice versa. In our numerical simulations, this region is the USA so that in Figure 2b all regions to the left of the USA are sellers in scenario *strategic* and those to the right are buyers of emissions reductions. Intuitively, regions with high marginal benefits of abatement like Korea and the EU will accept ERCs above the level that they intend to abate domestically if they can tap the potential of cheaper emissions reductions in other regions.

Figure 6 provides insights into the inframarginal costs of climate policies for individual regions – both in terms of gross costs as well as net costs (the latter includes the valuation of environmental benefits). Recall that we interpret the regional marginal abatement costs from scenario *notrade* as the regions' revealed preferences for abatement and use this to calculate the economic value of changes in global emissions of the individual regions. More precisely, we quantify the gross benefits from emissions abatement for each region in our different climate policy scenarios as the product of global emissions reductions times the region-specific willingness to pay derived in scenario *notrade*.

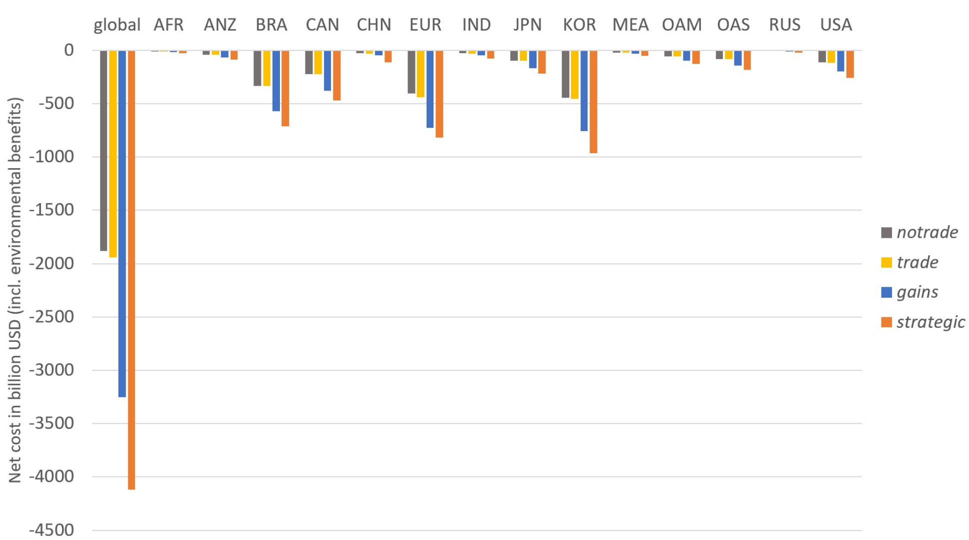
The gross costs shown in Figure 6a include the abatement costs for the specific region as well as its expenditures or revenues from trading emissions reductions. At the global level, there are substantial cost savings from emissions trading with a mean value of 63% in scenario *trade* as compared to the reference scenario *notrade* where global gross costs amount to 92.2 bn$. Obviously, all regions gain from where-flexibility, but there are substantial differences. Intuitively, those regions with the largest difference between regional marginal abatement costs in scenario *notrade* and the global CO_2 price in scenario *trade* gain most. From Figure 2b, these are especially South Korea and Europe who realize substantial cost savings from buying emissions reductions abroad that replace costly domestic abatement. In comparison, large sellers of emissions reductions such as China, India, or Russia gain less, reflecting a lower differential between their initial marginal abatement cost and the after-trade CO_2 price. When interpreting the gross costs for scenario *strategic* it is important to keep in mind that compliance costs, as the sum of abatement costs and trade costs (negative or positive), emerge from more compre-

Figure 6: Regional costs of climate policies

(a) Gross costs (excluding environmental benefits)



(b) Net costs (including environmental benefits)



Mean values across models. For region keys see Table 2.

hensive cost-benefit considerations where regions strategically choose their ERCs (subject to a lower bound constraint at their initial NDCs of the Paris Agreement) to maximize their net benefits (including environmental benefits). High-benefit-of-abatement regions such as Europe, South Korea, Brazil, or Canada are willing to accept substantially higher gross costs by choosing ERCs beyond their *notrade* NDC level and thereby drive up global abatement even beyond the *gains* level along with higher global gross costs of abatement. At the same time, low-benefit-of-abatement regions such as China, India, Africa, or Russia realize revenues from selling additional emissions reductions at higher CO_2 prices which can lead to substantial economic gains for these regions even when abstaining from the valuation of reduced climate damages.

Overall, if regions simply use their current NDCs as a starting point to trade emissions reductions in scenario *trade*, then global gross costs amount to 33.7 bn$. In contrast, if regions are allowed to adjust their NDCs – now that where-flexibility can be exploited – as in scenario *strategic*, they are willing to accept global gross costs of 156.9 bn$, which is more than four times as much. Noting that this is the non-cooperative Nash equilibrium solution shows the remarkably high potential of emissions trading for tapping regions' willingness to pay for climate policies. Furthermore, the global gross costs in scenario *strategic* exceed the global gross costs in scenario *gains* of 92.2 bn$, reflecting that the abatement level in *strategic* is higher than in *gains* (see Eq. 15).

Taking into account region-specific environmental benefits, Figure 6b compares the net costs across the four climate policy regimes. Net costs are negative for all regions across all scenarios, which means that benefits always exceed the costs. At the global level, the cost savings from reduced climate damages are an order of magnitude higher than the abatement costs (with increasing net benefits towards higher global abatement) – highlighting the scope for significant welfare gains from more ambitious climate action than is the case with the current NDCs under the Paris Agreement. There is an unambiguous (Pareto) welfare ranking across all regions where scenario *notrade* is the least desirable, followed by a slight margin by scenario *trade*, and then with markedly higher welfare levels by scenarios *gains* and *strategic* – with the latter clearly superior.

5 Conclusions

In this paper, we investigated how emissions trading can increase global emissions reductions as codified by the NDCs under the Paris Agreement. For our assessment we combined theoretical analysis with numerical simulations based on empirical data. We find that emissions trading can lead to substantial increases in global emissions reductions compared to domestic abatement stand-alone. Remarkably, our study reveals that if countries are allowed to exploit the costs savings of where-flexibility from emissions trading, then non-cooperative choices of emissions reduction targets can result in even higher global emissions reductions than if countries invested cooperatively all their cost savings from emissions trading into additional abatement. The numerical simulations show that the pledge and review approach of the Paris Agreement together with the provision that revised NDCs have to be more ambitious than existing ones are crucial for this outcome as they avoid "hot air".

With the adoption of the Article 6 rule book at the COP 26 in 2021, the rules for parties wishing to enter into ITMO transactions are starting to emerge. Nevertheless, it is still a rather long way towards establishing a global system of tradable greenhouse-gas emissions reductions. Our analysis shows how much potential is lost by such a half-hearted approach. If countries were allowed to fully exploit the cost savings from where-flexibility, this could increase global abatement in an incentive compatible way substantially beyond the initial NDC targets. However, this requires that the establishment of a trading system, which makes abatement substantially cheaper, is linked to the pursuit of higher NDCs. According to our numerical simulations, the non-cooperative Nash equilibrium where countries adjust their NDCs now that they are tradable (our scenario *strategic*) would lead to overall abatement costs that exceed those where current NDCs are simply traded (our scenario *trade*) by a factor of 4. Moreover, countries not only accept substantially higher abatement costs, but also does trading lead to cost-efficiency. Therefore, in our numerical simulations reduction efforts by 2030 could even be aligned with the abatement requirements to meet the 2°C target — without relying on cooperative behavior.

In our numerical simulations, we used BaU projections for 2030 from EMF36 which are based on data from the International Energy Outlook (IEO, EIA, 2017). As EMF36 also provides an alternative BaU based on data from the World Energy Outlook (WEO, IEA, 2018), we also ran simulations with this alternative WEO BaU projections to investigate the robustness of our key findings. The alternative WEO BaU projections result in only slightly lower mean global CO_2 reductions for each climate policy scenario while the ranking of climate policies in terms of their environmental effectiveness remains stable (further details are presented in Appendix C).

We derived countries' marginal benefits of abatement by arguing that the NDCs that countries have chosen reveal their preferences for abatement. An alternative approach would be to use estimates for the social costs of carbon from integrated assessment models. This might be combined with the explicit incorporations of equity motives in countries' payoff functions. Future research might also consider greenhouse gas emissions other than CO_2.

Appendix A: Proofs

Proof of Proposition 1. The statement that high-benefit-of-abatement countries are buyers of emissions reductions is implied by Definition 1, according to which no country with $b_i'(\omega) > b_r'(\omega)$ can be a seller. Hence, to prove the claim we need to show that all countries with $b_i'(\omega) \leq b_r'(\omega)$ are sellers of emissions reductions. First, consider such countries for which the constraint does not bind ($\mu_i = 0$). Then $b_i'(\omega) - p^*(\omega) \leq b_r'(\omega) - p^*(\omega) + \mu_r \leq 0$, where the last inequality follows from the definition of r as a seller ($\omega_r - a_r^*(\omega) \leq 0$)) and Eq. (13). Hence, from Eq. (13) such countries are also sellers of emissions reductions.

Next, consider countries for which the constraint does bind ($\mu_i > 0$) so that $\omega_i = a_i^N$ from Eq. (14). By contradiction, suppose that a country with $\mu_i > 0$ and $b_i'(\omega) \leq b_r'(\omega)$ is a buyer of emissions reductions so that $a_i^N - a_i^*(\omega) > 0 \Longleftrightarrow c_i'(a_i^N) > c_i'(a_i^*(\omega))$, where the equivalence follows from strict convexity of the abatement cost function. Similarly, as country r is a seller by definition, $a_r^*(\omega) - \omega_r \geq 0 \Longleftrightarrow c_r'(a_r^*(\omega)) \geq c_r'(\omega_r) \geq c_r'(a_r^N)$, where $c_i'(\omega_i)$ denotes a country's marginal abatement costs if it does not trade emissions reductions (i.e., $c_i'(\omega_i) := c_i'(a_i)$ for $a_i = \omega_i$), and the last inequality follows from the NDC constraint $\omega_i \geq a_i^N$. Moreover, from the equilibrium conditions (4) on the permit market $c_i'(a_i^*) = c_r'(a_r^*)$. Combining these conditions yields $c_i'(a_i^N) > c_i'(a_i^*(\omega)) = c_r'(a_r^*(\omega)) \geq c_r'(a_r^N)$. However, using Assumption 1 of a consistent ranking of countries' marginal benefits, and the first-order condition (2) for abatement choices in scenario *notrade*, $b_i'(\omega) \leq b_r'(\omega) \Longleftrightarrow b_i'(a^N) \leq b_r'(a^N) \Longleftrightarrow c_i'(a_i^N) \leq c_r'(a_r^N)$; hence we have a contradiction. □

Proof of Proposition 2. Note that ERCs in the *unconstrained* solution follow from condition (13) if we set $\mu_i = 0$ for all i. Thus, summation of Eq. (13) over all countries yields $\sum_{i=1}^{I} \left(b_i'(\omega^{uS}) - p^*(\omega^{uS})\right) = 0$ for the *unconstrained* and $\sum_{i=1}^{I} \left(b_i'(\omega^{S}) - p^*(\omega^{S}) + \mu_i^S\right) = 0$ for the constrained solution. Combining this yields

$$\sum_{i=1}^{I} \left(b_i'(\omega^{uS}) - p^*(\omega^{uS})\right) = \sum_{i=1}^{I} \left(b_i'(\omega^{S}) - p^*(\omega^{S}) + \mu_i^S\right) \tag{22}$$

By contradictions, suppose that $\omega^{uS} \geq \omega^{S}$, and that there is at least one country for which the NDC constraint binds. Then $\sum_{i=1}^{I} \mu_i^S > 0$ and $p^*(\omega^{uS}) \geq p^*(\omega^S)$ from Eq. (10). Moreover, $\sum_{i=1}^{I} b_i'(\omega^{uS}) \leq \sum_{i=1}^{I} b_i'(\omega^S)$ as $b_i''(a) < 0$ by assumption. Obviously, this would violate Eq. (22) and we conclude that $\omega^S > \omega^{uS}$. This implies $p^*(\omega^S) > p^*(\omega^{uS})$ and $a_i^*(\omega^S) > a_i^*(\omega^{uS})$ from Eqs. (10) and (11). $\square$

Proof of Proposition 3. From Proposition 1, there exists a "critical" country r such that a country i is a seller of emissions reductions if and only if $b_i'(\omega) \leq b_r'(\omega)$. Note that Proposition 1 also includes the case where $\mu_i = 0$ for all i so that it also applies to the *unconstrained* solution. By contradiction to Proposition 3, suppose that there are less sellers of emissions reductions in the situation with the constraint. Using Assumption 1 of a consistent ranking of countries' marginal benefits, this requires that the critical country of the *unconstrained* solution (a seller by definition), indexed ru, becomes a buyer of emissions reductions in the constrained solution.[17] Accordingly, using Eq. (13) we must have

$$b_{ru}'(\omega^{uS}) - p^*(\omega^{uS}) \leq 0 \quad \text{and } b_{ru}'(\omega^S) - p^*(\omega^S) + \mu_{ru}^S > 0, \qquad (23)$$

where superscript *uS* indicates the *unconstrained* solution.

However, from Proposition 2 we have $\omega^{uS} < \omega^S$ so that $p^*(\omega^{uS}) < p^*(\omega^S)$ from Eq. (10), and $b_i'(\omega^{uS}) \geq b_i'(\omega^S)$ by concavity of the benefit function. Therefore, $b_i'(\omega^{uS}) - p^*(\omega^{uS}) > b_i'(\omega^S) - p^*(\omega^S)$ for all i and, thus, also for the critical country ru. For $\mu_{ru}^S = 0$ this yields a contradiction to Eq. (23).

Alternatively, if $\mu_{ru}^S > 0$, we have $\omega_{ru}^S = a_{ru}^N$ from Eq. (14). Moreover, $c_{ru}'(a_{ru}^N) = b_{ru}'(a^N)$ from Eq. (2), $b_{ru}'(a^N) = b_{ru}'(\omega^{uS})$ from our assumption of constant marginal benefits, and $p^*(\omega^{uS}) = c_{ru}'(a_{ru}^*(\omega^{uS}))$ from Eq. (4). If, by contradiction to the statement in the proposition, country ru were a buyer of emissions reductions in scenario *strategic* (i.e., $\omega_{ru}^S > a_{ru}^*(\omega^S)$, expression (23) would imply $b_{ru}'(\omega^{uS}) \leq p^*(\omega^{uS})$ and combining these relations yields $c_{ru}'(a_{ru}^N) \leq c_{ru}'(a_{ru}^*(\omega^{uS}))$. Moreover, we would have $\omega_{ru}^S = a_{ru}^N > a_{ru}^*(\omega^S) \Longleftrightarrow c_{ru}'(\omega_{ru}^S) = c_{ru}'(a_{ru}^N) > c_{ru}'(a_{ru}^*(\omega^S))$. Together with the preceding inequality we get $c_{ru}'(a_{ru}^*(\omega^{uS})) \geq c_{ru}'(a_{ru}^N) > c_{ru}'(a_{ru}^*(\omega^S))$,

[17] Note that Figure 1 depicts the opposite (correct) situation.

which requires $a^*_{ru}(\omega^{uS}) > a^*_{ru}(\omega^S)$. But $\omega^S > \omega^{uS}$ (from Proposition 2) and $a'_i(\omega) > 0$ from Eq. (11) so that $a^*_{ru}(\omega^{uS}) < a^*_{ru}(\omega^S)$, yielding a contradiction. □

Proof of Proposition 5. Eq. (17) implements the Taylor approximation using the marginal abatement costs at a_i^N. The equivalent expression that uses the marginal abatement costs at $a_i^*(\omega^S)$ is

$$c_i(a_i^N) = c_i(a_i^*(\omega^S)) + c'_i(a_i^*(\omega^S)) \left[a_i^N - a_i^*(\omega^S)\right] + 0.5c''_i(y_i) \left[a_i^N - a_i^*(\omega^S)\right]^2. \tag{24}$$

Combining this with Eq. (17), canceling common terms, and using $p(\omega^S) = c'_i(a_i^*(\omega^S))$ from Eq. (4) yields Eq. (18). Eq. (19) then follows straightforwardly by substitution of Eq. (18) into Eq. (17) and using Eq. (15). □

Appendix B: Data

The EMF36 study is based on quantitative analysis from 14 established computable general equilibrium (CGE) models run by different international expert groups. For our meta-analysis we selected those (nine) models that feature multi-region trade across the 14 regions that had been identified by EMF36 as both geopolitically important and amenable to parametrization with publicly available data. Table 4 lists the EMF36 models used in the meta-analysis together with their institutional hosts and the modeling experts and Table 5 shows the country coverage of the regions.

The expert teams used their multi-region CGE models for the global economy to obtain explicit reduced-form representations of marginal abatement cost curves. For each region, marginal abatement cost functions are generated through a sequence of hypothetical tax scenarios with region-specific CO_2 taxes starting from \$0 to \$200 per ton of CO_2 in steps of \$1. At each CO_2 price, the CGE models quantify the induced emissions reduction. We use this information to derive regional marginal abatement cost curves for each of the nine EMF36 models based on a least-square fit to polynomial functions of third degree:

$$c_i'(a_i) = k_{1i}a_i + k_{2i}a_i^2 + k_{3i}a_i^3, \tag{25}$$

where k_{1i}, k_{2i}, k_{3i} denote the coefficients for region i. Table 7 summarizes all the coefficients of the least-square approximation that translate into Figs. 7-15. In addition, we report the BaU emissions across all models which emerge from their forward-projection to the IEO data on GDP growth and fossil fuel demands in 2030 (see Table 4).

The information on NDCs provided in Table 2 of the paper together with the BaU emissions in 2030 (Table 6) and the coefficients of marginal abatement cost curves (Table 7) is sufficient to reproduce all of the results in our central case simulations.

Table 4: EMF36 models used in the meta-analysis

Model	Institution	Experts
CEPE	Swiss Federal Institute of Technology (ETH) Zürich	Florian Landis, Gustav Fredriksson, Sebastian Rausch
DREAM	Fudan University	Haoqi Qian, Shuaishuai Zhang, Libo Wu
ENVISAGE	Purdue University	Maksym Chepeliev, Israel Osario-Rodarte, Dominique van der Mensbrugghe
GEM-E3	European Commission - Joint Research Centre (JRC)	Toon Vandyck, Matthias Weitzel, Krzysztof Wojtowicz, Luis Rey Los Santos, Anamaria Maftei, Sara Riscado
ICES	Euro-Mediterranean Center on Climate Change (CMCC)	Ramiro Parrado
PACE	Centre for European Economic Research (ZEW)	Sebastian Rausch
SNOW	Statistics Norway	Taran Fæhn, Hidemichi Yonezawa
TUB	Technical University (TU) Berlin	Mohammad M. Khabbazan, Christian von Hirschhausen
UOL	University of Oldenburg	Christoph Böhringer, Jan Schneider

Source: EMF36 (Böhringer et al., 2021).

Table 5: Countries and regions

Countries and regions	
Aggregated regions	*consisting of*
Africa (AFR)	Egypt, Morocco, Tunisia, Rest of North Africa, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, South Africa, Rest of South African Customs Union
Australia and New Zealand (ANZ)	Australia, New Zealand
Europe (EUR)	Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Croatia, Cyprus, Latvia, Lithuania, Malta, Romania, Switzerland, Norway, Rest of EFTA, Albania, Belarus, Bulgaria, Ukraine, Rest of Eastern Europe, Rest of Europe
Middle East (MEA)	Bahrain, Iran, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Rest of Western Asia, Israel, Turkey
Other Americas (OAM)	Mexico, Chile, Rest of North America, Argentina, Bolivia, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean
Other Asia (OAS)	Rest of Southeast Asia, Rest of East Asia, Mongolia, Nepal, Pakistan, Sri Lanka, Taiwan, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Rest of the World
Countries	
Brazil (BRA)	
Canada (CAN)	
China (CHN)	
India (IND)	
Japan (JPN)	
Russia (RUS)	
South Korea (KOR)	
United States (USA)	

Table 6: Business-as-usual (BaU) emissions projections for EMF36 modeling teams and EMF36 model regions

	BaU emissions in 2030 in Mt CO_2								
	CEPE	**DREAM**	**ENVISAGE**	**GEM-E3**	**ICES**	**PACE**	**SNOW**	**TUB**	**UOL**
AFR	1256.67	1264.47	1275.06	1264.39	1264.51	1305.57	1261.13	1260.28	949.32
ANZ	452.54	452.64	460.38	451.97	452.22	440.19	451.33	451.67	411.62
BRA	467.25	464.12	462.17	469.55	464.25	484.58	463.98	463.90	371.80
CAN	559.58	563.75	553.63	562.30	563.35	527.83	562.02	562.67	522.60
CHN	8062.37	8308.35	8532.27	8316.32	8318.13	8344.19	8296.04	8295.64	7083.08
EUR	3677.40	3756.51	3765.57	3714.42	3752.80	4035.59	3744.07	3744.46	4202.14
IND	3292.95	3300.52	3259.58	3301.96	3292.22	2832.30	3291.18	3291.42	1771.16
JPN	899.33	928.21	939.03	925.03	927.36	885.05	900.27	900.09	998.37
KOR	602.61	605.96	607.14	605.64	604.71	577.72	604.48	604.32	501.74
MEA	2185.64	2320.07	2402.06	2313.76	2312.54	1770.91	2182.46	2185.03	1709.23
OAM	1356.14	1342.76	1370.50	1363.68	1342.31	1292.30	1323.92	1325.00	1153.14
OAS	3221.46	3157.91	3166.18	3190.76	3152.70	3048.34	3139.00	3138.65	2119.20
RUS	1419.21	1427.44	1396.12	1430.26	1429.27	1317.03	1424.08	1425.14	1499.67
USA	4562.32	4554.63	4716.87	4554.01	4554.25	4587.13	4553.09	4553.18	5107.37

Column labels refer to modeling teams and row labels refer to model regions. Region keys: global — global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

Table 7: Coefficients for marginal abatement cost curves across EMF36 modeling teams and EMF36 model regions (index i)

	CEPE	DREAM	ENVISAGE	GEM-E3	ICES	PACE	SNOW	TUB	UOL
					k_{1i}				
AFR	0.1126	0.1684	0.1306	0.1761	0.0876	0.1137	0.1664	0.2065	0.1187
ANZ	0.4488	0.5046	0.8549	0.6215	0.3791	0.3941	0.5056	0.9043	0.5544
BRA	0.6272	0.6194	0.9064	0.7692	0.5826	0.6065	0.4794	0.8880	1.0541
CAN	0.2996	0.3259	0.5078	0.5321	0.2789	0.3464	0.3492	0.4306	0.4224
CHN	0.0285	0.0234	0.0272	0.0204	0.0321	0.0233	0.0187	0.0349	0.0147
EUR	0.0680	0.1205	0.1100	0.0770	0.0550	0.0484	0.0723	0.1069	0.0756
IND	0.0801	0.0598	0.0584	0.0459	0.0520	0.0496	0.1216	0.0672	0.0771
JPN	0.2855	0.4614	0.5017	0.2929	0.2612	0.2427	0.2405	0.4988	0.3769
KOR	0.3438	0.4115	0.3841	0.3836	0.2759	0.3123	0.3436	0.5854	0.4674
MEA	0.1063	0.1044	0.1066	0.1243	0.0862	0.1185	0.1159	0.2814	0.1814
OAM	0.1687	0.1893	0.1897	0.1996	0.1427	0.1941	0.1343	0.4485	0.2241
OAS	0.0520	0.0733	0.0626	0.0700	0.0450	0.0522	0.0661	0.1100	0.0794
RUS	0.0899	0.1586	0.1183	0.1416	0.1361	0.1208	0.0603	0.2223	0.1221
USA	0.0413	0.0508	0.0493	0.0525	0.0337	0.0415	0.0431	0.0912	0.0409
					k_{2i}				
AFR	-0.0004	0.0000	-0.0001	-0.0001	-0.0001	-0.0002	-0.0010	0.0002	0.0004
ANZ	-0.0016	-0.0002	0.0017	0.0002	-0.0003	-0.0025	-0.0047	0.0017	0.0001
BRA	0.0031	0.0010	0.0060	0.0029	0.0026	0.0024	0.0019	0.0056	0.0065
CAN	-0.0001	-0.0005	0.0004	0.0007	-0.0006	0.0001	-0.0001	0.0006	0.0006
CHN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
EUR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000
IND	-0.0001	0.0000	-0.0001	0.0000	-0.0001	-0.0001	-0.0002	0.0000	-0.0001
JPN	0.0002	0.0004	0.0010	0.0002	0.0004	0.0002	-0.0008	0.0010	0.0010
KOR	-0.0013	0.0001	-0.0004	0.0000	-0.0003	-0.0009	-0.0023	0.0010	0.0005
MEA	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000	0.0002	0.0003
OAM	0.0002	0.0000	0.0003	0.0002	0.0001	0.0002	0.0002	-0.0003	0.0002
OAS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0001	0.0001
RUS	0.0000	-0.0001	-0.0001	0.0000	0.0002	0.0002	0.0001	0.0002	0.0004
USA	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
					k_{3i}				
AFR	1.4E-06	5.1E-07	1.3E-06	1.4E-06	7.0E-07	7.4E-07	2.8E-06	5.1E-07	5.9E-07
ANZ	3.2E-05	1.2E-05	2.0E-05	2.3E-05	1.5E-05	2.2E-05	4.6E-05	2.2E-05	3.7E-05
BRA	2.6E-05	1.1E-05	2.7E-05	4.9E-05	1.0E-05	1.6E-05	2.9E-05	1.1E-05	5.0E-05
CAN	1.3E-05	6.8E-06	1.6E-05	1.3E-05	7.0E-06	1.0E-05	1.4E-05	1.1E-05	1.3E-05
CHN	4.2E-09	2.1E-09	3.2E-09	2.4E-09	2.8E-09	2.6E-09	1.9E-09	1.0E-09	2.3E-09
EUR	9.1E-08	3.3E-08	5.0E-08	7.8E-08	3.2E-08	3.8E-08	1.6E-07	6.5E-08	4.8E-08
IND	7.1E-08	4.0E-08	5.1E-08	3.2E-08	3.9E-08	5.5E-08	9.2E-08	3.2E-08	2.5E-07
JPN	6.7E-06	1.8E-06	3.1E-06	3.0E-06	1.8E-06	3.5E-06	6.6E-06	3.5E-06	4.3E-06
KOR	1.4E-05	5.2E-06	9.2E-06	8.7E-06	6.6E-06	9.9E-06	1.5E-05	9.3E-06	1.9E-05
MEA	2.3E-07	1.0E-07	1.4E-07	1.3E-07	8.9E-08	2.0E-07	3.1E-07	1.6E-07	2.2E-07
OAM	6.9E-07	4.5E-07	8.3E-07	8.0E-07	5.9E-07	8.1E-07	7.2E-07	1.8E-06	1.6E-06
OAS	8.5E-08	3.4E-08	7.7E-08	1.1E-07	3.8E-08	5.3E-08	1.4E-07	4.5E-08	8.5E-08
RUS	7.3E-07	4.0E-07	6.5E-07	8.1E-07	3.1E-07	5.8E-07	8.6E-07	4.3E-07	2.0E-07
USA	2.5E-08	9.2E-09	1.6E-08	3.2E-08	1.4E-08	2.2E-08	3.1E-08	1.8E-08	2.0E-08

Column labels refer to modeling teams and row labels refer to model regions. Region keys: global — global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

Figure 7: Marginal abatement cost curves by CEPE - Swiss Federal Institute of Technology (ETH) Zürich

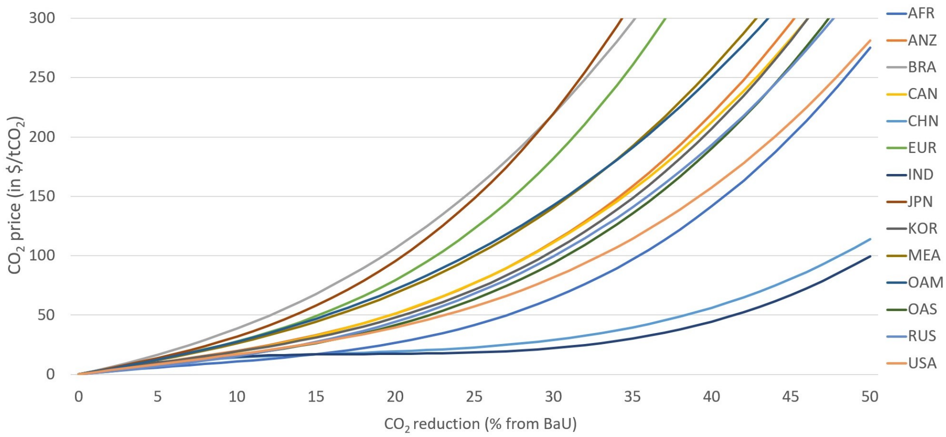


Figure 8: Marginal abatement cost curves by DREAM - Fudan University

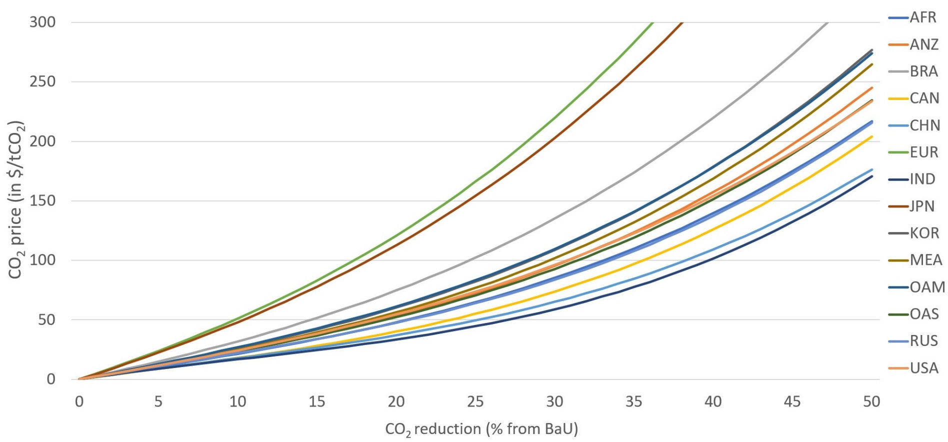
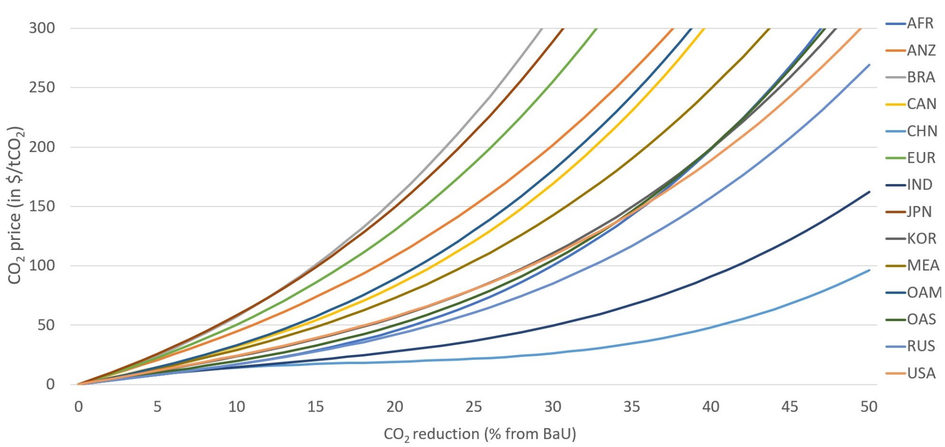


Figure 9: Marginal abatement cost curves by ENVISAGE - Purdue University



Region keys: global — global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

Figure 10: Marginal abatement cost curves by GEM-E3 - European Commission Joint Research Centre (JRC)

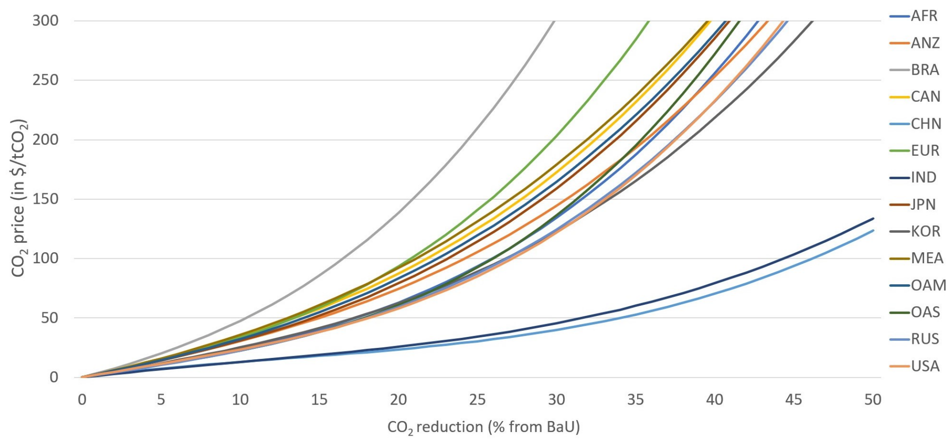


Figure 11: Marginal abatement cost curves by ICES - Euro-Mediterranean Center on Climate Change (CMCC)

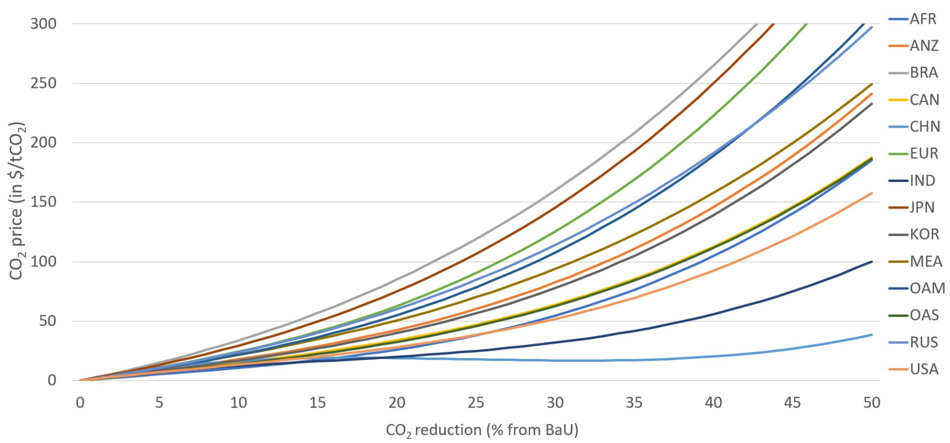
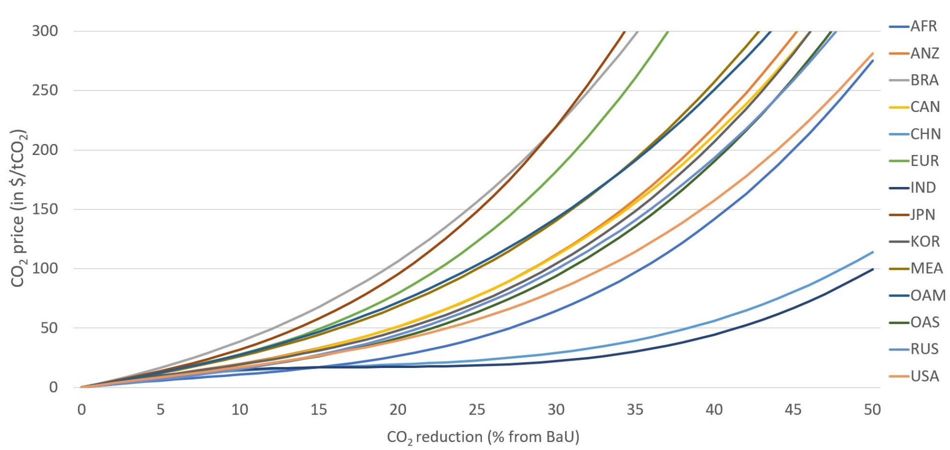


Figure 12: Marginal abatement cost curves by PACE - Centre for European Economic Research (ZEW)



Region keys: global — global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

Figure 13: Marginal abatement cost curves by SNOW - Statistics Norway

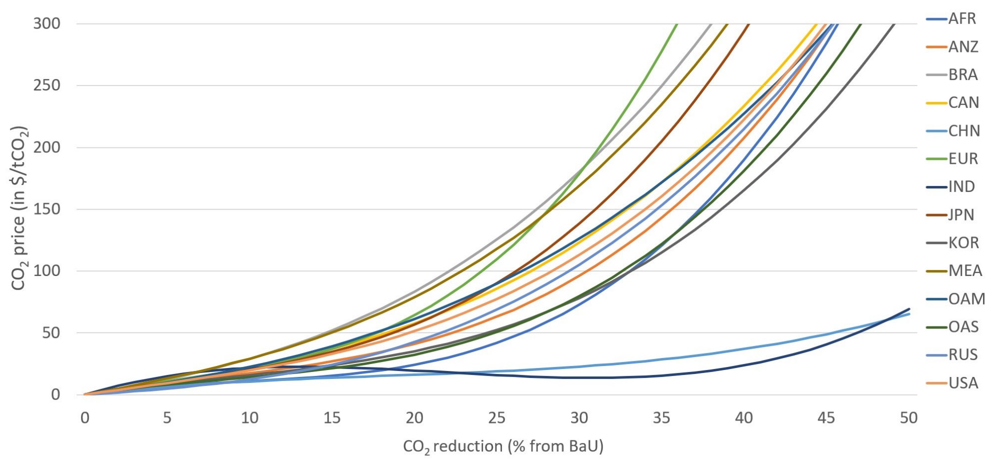


Figure 14: Marginal abatement cost curves by TUB - Technical University (TU) Berlin

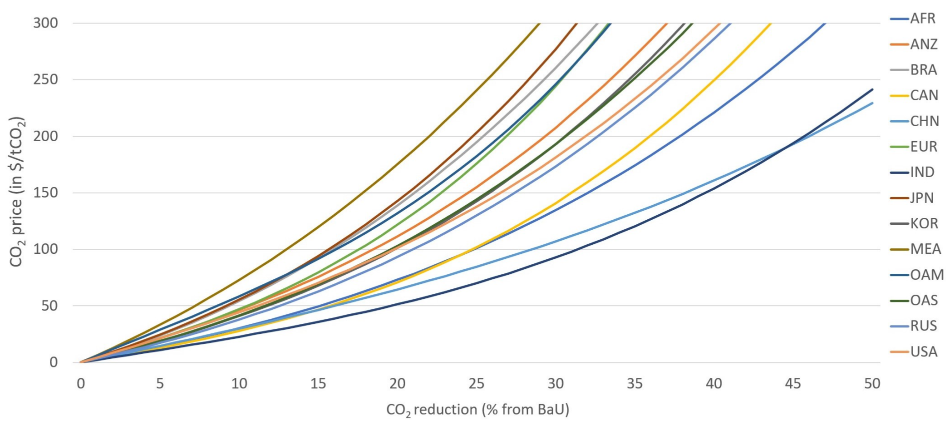
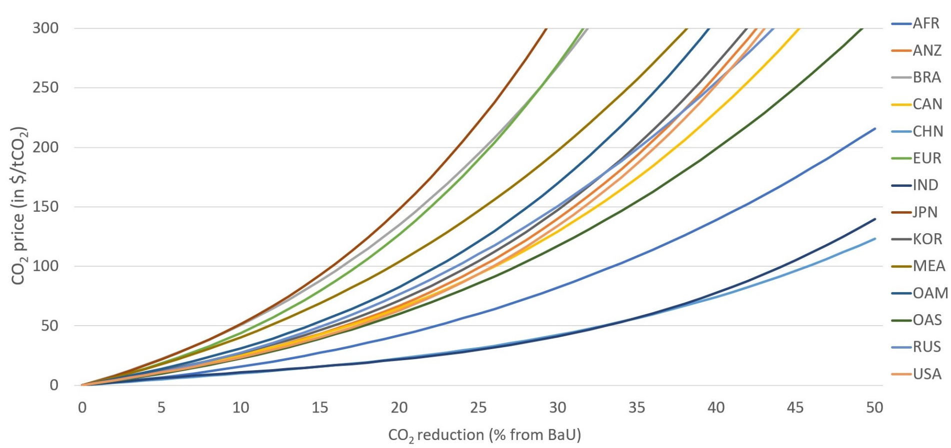


Figure 15: Marginal abatement cost curves by UOL - University of Oldenburg



Region keys: global — global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

Appendix C: Further details on simulation results

NDC constraint in scenario *strategic*

As the negotiations on Article 6 of the Paris Agreement are ongoing for many years, economists are criticizing that the gains from where-flexibility are not exploited. However, if the regions would have chosen emissions allowances right at the beginning before setting national emissions reduction targets, this would have led to "hot air" as low-benefit-of-abatement regions would choose more emissions allowances to increase their revenues from selling them (see also Helm, 2003). Adding the trading of emissions reductions in a second stage after setting NDCs as national targets turns out to be an advantage as it appears reasonable that the NDCs constitute a lower bound for ERCs, i.e., the abatement targets under trading. Thus the constraint that these abatement targets must not fall below the initial NDC abatement levels avoids the hot air problem. To demonstrate the relevance of the NDC constraint for our policy conclusions, we examine how results change if we do not include the constraint. We run additional simulations for a scenario variant which we call *unconstrained* where regions choose their ERCs strategically in their own best interest as in scenario *strategic* but are not constrained in their choice.

Table 8 shows that, without the NDC constraint, regions with a low willingness to pay (Russia, Africa, Middle East, India, China, Australia and New Zealand) choose ERCs which are substantially lower than their NDC abatement levels in order to increase their revenues from selling emissions reductions. Some regions even choose negative ERCs so that their corresponding CO_2 emissions levels then even exceed their BaU emissions (compare Table 2 of the paper), triggering "hot air". The implied CO_2 emissions from the ERC choices of these regions are higher than in scenario *strategic*, leading to more climate damages, which raises the willingness of regions with high marginal benefits to increase their ERCs even more than in scenario *strategic* (USA, Japan, Europe, Canada, Other Asia, Other Americas). However, this is more than compensated by the low-benefit-of-abatement regions which choose lower ERCs, so that the global emissions level in *unconstrained* is higher than in *notrade*. Conversely, the NDC constraint in *strategic* results in the

Table 8: Comparison of scenario *strategic* with NDC constraint and variant *unconstrained* without NDC constraint

Region	CO_2 emissions levels corresponding the ERCs			CO_2 reduction	
	notrade	*unconstrained*	*strategic*	*unconstrained*	*strategic*
	Mt of CO_2	Mt of CO_2	Mt of CO_2	% from BaU	% from BaU
global	28567.9	29080.6	24757.8	8.7	22.3
AFR	1211.3	3636.6	1211.3	10.5	22.0
ANZ	426.0	1298.1	426.0	7.0	16.7
BRA	370.7	0.0	0.0	4.7	11.0
CAN	432.5	0.0	123.6	7.7	17.4
CHN	7764.3	8659.2	7690.7	11.7	34.6
EUR	2869.8	0.0	211.9	5.5	12.6
IND	2916.9	4056.9	2916.9	11.4	29.7
JPN	847.4	6.3	844.4	5.1	11.8
KOR	393.4	0.0	0.0	7.5	17.5
MEA	2108.4	4034.6	2108.4	5.7	13.5
OAM	1240.3	1158.3	1240.3	5.9	13.9
OAS	2667.5	1230.4	2667.5	8.5	19.1
RUS	1403.7	4065.3	1403.7	8.3	17.7
USA	3915.7	934.9	3913.0	7.8	18.7

Region keys: global — global average; AFR — Africa; ANZ — Australia and New Zealand; BRA — Brazil; CAN — Canada; CHN — China; EUR — Europe; IND — India; JPN — Japan; KOR — South Korea; MEA — Middle East; OAM — Other Americas; OAS — Other Asia; RUS — Russia; USA — United States.

global abatement being more than doubled compared to *notrade*. This is also the case for the abatement of each region (see Proposition 2 of the paper) and illustrates the importance of the NDC constraint for the high global abatement level in *strategic*. The reasoning behind is that the NDC constraint avoids the "hot air" emerging in the variant *unconstrained* while some regions with high benefits of abatement go beyond their NDC ambition. Also, the CO_2 price in scenario *strategic* (48.74\$/tCO_2) is more than twice as high as in *unconstrained* (17.38\$/tCO_2), leading to more regions selling emissions reductions compared to variant *unconstrained* (see Proposition 3 of the paper).

Business-as-usual projections

The costs of complying with future emissions constraints depend on the structural characteristics of an economy exhibited in a hypothetical business-as-usual (BaU) situation without such emissions constraints in place (Dellink et al., 2020). The BaU determines how *nominal* NDCs, stated as a cap of historical emissions, translate into *effective* abatement requirements, i.e., the difference between the projected business-as-usual emissions and the emissions cap. At the same time, the BaU captures the ease of emissions abatement for some target year via the slope of region-specific marginal abatement cost curves. Our central case simulations draw on BaU projections for 2030 from EMF36 which are based on common data inputs from the International Energy Outlook (IEO, EIA, 2017). EMF36 in addition provides an alternative BaU drawing upon another official and widely-used data source, the World Energy Outlook (WEO, IEA, 2018). In our sensitivity analysis, we run simulations with data inputs for all nine modeling teams using the alternative business-as-usual projections. Figure 16 visualizes the implications of alternative BaU projections for global CO_2 emissions reduction across the four climate policy regimes.

As we can see, WEO just implies slightly lower mean global CO_2 reductions for each climate policy scenario, meaning that the ranking of climate policies in terms of their environmental effectiveness remains robust both in qualitative as well as in quantitative terms.

Figure 16: Global CO_2 emissions reduction with IEO and WEO projections

Note: Box–Whisker plot shows the median (line), mean (cross), first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range. Dots indicate outliers.

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