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Economic gains from global cooperation in fulfilling climate pledges

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ABSTRACT

Mitigation of CO_2 emissions is a global public good that imposes different regional economic costs. We assess the distributional effects of cooperative versus non-cooperative CO_2 markets to fulfil the Nationally Determined Contributions (NDCs), considering different CO_2 permit allocation rules in cooperative markets. We employ a global computable general equilibrium model based on the GTAP-9 database and the add-on GTAP-Power database. Our results show the resulting winners and losers under different policy scenarios with different permit allocation rules. We see that in 2030, we can obtain gains as high as $106 billion from global cooperation in CO_2 markets. A cooperative CO_2 permit market with equal per capita allowances results in considerable monetary transfers from high per capita emission regions to low per capita emission regions. In per capita terms, these transfers are comparable to the Official Development Assistance (ODA) transfers. We also disaggregate the mitigation costs into direct and indirect shares. For the energy-exporting regions, the largest cost component is unambiguously the indirect mitigation costs.

1. Introduction

It is widely recognized that climate change is caused by anthropogenic interference with the Earth's climate system and will have a massive impact on the environment, i.e., it will affect precipitation, temperatures, weather patterns, sea levels, acidity, and biodiversity (IPCC, 2014). Of particular concern is that climate change is expected to have disproportionate effects on regions where severe poverty is already widespread. Therefore, social justice and equity are considered core principles of 'climate-resilient development pathways for transformational social change' (Roy et al., 2018).

Starting from the experiences with the Kyoto Protocol, it has been clear that reaching an effective international climate agreement is complex due to international politics. The Kyoto Protocol was a top-down agreement meaning that the global emission reduction target was set. Subsequently, countries negotiated on how this global target would be distributed among them. Unlike this approach, the member states of the Paris Agreement followed bottom-up negotiations, where countries voluntarily committed to targets, formally known as (Intended) Nationally Determined Contributions (NDCs), without a pre-determined global emission reduction target. Additionally, under Article 6 of the Paris Agreement, countries were also encouraged '… to pursue voluntary cooperation in the implementation of their nationally determined contributions to allow for higher ambition in their mitigation and adaptation actions and to promote sustainable development and environmental integrity' (UNFCC, 2015).

In the literature, studies that analysed the economic impacts of different emission reduction targets have shown that potential gains could be achieved by cooperation between countries. A cross-model review conducted by Hof et al. (2009) concludes that across literature, a fragmented regime is more costly than a universal regime even though a fragmented regime with 'a coalition of the willing' is more likely to be politically feasible. In the context of the first NDC targets pledged by countries, modelling studies (like Akimoto et al., 2017, Aldy et al., 2016, Aldy et al., 2017, Dai et al. (2017), Fujimori et al. (2016), Hof et al. (2017), Liu et al. (2020) and Vandyck et al. (2016)) have estimated regional carbon prices and Gross Domestic Product (GDP) impacts of fulfilling the NDC targets. Akimoto et al., 2017 and Fujimori et al. (2016), quantified the gains from cooperative action by modelling scenarios with and without cooperation. Fujimori et al. (2016) use the AIM-CGE model and estimate the gain in global GDP from cooperation to be 0.3 percentage points higher than unilateral action by countries. Akimoto et al., 2017 use the DNE21+ model and estimate that the global GDP losses would be reduced by 0.12 percentage points if countries

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cooperated to meet the NDC targets. In contrast to both Akimoto et al., 2017 and Hof et al. (2017), we derive national abatement costs in a general equilibrium framework and thus, take spill-over effects between countries resulting from trade into account. Akimoto et al., 2017 and Hof et al. (2017) estimate only direct national abatement costs, e.g., national costs induced by emission cuts in their own country, while indirect abatement costs resulting from emission cuts in other countries are neglected.

Studies have also quantified how regional targets differ under different effort-sharing approaches. The stylized practice for modelling global cooperation is through an international emissions trading scheme (ETS). For designing an ETS, a fundamental question is related to the regional distribution of emission permits. Since we model a social justice scenario with full global cooperation under the assumptions of carbon egalitarianism, the allocation of permit rights is of interest to us. Höhne et al. (2014) present a cross-study comparison of 40 studies using seven categories of effort sharing methods based on equity principles of responsibility, equality, and capability. They conclude that targets based on equity principles and equal per capita emission rights lead to stricter emission reductions in OECD[1] countries and, in some cases, even negative permits in 2030 relative to 2010 emission levels. Höhne et al. (2014) also see that there could be large monetary transfers between regions in a global, cost-effective case if 'equal cumulative per capita emissions' and 'responsibility, capability and need' are used for effort sharing. van den Berg et al. (2020) analyse the implication of a wide range of effort-sharing approaches on national emission pathways. While van den Berg et al. (2020) focus on the impact of different effort sharing approaches on national emissions pathways, they do not yet include analysis of the impact on abatement costs and national shares in total abatement costs. Compared to van den Berg et al. (2020), our paper focuses on national and total abatement costs and the impact that different economic mechanisms to implement NDC have on them.

Against this background, our paper aims to analyse the economic impacts of cooperative and non-cooperative action in reaching the initial NDC targets, considering different CO_2 permit allocation rules in cooperative markets. We provide a general equilibrium analysis of regional and sectoral costs and benefits, CO_2 permit allocations, and the monetary transfers that would result from the three different policy scenarios. We contribute to the existing literature that estimates the gains of cooperation by including the national and international cost spill-overs through the CGE framework. Moreover, we also contribute to the literature on the impact of different effort-sharing approaches by calculating the abatement costs in the CGE framework under two effort-sharing approaches, namely allocating permit rights based on national shares in emission reduction pledges versus allocating permit rights based on national shares in total population.

The rest of the paper is organized as follows. Section 2 describes the DART model. Section 3 defines the scenarios, followed by the analysis of the results in Section 4. Finally, we conclude with a discussion of the results in Section 5.

2. Methodology

2.1. Model description

The CGE setup is a unique framework that incorporates the inter-linkages between different sectors within an economy and other economies through international trade. Such a design can holistically evaluate the impacts of policies ex-ante, and, therefore, the CGE approach is widely used when informing policymakers. The Dynamic Applied Regional Trade (DART) model is a numerical multi-sectoral, multi-regional recursive dynamic CGE model and has been applied to study international climate policies (e.g., Peterson and Klepper, 2007; Weitzel et al., 2012) and biofuel policies (Calzadilla et al., 2014). The model is based on the GTAP-9 database (Aguiar et al., 2016).

Our study focuses on assessing the impact of climate policies through CO_2 pricing, and such policies typically have direct implications for the energy sectors. Therefore, we use the GTAP-Power supplementary database (Peters, 2016), which provides comprehensive data about different technologies in the power sector and consists of five types of renewable and three types of fossil-based technologies. To our knowledge, this is the first study that uses the GTAP–Power database to conduct such an analysis thus, adding novelty to our results. The GTAP-power database differentiates between the baseload and peak load for gas, oil, and hydro technologies. Our study aggregates the base and peak load technologies for each of these three sectors and does not differentiate between them. For this study, we aggregate the original dataset to 20 sectors and 24 regions as listed in Table A1 and Table A2 in the Appendix. Further, since we want to model climate policies, data on CO_2 emissions is also included in DART, which captures the emissions generated by the burning of fossil fuels for energy use in production and consumption activities. In the 2011 (base year of GTAP9 database), CO2 emissions form the use of fossils account for about 71% of all GHG emissions.

With regard to the modelling of emissions in DART, we only consider CO_2 emissions from burning fossil fuels and exclude other sources of GHG emissions like emissions from LULUCF, GHGs other than CO_2 and GHG emissions from production processes. Naturally, to maintain consistency in our analysis the CO_2 mitigation targets used in our policy scenarios exclude LULUCF pledges made by countries (details in Section 2.2). The exclusion of the other GHGs reduces mitigation flexibility in our model since multi-gas flexibility lowers abatement costs in regions (Thube et al., 2021). Furthermore, the omission of process emissions could lead to an over-estimation of abatement costs from certain sectors (like cement) where emissions from production processes are high though the potential bias depends on the relative share of CO_2 emissions that have been ignored.

The core structure of the DART version used in this paper is identical to the previous studies (Klepper et al., 2003; Springer, 1998). As in all CGE models, the DART model consists of behavioural equations that describe the economic behaviour of each agent in the model based on microeconomic theory. Identity equations impose constraints to ensure that supply matches demand in factor and commodity markets, and macro closure rules determine the macroeconomic equilibrium conditions of the model. DART is a recursive dynamic model, and the yearly static equilibria are linked by exogenous assumptions of population change, technological progress, savings, and capital depreciation. There are three primary factors of input; land, labour, and capital. Land is a homogenous input for the agricultural and forest sectors only.

Labour is determined exogenously in the model based on the forecasts from OECD (2019) for the regional working population. Capital is modelled as putty-clay such that new capital complements the existing sectoral capital and, new investments are distributed to sectors based on the efficiency of the existing capital. Savings rate as a share of GDP is exogenously defined based on the OECD (2019) projections. Trade is modelled under Armington assumptions meaning that regions are connected via bilateral trade flows, where domestic and foreign goods are imperfect substitutes and distinguished by country of origin. Armington trade elasticities[2] and all income elasticities are taken from the GTAP-9 (Aguiar et al., 2016). The time horizon of the model is up to 2030. The production in every sector is represented by a nested constant elasticity of substitution (CES) function. The nesting of non-energy sectors and the power sector with updated elasticities are shown in Fig A1 and Fig A2 in

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[1] Here OECD countries consist of North America, Western Europe, Japan, Australia, and New Zealand.

[2] An upper limit of 12.8 is imposed on the Armington trade elasticity for sector GAS. Additionally, we assume CRU has identical trade elasticities as sector GAS. The rest of the trade elasticities are exactly as in the GTAP database.

the Appendix, respectively.

2.2. Calculation of the NDCs

There are differences in how commitments are submitted by countries, e.g., through differences in the target year, target sectors, greenhouse gas coverage, conditionality on financial and technological support, and the reference emission pathway (King & van den Bergh, 2019). Moreover, the NDCs have been framed relative to a diverse set of benchmarks – base year, GHG coverage, sector and source-specific targets, and target years. This forms a challenge when defining consistent reduction targets by country to be used for modelling. Different approaches have been used to aggregate these commitments to a single regional emission reduction target and we use the NDC targets as calculated in Böhringer et al. (2021), which is based on the approach proposed in Kitous et al. (2016). In essence, the aggregation of commitments is done as follows.

Kitous et al. (2016) convert all NDC targets for the energy sector (including renewable targets and sectoral targets) into policy measures using an energy system model. Furthermore, for countries that have pledged a GHG target, they calculate the CO_2-only reduction targets using a correction factor. The NDC targets are calculated as the net CO_2 emission reductions that regions would experience if all the targets in the energy sector (excluding CO_2 changes from LULUCF) are implemented as policies. In our analysis, we use this net CO_2 reduction as the equivalent NDC target that is achieved with a uniform (regional or global) carbon price.

Other commitments like reducing emissions from land use change, specific targets for green technologies or reduction targets for non-CO_2 GHGs are not modelled in our study. Thus, The regional mitigation targets are shown in Table 2, and they correspond to the conditional NDC pledges as derived using Böhringer et al. (2021). In the rest of the paper, NDC targets refer to the first round of conditional NDC pledges committed by countries (i.e. before 2020).

3. Description of scenarios

We define three policy scenarios in addition to the baseline. The policy scenarios differ in how climate policies are implemented and, thus, the implicit degree of cooperation between regions. The climate policies are enforced by imposing a CO_2 price on fossil fuels in production and consumption activities from 2021 onwards in all regions. The regional emission reduction goals are based on the emission reduction targets committed by countries in their NDC pledges (UNFCC, 2015). The total global emissions pathway is identical in the three policy scenarios, albeit with differences in the underlying fairness principle. By having the same global emission reduction across all the policy scenarios, the policy shocks in the scenarios remain comparable. This setup allows us to assess the distributional effects of costs across regions based on differences in cooperation between regions and permit allocation rules. Table 1 provides an overview of the scenarios.

Scenario **BASE** acts as the reference against which outcomes from the policy scenarios are compared. Our baseline scenario carries forward the GTAP-9 base year data from 2011 until 2030 by including projections of important drivers such as population growth, savings rate, and labour growth taken from the OECD (2019) forecasts. The DART baseline scenario is calibrated to match the regional GDP growth rate from OECD (2019) and the regional CO_2 emissions growth rate from IEA (2018). Given that the results from the policy scenarios are compared to BASE, it is essential to understand the global and regional economic trends in BASE.

Table 1
Overview of scenarios.

	NDC targets	Global emission reduction in 2030 relative to BASE	Geographical coverage of permit market	Degree of cooperation
BASE	no	–	none	–
REG	yes	11.8%	Regional	No cooperation
GLOB	yes	11.8%	Global	Full cooperation
PERCAP	yes	11.8%	Global	Full cooperation with carbon egalitarianism

Regional GDP is increasing in all the world regions with different growth rates. Following OECD (2019), globally, GDP increases by 65% in 2030 relative to 2011. GDP growth is the highest in India and China and, lowest in Russia. Global population increases by 22% in 2030 relative to 2011, with the highest growth forecast in Sub-Saharan Africa. Global emissions increase by 20% from 2011 to 2030 with regional differences. As a result, per capita emissions in 2030 vary between $0.5tCO_2$ in Sub-Saharan Africa to $13.3tCO_2$ in the USA. In the context of international commodity trade, in BASE the net exports of coal, gas, and crude oil increase by 30%, 24%, and 20%, respectively. The net exporters of energy are Sub-Saharan Africa, Canada, the Former Soviet Union (except Russia), Central- and South America, Middle East-North Africa, EFTA, and Russia. The baseline growth rates for the regional GDP, population, and emissions are shown in Table A3 in the Appendix.

In scenario **REG**, we model the regional reductions in emissions based on NDCs by unilateral action through cost-optimal national CO_2 prices. A linear emission reduction pathway is calculated to reduce emissions from baseline values in 2021 to meet the target values in 2030 via an endogenously determined yearly regional CO_2 price.

In scenario **GLOB** the cooperative implementation of the NDCs is modelled via a global CO_2 permit market. We assume that the yearly regional permit rights between 2021-30 correspond to the regional emission reduction pathway as calculated in scenario REG. However, instead of regional CO_2 prices, there is a global permit market where regions trade, and the model endogenously determines the corresponding global CO_2 price.

Scenario **PERCAP** is an adaptation of the scenario GLOB. This scenario is based on the principle of carbon egalitarianism, which means that each individual has an equal right to emit CO_2. This assumption implies that from 2021 onwards, the yearly regional CO_2 emission rights are distributed in proportion to the regional population, such that the global emissions are reduced according to the cumulative NDC pledges of all regions. Therefore, this scenario also represents cooperative action by the regions, although with additional fairness because of the carbon egalitarianism assumption.

Unlike REG, in scenarios COOP and PERCAP the regions trade permits. Thus, the resulting regional emissions could differ from their NDC pathway. We expect that regions that sell emission permits reduce more emissions than their NDC targets, while the permit buying regions will reduce fewer emissions than their NDC. We assume there are no transaction costs for the allotment and trade of permits. Further, the regional revenues from the trade of permits are transferred to the representative consumer (public and private) as a lump sum amount.

4. Results

We continue discussing how the regional and sectoral impacts differ from the three different policy designs described above. In the presented results, real GDP changes are calculated in \$2011. Welfare impacts refer to percentage Hicks Equivalent Variation relative to BASE. All the results discussed are relative to the BASE scenario for the year 2030, and it also coincides with the time horizon of the NDC targets. The only difference in reporting the results arises in Fig. 4, where accumulated discounted welfare values are shown for the policy duration, i.e., 2021–2030.

4.1. Impact on CO_2 prices and CO_2 market

As indicated in Section 3, the total global reduction in CO_2 emissions is the same across all the scenarios, while the regional emission cuts vary across the scenarios. Fig. 1 shows the resulting CO_2 emission reduction and the emission allocated to each region according to the scenario assumptions. By design, the emission reductions under REG are identical to the regional emissions under the NDC pathway. Relative to BASE, the largest reductions are in Pacific Asian regions, EFTA, Benelux, and the Former Soviet Union (except Russia). At the same time Russia, Australia, New Zealand, and India have the lowest emission reduction targets. The corresponding regional CO_2 price required to achieve these regional emission reductions is shown in Table 2.

Compared to REG, costs regions either decrease or increase their net emissions reductions under GLOB and PERCAP depending on the regional mitigation. This implies that regions with regional CO_2 prices lower than the harmonized global CO_2 price (like China, India, Russia, Sub-Saharan Africa) mitigate more than their unilateral targets and sell the permit rights to regions with CO_2 prices higher than the global price. Regions with CO_2 prices above the global CO_2 price (like Central-South America and the Middle East and North Africa) can also sell permits to regions with even higher regional CO_2 prices. However, this would only happen if the regions with lower CO_2 prices cannot meet the permit demand. Generally, permit trade is beneficial to both the seller and buyer of permits and minimizes the total cost of mitigation while also achieving the global climate target. To understand which regions are the buyers and sellers of permits, we elaborate on the resulting CO_2 prices in REG and GLOB.

Regional abbreviations: AFR-Sub Saharan Africa, ANJ- Australia, New Zealand and Japan, BLX- Benelux, BRA- Brazil, CAN-Canada, CHN-China and Hong Kong, DEU- Germany, EFTA- European Free Trade Agreement members, FRA-France, FSU- Former Soviet Union (Except Russia), GBR- United Kingdom and Ireland, IND- India, LAM- Central- and South America, MEA- Middle East and North Africa, MED- Mediterranean Europe, PAS- Pacific Asia, RUS- Russia, SCA- Scandinavia, USA-the United States of America.

In 2030, CO_2 prices in scenario REG range from $6.5/t$CO_2$ in Russia to $236.4/t$CO_2$ in EFTA countries (see Table 2). The weighted average price of CO_2 in the EU is $80.4/t$CO_2$, while the weighted global price is $42/t$CO_2$.[3] Under global permission markets, there is a single harmonized global price of CO_2 in GLOB and PERCAP. These prices are within the range of the regional prices and are equivalent to $16.2/t$CO_2$ and $16.3/t$CO_2$, respectively.[4] Comparing the global CO_2 prices from GLOB and PERCAP with the weighted global CO_2 price from REG indicates that the CO_2 price needed for abating the same amount of global emissions is significantly lower when regions cooperate rather than when they act non-cooperatively.

To estimate the overall potential monetary gains from cooperation, we compare the total mitigation costs across the scenarios by multiplying the CO_2 prices and the total emissions abated at this price. In REG, the total global costs are the highest and amount to around $172 billion in 2030 alone. Comparatively, the global costs are close to $66 billion and therefore around 60% lower when regions cooperate in scenarios GLOB and PERCAP. This difference in the total mitigation costs is significant and highlights how Article 6 of the Paris Agreement could be a powerful tool for cost-efficient climate policy. If supported by all countries, cooperative action can reduce about $106 billion in global costs in 2030. Possibly further gains can be generated from recycling the revenue to enhance mitigation efforts, leading to even further reductions in global emissions without incurring any additional costs. Studies like Edmonds et al. (2019) estimate that recycling cost savings towards enhancing pledges could lead to an additional global abatement of an additional 50%, approximately equivalent to about 5GtCO_2 in 2030. While global costs for climate policies are reduced with global permit markets, it does not necessarily reduce costs for single regions (see section 4.3).

Fig. 2 and Fig. 3 show the difference between allocated permits and actual emissions across regions in scenario GLOB and PERCAP, respectively. The regions above the x-axis are sellers of permits, while regions below the x-axis are buyers of permits.

In scenario GLOB, we typically see that regions with regional CO_2 prices lower than the global CO_2 price of $16.2/t$CO_2$ are sellers of permits (Fig. 2). Accordingly, China, India, Russia, and Sub-Saharan Africa are sellers of permits. From 2021 to 2030, China is the largest seller of permits, and its market share remains close to 50% over all the years. Central- and South America and, Middle East and North Africa provide two interesting cases that switch from sellers to buyers of permits over time. With a starting CO2 price of $2.4/t$CO_2$ and $2.8/t$CO_2$ in 2021 the regional CO_2 prices in these regions increase to $20/t$CO_2$ and $24/t$CO_2$, respectively. These prices happen to be the lowest prices among the countries with CO_2 prices above the global CO_2 price of $16.2/t$CO_2$. Therefore, these two regions can trade at the fringe of the permit market by selling permits to regions with even higher regional CO_2 prices. Over the years, their market share shrinks from 5% to zero, and eventually, in 2030, both these regions are buyers of permits. The largest buyer of permits in GLOB is the Pacific Asia region which purchases close to 50% of the traded permits because it strongly increases emissions in BASE, a high emission reduction target (see Fig. 1), and a relatively high CO_2 price of $62/t$CO_2$.

We observe a change in the grouping of buyers and sellers in scenario PERCAP from that in GLOB (see Fig. 3). In PERCAP, the criterion for whether a region is a seller or buyer of permits indeed directly depends on the annual rate of regional population growth and the average global per capita emissions. Thus, regions having higher per capita emissions than the global average are buyers of permits, while regions with per capita emissions lower than the global average are sellers of permits.

From 2021 to 2030, the average global per capita emissions are reduced from 4.1tCO_2 to 3.5tCO_2 per year. Sub-Saharan Africa, Brazil, India, Central- and South America, and Pacific Asia are five regions that throughout this period have regional per capita emissions lower than the global average. As a result, these regions are sellers of permits in the PERCAP scenario. Sub-Saharan Africa has the highest growth in population from 2011 to 2030 in the baseline. Therefore, according to the allocation rule, it also receives the highest share of permits each year from 2021 onwards. However, the emissions in Sub-Saharan Africa do not increase at the same rate, and as a result, it ends up being the largest seller of permits and consistently has a market share of about 50% each year.

Brazil and Pacific Asia are buyers of permits in GLOB, while in PERCAP, they are sellers of permits because their per capita emissions are lower than the global average. An interesting turn is seen in China, which changes from being the largest seller of permits in scenario GLOB to being the second-largest buyer of permits by buying 30% of the total permits sold in scenario PERCAP because in 2030, China's per capita emissions are 6.1tCO2. Therefore, to fulfil the demand for emissions, China buys permits on the market. The largest buyer in PERCAP is unsurprisingly the USA since it has the highest per capita emissions of 11.2tCO_2 per year in 2030.

The results from scenarios GLOB and PERCAP show that market design and the fairness principle underlying the allocation of permits can lead to different outcomes regarding which regions buy or sell in permit trade. In addition, the global size of the market and the number of permits traded considerably varies based on the initial allocation of permits. In 2030, the total number of permits traded in scenario PERCAP embodies 8.8 billion tCO_2 which is more than four times what is traded in scenario GLOB. The resulting magnitude of the financial market

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[3] The weighted global average price is calculated by weighing the regional CO_2 price of each region by the share of emission reduction in overall global emission reduction. A similar method is used for calculating the weighted average EU CO_2 price.

[4] Though the quantity of global permits is identical in GLOB and PERCAP, the general equilibrium effects of income generated through permit trade differ. Thus, the CO_2 prices are similar but not identical in these two scenarios.

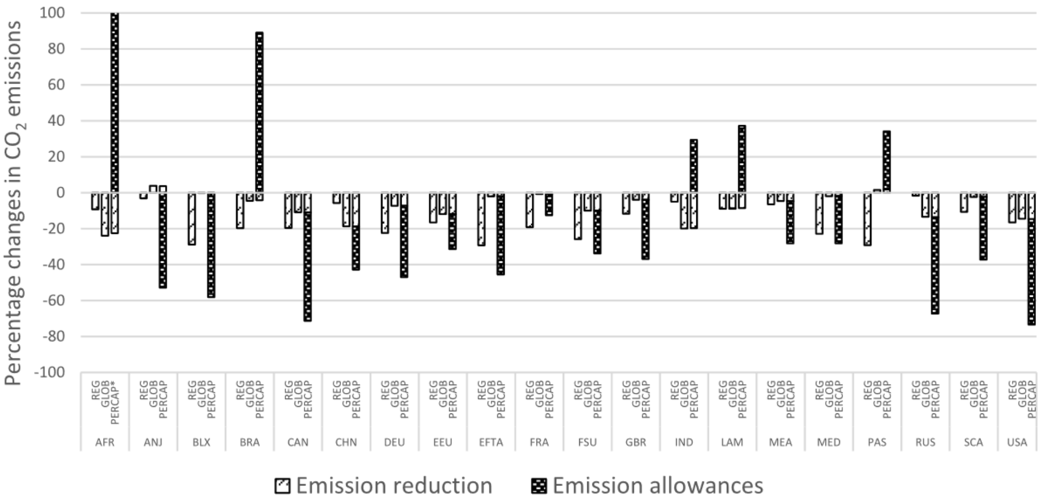

Fig. 1. Allocated and realised CO_2 emission reductions as percentage changes relative to baseline in 2030. The allocated emissions in GLOB are the same as the emission reduction achieved in REG. *Note that for AFR the allocated emission rights are higher in PERCAP relative to baseline by 619% in 2030 but to maintain the readability of the graph the y-axis is limited to 100.

Table 2
Regional percentage changes in macroeconomic variables across scenarios relative to BASE in 2030.

	Allowances in 2030 (in GtCO2)		NDC for 2030 (%)	CO_2 price (per tCO2)	GDP (%)			Welfare (%)			Energy production (%)		
	GLOB	PERCAP	ALL	REG	REG	GLOB	PERCAP	REG	GLOB	PERCAP	REG	GLOB	PERCAP
AFR	654	5176	9.2	10.5	−0.7	−0.3	3.4	−1.6	−0.7	7.7	0.1	−2.5	−0.8
ANJ	1237	602	3.1	29.4	−0.1	−0.2	−0.3	−0.4	−0.6	−1.3	0.0	0.4	0.4
BLX	192	113	28.8	162.8	−0.2	−0.1	−0.1	−0.7	−0.2	−0.5	−8.6	−0.9	−0.8
BRA	345	812	19.7	72.9	−0.1	0.0	0.3	−0.3	−0.1	1.2	−2.8	−0.6	−0.6
CAN	423	151	19.6	30.1	−0.5	−0.3	−0.6	−1.8	−1.1	−2.0	−4.0	−2.3	−2.4
CHN	8599	5218	6.7	12.0	0.2	0.1	−0.4	0.2	0.2	−0.6	0.4	−0.9	−1.0
DEU	453	310	22.4	41.6	0.2	0.1	0.0	0.7	0.3	0.0	−2.2	−1.1	−1.1
EEU	484	398	16.5	25.5	0.2	0.0	−0.1	0.6	0.1	−0.1	−0.9	−0.7	−0.8
EFTA	75	58	29.2	236.4	−1.2	−0.4	−0.4	−4.3	−1.4	−1.4	−8.3	−0.8	−0.7
FRA	249	270	19.2	113.3	−0.1	0.0	0.1	−0.4	0.2	0.3	−6.0	−0.7	−0.7
FSU	643	574	25.8	34.6	−1.2	−0.7	−0.8	−2.6	−1.5	−1.8	−3.4	−1.3	−1.3
GBR	396	283	11.8	41.0	0.0	0.0	−0.1	0.1	0.0	−0.2	−0.9	−0.5	−0.5
IND	3937	5365	5.0	13.7	1.2	0.9	1.6	1.7	1.2	2.2	1.2	−0.3	0.0
LAM	1171	1763	8.9	20.4	−0.3	−0.2	0.2	−0.9	−0.4	0.4	−2.9	−2.6	−2.5
MEA	2882	2212	6.4	24.4	−1.0	−0.3	−0.5	−2.2	−0.7	−1.1	−2.9	−2.2	−2.3
MED	516	481	22.9	109.5	−0.2	0.0	0.0	−1.5	0.3	0.1	−4.6	−0.8	−0.9
PAS	2595	4915	29.2	62.3	−0.1	−0.2	0.5	−0.2	−0.4	1.0	−4.2	−0.8	−0.7
RUS	1531	510	1.7	6.5	−2.2	−0.8	−1.8	−19.4	−7.0	−15.2	−0.8	−2.0	−2.1
SCA	121	85	10.7	52.9	0.0	0.0	0.0	0.0	0.0	−0.1	−1.2	−0.4	−0.4
USA	4099	1309	16.6	19.1	−0.1	−0.1	−0.4	−0.4	−0.4	−1.4	−3.3	−3.2	−3.3
WORLD	30603	30603	11.8	42.0	−0.13	−0.05	−0.04	−0.32	−0.11	−0.02	−1.8	−1.3	−1.3

Note: The sensitivity of the results was checked by performing simulations with doubled and halved Armington elasticities. The key results of global gains from cooperation in GDP (between 0.09 and 0.12% in GLOB and between 0.01 and 0.02% in PERCAP) and welfare (between 0.2 and 0.3% in GLOB and between 0.08 and 0.13% in PERCAP) hold. Detailed results are available upon request from authors.

arising from the permit trade in 2030 is around \$33.8 billion and \$144 billion in GLOB and PERCAP, respectively.

Apart from this, in scenario GLOB, the CO_2 market expands in size with each year because the historical trends of emissions are essentially carried forward in the future regional trends. Consequently, regions that emitted more than others until 2020 continue to do so by simply buying permits from regions that have emitted less in the past. On the contrary, the CO_2 market in scenario PERCAP contracts in size over the years because of the permit allocation mechanism. The less emission-intensive regions are typically the developing regions; therefore, they receive more emission permits in scenario PERCAP than in GLOB. Since the global CO_2 price remains the same in GLOB and PERCAP, the market size and the corresponding revenues from selling these permits are much higher in PERCAP than in GLOB. This increase in CO_2 revenues leads to welfare improvements in the permit selling regions. Therefore, over the years, we see an increase in permit retention by these sellers to meet domestic needs, leading to a relatively smaller permit market.

4.2. Global economic effects

Similar to the effects on CO_2 markets, the macroeconomic effects in the three policy scenarios also diverge. The global GDP is reduced by 0.13% (\$155.6 billion) in scenario REG, by 0.03% (\$55.7 billion) in scenario GLOB and by 0.04% (\$51.3 billion) in scenario PERCAP. Undoubtedly, the global losses in GDP are much lower when regions cooperate than when regions act non-cooperatively. In scenario REG, there is a contraction of the global production by 0.3%. On the contrary, in GLOB and PERCAP scenarios, global production increases by 0.1%

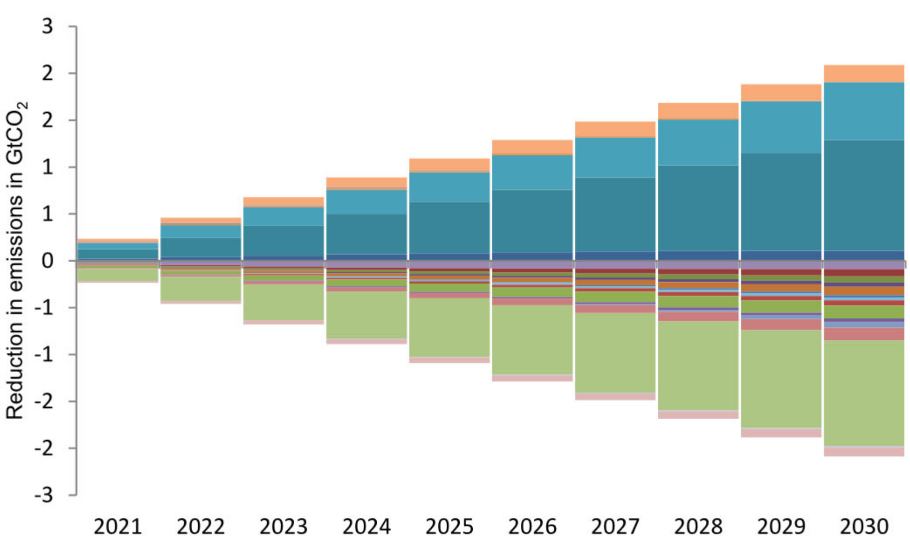

Fig. 2. Difference between allocated permits and observed emissions in scenario GLOB. *Regions above the x-axis are sellers of permits and regions below the x-axis are buyers of permits.*

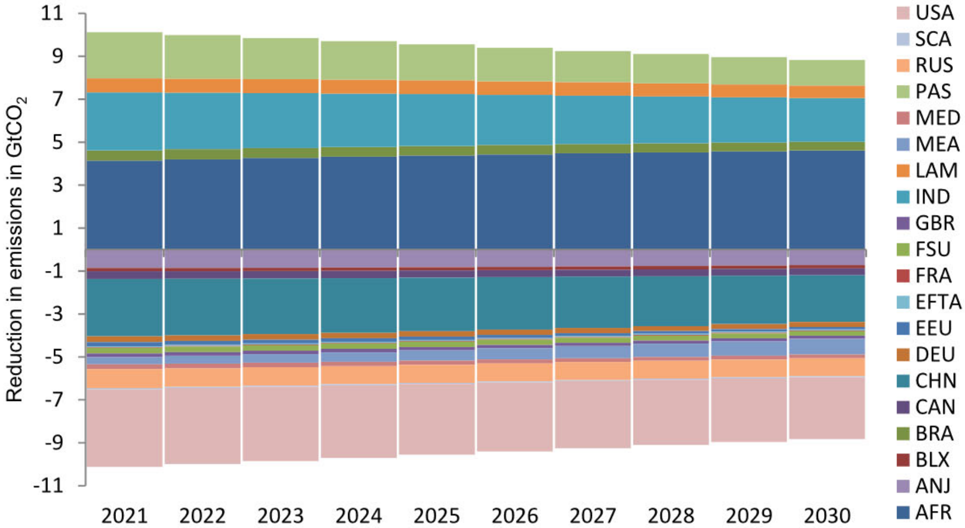

Fig. 3. Difference between allocated permits and observed emissions in scenario PERCAP. *Regions above the x-axis are sellers of permits and regions below the x-axis are buyers of permits.*

and 0.01% despite reducing global CO_2 emissions by the same amount as in scenario REG. Correspondingly, the household expenditure sees losses of 0.2% in the REG scenario with no effect under the GLOB scenario but gains of 0.6% in PERCAP. This is a key result highlighting that cooperation reduces global economic costs (in both GDP and welfare), and therefore, cooperation between regions is globally advantageous.

Expectedly, the presence of CO_2 prices affects the energy markets and alters the fuel mix of regions. As a result, producers either reduce the use of CO_2-intensive fuels or switch to less CO_2-intensive fuels. Switching to less CO_2-intensive fuels covers cases where producers reduce the CO_2 intensity of their fossil energy portfolio (e.g., from coal power to oil or gas power because oil and gas are less CO_2-intensive than coal) and when producers entirely replace fossil energy sources with renewables. These patterns in fuel switching are seen in the global production of fossil-fired power in different magnitude in the three policy scenarios.

The global production of coal decreases by 17–20% and that of gas by 5–8% across the three scenarios in 2030. Crude oil production falls by 0.3–0.8% across the scenarios. Production of fossil power falls by 17% globally in REG and 11% in GLOB and PERCAP scenarios. Within the energy sectors, there are reductions in coal and gas power, while increases in power from petroleum and coal products. Thus, the biggest burden of emission reduction is absorbed by coal because globally, on average, coal is the most CO_2-intensive fuel (considering end-of-pipe emissions only). The global renewable power production responds to the decrease in fossil production and increases production by 8% in the REG scenario and 5% in both GLOB and PERCAP. Within the renewable power sectors, Solar increases by 6–13%, wind by 8–10%, and other renewable technologies (biofuels, waste, geothermal and tidal technologies) by 9–16% in the three policy scenarios.

These global patterns described above cannot be generalized for each region simulated in DART. The impacts on different regions depend on several region-specific economic structures, and we discuss these in Section 4.3.

4.3. Regionally differentiated effects

Typically, the regional mitigation costs can be disentangled into two components; direct costs and indirect costs. Direct costs arise because regional CO_2 prices principally increase the (intermediate) input costs of energy, assuming the absence of pre-existing market distortions. The net direct costs depend significantly on the flexibility in the energy markets and the degree to which substitution is allowed between different energy sources. Indirect costs primarily arise from spill-over effects and their feedbacks between the domestic and international energy-related sectors. The regional CO_2 prices cause a reduction in the demand for global energy, which impacts the global prices of energy commodities.[5] Depending on whether a region is an importer or exporter of energy commodities, the domestic production and traded (imports and exports) quantities of energy commodities would be impacted differently. The sum of these two components determines the net regional abatement cost.

We disentangle these two cost components for the net welfare changes in scenario REG (see Fig. 4). We use the approach followed in Peterson and Weitzel (2016) to separate the direct and indirect costs. To calculate the direct costs, we implement the NDC target for each region while keeping the international prices faced by this region fixed to those in BASE. Such a modelling setup is equivalent to a region fulfilling its mitigation target while with no feedback on the international prices and gives us the direct mitigation cost component. The difference between the total costs and the direct costs gives us the indirect costs of mitigation.

In scenario REG, we see that the regions which are net exporters[6] of energy commodities in the baseline face losses in GDP and welfare with CO_2 prices. This is because both the regional characteristic of being a net exporter of energy and the levied CO_2 price for mitigation create a downward push on GDP. To understand this, we take the example of Russia. Russia has the lowest CO_2 price of \$7/tCO2 and yet faces the highest regional GDP loss of 2.2% (\$48.1 billion) and the highest welfare loss of almost 20% (\$3.3 billion). However, from Fig. 4, we see that almost all of the costs faced by Russia are rising from the indirect effects of mitigation, and the direct mitigation costs are marginal. This can be chiefly attributed to the high share of energy exports in the GDP of Russia. As a result, even though Russia has a relatively low mitigation target, the reduction in energy prices has a substantial impact on the Russian economy. Similarly, the energy-exporting regions also experience a bigger share of costs from changes in the international energy sector relative to the domestic emission reduction.

Different from the energy-exporting regions, there could either be gains or losses in the energy-importing regions because the two channels of impact could affect the opposite or same direction. Therefore, the net costs (or gains) are determined by the dominant channel in a region. Unlike in the energy-exporting countries in energy-importing countries, we see some regions gaining and others losing. On the one hand, we have regions with GDP gains like India,[7] which has the highest GDP gains of 1.2% (\$71 billion), followed by 0.2% gains in both Eastern Europe (\$6 billion) and China (\$34 billion). Net welfare gains are also seen in these regions. With a low CO_2 price of \$14/tCO_2 in India, production increases by 0.7% (with a 1.2% increase in the energy sectors), and private consumption increases by 1.1%.

On the other hand, we have regions with GDP losses like France, the USA, and Brazil. For instance, France has a high CO_2 price of \$113/tCO_2. Therefore, energy production falls by 6%, with an overall drop of 1.9% in exports and 0.6% in imports. Thus, the cost of high CO_2 price outweighs the gains of being a net energy importer and overall, France faces a GDP loss of 0.1% (\$2.8 billion). In the energy-importing regions, we do not see a dominating cost component.

In the analysis of GLOB and PERCAP, we use the same two channels of impact; CO_2 price and global energy price. Besides, we now have a third channel stemming from the monetary transfers that arise from the trade of permits between regions. The significant difference between REG and GLOB comes from the CO_2 price that regions face wherein, unlike in REG all the regions have the same CO_2 price of \$16.2/t CO_2 in GLOB. We also observe a decrease in the prices of fossil commodities in GLOB, although relative to REG, the price drop is lesser for gas and crude oil and slightly higher for coal (see footnote 7).

From the discussions in section 4.2, we know that regions with CO_2 prices lower than \$16.2/tCO_2 in REG generate revenues by selling permits to regions with CO_2 prices higher than \$16.2/tCO_2 in REG. Under GLOB, all energy-exporting regions still experience losses in GDP; however, the magnitude of losses is reduced, mainly since energy prices fall less than the REG scenario. For example, the losses in Russia's GDP are reduced from −2.2% (\$48.1 billion) to −0.8% (\$17.5 billion). Russia is a seller of permits and gains about 0.1% of GDP (\$3 billion) from the permit market in 2030. Total production in Russia is reduced by 0.5% in GLOB, comparable to the 0.4% fall in REG. However, the sectoral components of total production activities are quite different in REG and GLOB. Given the comparatively higher CO_2 price in GLOB, the production of high energy input sectors like chemical, rubber, and plastic sectors, energy-intensive industry sectors,[8] heavy and light industry sectors increase by a smaller amount compared to REG.

Among the energy-importing, France switches from losing GDP by 0.1% (\$2.8 billion) under REG to slightly gaining in GDP by 0.02% (\$1.1 billion) under GLOB. This happens because France faces one of the highest regional CO_2 prices in REG of \$113/tCO_2 and, therefore, benefits from the lower CO_2 price of \$16.2/tCO_2 in GLOB. Production of energy sectors falls by 0.7% (compared to 6% in REG), and total production remains unchanged relative to the baseline. Among the energy-importing countries, China is an example of a region that gains less in GDP in GLOB (0.1%; \$27.5 billion) than REG (0.2%; \$34.8 billion). China is a permit selling region in GLOB, and the monetary gains from the permit market add up to 0.1% of GDP in 2030. The input costs of energy are higher in GLOB than REG since China faces a higher CO_2 price in GLOB. Therefore, we see a reduction in the total production in China by 0.2%. The largest reductions in production are in the energy-intensive industry (0.5%) and mobility sector (0.3%), with a reduction of 0.9% in the energy sectors. Comparatively, all these sectors increased production in REG because of the low CO_2 price in China.

In the PERCAP scenario, the losses and gains are distributed quite differently. Regions with a high population and low emissions per capita have the highest increases in GDP. GDP increases by 3.4% in Sub Sahara Africa and 1.6% in India than the baseline in 2030. These increases are predominantly driven by revenues from selling permits which amount to 2.5% of GDP in Sub-Saharan Africa (\$7.5 billion) and 0.5% in India (\$3.3 billion). With a substantial increase in consumption (2.1%), Sub-Saharan Africa increases net imports by 10%. It is, together with India (0.1%), the only region where total production rises under the PERCAP scenario (0.6%), mainly driven by the service sector (2%). Also, Central- and South American countries that lose GDP under the REG and GLOBAL

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[5] Global prices of commodities are calculated using the regional prices weighted by regional production quantities in 2030 relative to baseline. In REG, the global price of coal, gas, crude oil drops by 24.1%, 12.8%, and 2.4%, respectively. In GLOB the global prices of coal, gas, crude oil drops by 25.2%, 6.5%, and 0.5%, respectively, and in PERCAP they decrease by 24.9%, 6.1%, and 0%, respectively.

[6] The energy-exporting regions in the base data include AFR, CAN, FSU, LAM, MEA, EFTA, and RUS. The rest of the regions are net importers of energy.

[7] It should be highlighted that in our analysis, we observe gains for India in both direct and indirect cost components. We interpret this as India having tax distortions in the economy that are corrected by the CO_2 price, thus leading to welfare gains while emissions are reduced. Such an effect is not observed in any other region in our analysis.

[8] In DART, the energy-intensive sectors consist of mineral products, ferrous and other metals, and pulp and paper products.

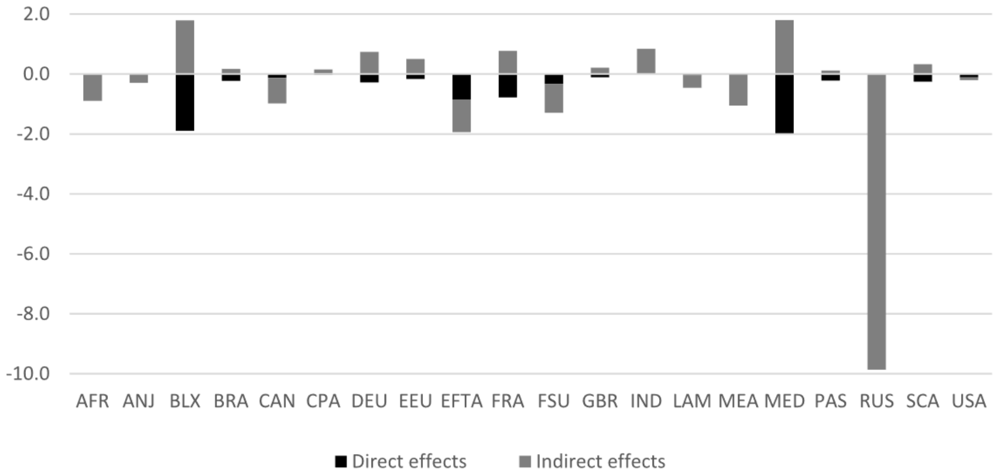

Fig. 4. Direct and indirect components of cumulated-discounted welfare in REG.

scenarios have rising GDP values under PERCAP, since they benefit from selling emission permits due to relatively low emissions per capita (see Section 4.2).

In PERCAP, the highest GDP losses occur in regions with high per capita emissions and are net exporters of fossil fuels. For example, in Russia, an exporter of fossil fuels, we see GDP decline by 1.8%. This decrease is caused by the spending on permits ($1.3 billion or 0.6% of GDP) and a fall in total production (0.7%) and net exports (0.7%). Net exports of coal decline by 19%, those of gas by 8%. China, Canada, and the USA also have high emissions per capita and experience a drop in GDP (0.6–0.4%), which are higher than the GLOB scenario with almost equal reductions in emissions. This difference can be explained by expenditures for permits, which are very small under the GLOB scenario, but amount to about 0.2% of their GDP under PERCAP and losses in production (0.2%–0.3%). In China, for example, reductions in domestic consumptions are not compensated by more exports of heavy and light industry products to Sub-Saharan Africa, such that GDP declines. Hence, we see the following effect in the Chinese economy: expenditures to buy permits lead to less consumption and less production, but an increase in the exports to regions that benefit from selling permits.

5. Conclusion and policy implication

This study calculates the global costs and their regional distribution for achieving the NDC targets under different assumptions on cooperation between regions. Our results show that in 2030 global costs are lowered by 60% when regions cooperate compared to when they act unilaterally. Article 6 of the Paris Agreement urges countries ‘to pursue voluntary cooperation in the implementation of their nationally determined contributions to allow for higher ambition’ (UNFCC, 2015). However, this flexibility that regions can exploit in mitigation has yet to be seen widely in policy discussions. Evidently, with the significant reduction in economic costs that could be unlocked by allowing flexibility in emission mitigation, Article 6 of the Paris Agreement could play a key role in lowering the global costs of fulfilling the NDCs. It is expected that COP26, which is to be held in 2021, could be a decisive meeting in formulating the rules for cooperation through Article 6. Furthermore, as a part of the revision and resubmission of NDC targets so far 87 countries have submitted a new NDC target, 5 have proposed new targets while 72 have done neither.[9] Accordingly, if countries undertake cooperative action, the cost savings from the coordinated effort could be redirected and invested in enhanced mitigation action by boosting the revised NDC pledges, thereby providing economic and environmental gains.

Our results also highlight that the channels of costs are different for energy-exporting and energy-importing regions, leading to geopolitical tensions in ratcheting up the pledges. Notably, for energy-exporting countries, our results demonstrate that the dominant share of costs arises via the international energy market effects, and only a small share comes from the domestic abatement efforts. Thus, energy-exporting countries would stand to gain by discouraging the strengthening of pledges from the rest of the world. The bottom-up nature of the Paris Agreement could play a crucial role in avoiding such misalignment of global and regional incentives. In the Paris Agreement, unlike the previous top-down climate agreements, countries no longer have to negotiate within themselves to assign pledges to individual countries based on a commonly agreed global emission reduction target. Therefore, willing countries can circumvent the tedious political negotiations and voluntarily commit to higher pledges with limited influence of other countries.

We also show that the market design and distribution of emission permits matters and affects the regional gains and losses. The monetary transfers from the developed to the developing countries that are carried out under principles of carbon egalitarianism (scenario PERCAP) are substantial and comparable to the current monetary flows under Official Development Aid (ODA). For example, the per capita ODA received by Sub-Saharan Africa in 2018 is $47 by the World Bank database (World Bank). According to the per capita monetary transfers from the simulated permit trading scheme in PERCAP it would receive $51 in 2030. Therefore, if global justice is considered as a global public good, which similar to GHG mitigation, is underprovided, then the principle of carbon egalitarianism could promisingly combine an additional aspect to welfare, giving an important message for policymakers.

As mentioned in Section 2, our analysis focuses on CO_2 emissions resulting from the use of fossils for production and direction consumption activities which according to recent estimates account from about 73% of all GHG emissions (excluding LULUCF) in 2019 (Olivier and Peters, 2020). Hence, even though we do not have a complete coverage of CO_2 emissions from all sources and other GHG emissions we justifiably do account for a large share of CO_2 emissions which are our primary focus for this analysis. Additionally, the cost estimates from our study are derived under the assumption that regions use a single cost-optimal instrument (global or regional carbon price) to reach the equivalent CO_2 reduction while in practice countries might meet their targets with a

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[9] Source: Climate Actions Tracker https://climateactiontracker.org/climate-target-update-tracker/(Accessed on 22 September 2021).

policy mix. Thus, we expect our results to be a lower bound of costs of the analysed policies. In practical implementation, multiple policies would be implemented to reduce GHG emissions that would increase the costs and additional costs like would arise with their implementation (like setting up a regional carbon price or ETS, measuring and monitoring of emissions from different sectors), all of which are not considered in our model.

Lastly, as our analysis was done pre-Covid we have not considered the effect of the pandemic in our scenarios. There are updated forecasts in IEA,2021 related to the global demand for fossils, renewables and economic outcomes in the short-run until 2021. Since large uncertainties about the short- and long-term future of the recovery from Covid as well as the time-persistence of economic effects of the crisis still remain, we would see our results to hold under the assumptions that the recovery from the pandemic is not prolonged with long-lasting impacts and the global economy would return to the pre-Covid levels by 2030.

CRediT authorship contribution statement

Sneha D. Thube: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ruth Delzeit:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Christian H.C.A. Henning:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

In all the production sectors in DART, capital (K) and labour (L) are nested together with a Cobb Douglas production function. The KL aggregate is then nested with energy with a CES production function with an elasticity of substitution of 0.5.

The nesting of non-energy sectors is shown in Fig.A1 and that of the power sector in Fig.A2.

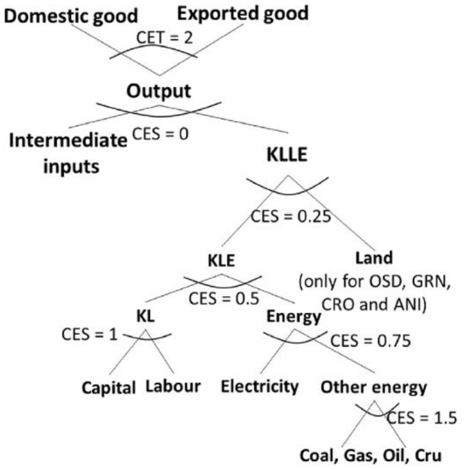

Fig. A.1. Nesting of non-energy sectors in DART

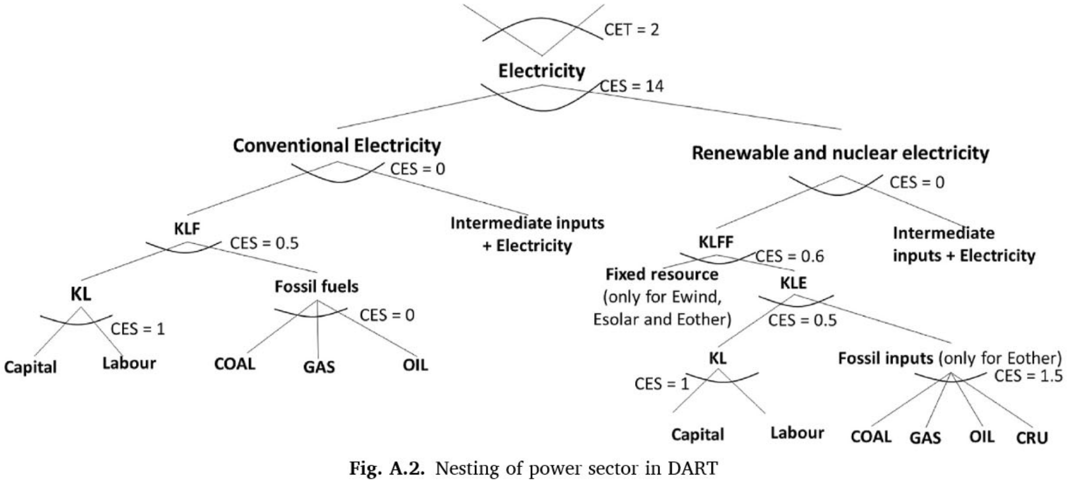

Fig. A.2. Nesting of power sector in DART

Table A1
Description of regions in DART

DART regions	Description
AFR	Sub Saharan Africa
ANJ	Australia, New Zealand and Japan
BLX	Belgium, Netherlands and Luxembourg
BRA	Brazil
CAN	Canada
CHN	China and Hong Kong
DEU	Germany
EEU	Czech Republic, Slovakia, Slovenia, Hungary, Estonia, Latvia, Lithuania, Bulgaria, Romania, Croatia, Austria, Poland
EFTA	EFTA and rest of the World: Norway, Iceland, Liechtenstein, Switzerland, Overseas Territories and Antarctica
FRA	France
FSU	Kazakhstan, Kyrgyzstan, Ukraine, Albania, Belarus, Armenia, Azerbaijan, Tajikistan, Turkmenistan, Uzbekistan, Georgia, Rest of Europe
GBR	United Kingdom, Ireland
IND	India
MED	Mediterranean Europe: Italy, Spain, Portugal, Malta, Greece, Cyprus
LAM	Central- and South America
MEA	Middle East, Northern Africa and Turkey
PAS	Pacific Asia
RUS	Russia
SCA	Sweden, Denmark and Finland
USA	USA

Table A2
Description of sectors in DART

Non-Energy Products (12)		Energy Products (12)	
CRP	Chemical Products (rubber, plastic)	**ENuclear**	Nuclear power
ETS	Energy-intensive production	**ESolar**	Solar power
MOB	Mobility	**EWind**	Wind power
OLI	Other light industries	**EHydro**	Hydro power
OHI	Other heavy industries	**ECoal**	Coal-fired power
SVCS	Services	**EGas**	Gas-fired power
TND	Transmission and distribution	**EOil**	Petroleum and coal products for power
ANI	Animal Products	**EOther**	Biofuels, waste, geothermal and tidal technologies
GRN	Grains	**COL**	Coal
OSD	Oilseeds	**OIL**	Petroleum and coal products
CRO	rest of crops	**GAS**	Gas
RAGR	Rest agriculture and other processed food	**CRU**	Oil

Table A3
Baseline assumptions in DART

	Annual % GDP growth rate	Annual % CO2 emissions growth rate	Per capita emissions in 2030 (in tCO2)	Emissions in 2020 (in GtCO2)	Emissions in 2030 (in GtCO2)
AFR	3.8	1.6	0.5	635	720
ANJ	1.5	−0.5	7.4	1544	1278
BLX	1.7	−0.2	8.3	278	269
BRA	1.8	0.8	1.9	401	430
CAN	1.9	0.2	12.2	527	526
CHN	5.2	1.5	6.1	8667	9123
DEU	1.4	−0.4	6.6	635	584
EEU	2.3	−1.2	5.1	677	580
EFTA	1.7	−0.3	6.4	111	106
FRA	1.4	−0.3	4.0	330	309
FSU	3.4	0.1	5.3	907	867
GBR	2.1	−0.5	5.5	486	448
IND	6.5	4.9	2.7	2939	4145
LAM	2.5	0.6	2.6	1215	1285
MEA	3.6	2.2	4.9	2571	3081
MED	0.9	−1.7	4.9	799	669
PAS	4.1	2.7	2.6	2908	3664
RUS	0.6	−0.1	10.7	1516	1558
SCA	1.9	−0.6	5.6	150	135
USA	2.0	−0.2	13.1	5090	4912

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