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LETTER

Will international emissions trading help achieve the objectives of the Paris Agreement?

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Abstract

Under the Paris Agreement, parties set and implement their own emissions targets as nationally determined contributions (NDCs) to tackle climate change. International carbon emissions trading is expected to reduce global mitigation costs. Here, we show the benefit of emissions trading under both NDCs and a more ambitious reduction scenario consistent with the 2 °C goal. The results show that the global welfare loss, which was measured based on estimated household consumption change in 2030, decreased by 75% (from 0.47% to 0.16%), as a consequence of achieving NDCs through emissions trading. Furthermore, achieving the 2 °C targets without emissions trading led to a global welfare loss of 1.4%–3.4%, depending on the burden-sharing scheme used, whereas emissions trading reduced the loss to around 1.5% (from 1.4% to 1.7%). These results indicate that emissions trading is a valuable option for the international system, enabling NDCs and more ambitious targets to be achieved in a cost-effective manner.

Abbreviations

AIM	Asia-Pacific Integrated Model
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
COP	Conference of the Parties
ET	Emissions trading
INDCs	Intended nationally determined contributions
OECD	Organisation for Economic Co-operation and Development
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

In 2015, the Conference of the Parties (COP) 21 to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement [1]. The Paris Agreement provides a framework for global actions to address climate change in the period after 2020. The objective of the agreement was to maintain the increase in global temperatures well below 2 °C above pre-industrial levels, whilst making efforts to limit the increase to 1.5 °C.

The Paris Agreement requires Parties to prepare nationally determined contributions (NDCs), indicating an individual country's emissions reduction commitments, the measures to be taken to achieve their objectives, and a requirement to report on progress. To raise the level of ambition over time, parties must submit updated NDCs every 5 years. Each party's new NDC must be more ambitious than its previous NDC.

Over 180 parties to the UNFCCC communicated their intended nationally determined contributions (INDCs) for 2025/2030 before COP21.

There have already been several assessments related to INDCs published in scientific papers reports and on websites [2–10]. Some propose alternative scenarios to achieve the 2 °C goal because the INDC based emissions are larger than those in the 2 °C scenarios. Some are comparable with the recent Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) scenario database [11], and make allocations based on multiple effort-sharing schemes. The consensus across the assessments at this stage is that current INDCs are not in line with the 2 °C goal, which was also stated in the Paris Agreement [1]. To achieve the 2 °C goal, either a further emissions reduction in 2030 or more drastic and rapid reductions are required afterwards.

Combating climate change will require the mobilization of substantial resources. Success will depend on the establishment of mechanisms and approaches that incentivize the mobilization of resources for cost-effective and ambitious mitigation action at all levels. Cooperation among parties and private and public-sector stakeholders is considered crucial. It is well-known that the international carbon emissions trading system is an economically cost-effective way to reduce global total mitigation cost [12–17][4]. Under the Kyoto Protocol, there are several such systems incorporating market mechanisms, namely international emissions trading, the clean development mechanism (CDM), and joint implementation. They enable parties to reduce emissions cost effectively and encourage the private sector to contribute to global emissions reduction.

However, there are also some difficulties with implementing the market mechanism. For example, systems for monitoring, reporting, and verification (MRV) of the emissions reduction are needed, but this imposes certain costs. Another issue is that if we establish a carbon market, we need to prepare the market infrastructure, with a positive carbon price being a necessity. For regarding the post-2020 climate actions, there have been some developments regarding the international transaction of carbon credit under bilateral agreements such as The Joint Crediting Mechanism by the government of Japan. Article 6 of the Paris Agreement provides a foundation to undertake international transfers of mitigation outcomes between parties. However, there have been no studies to clarify the effectiveness of an emissions trading system in the context of INDCs.

Here, we estimate the effectiveness of emissions trading under the current INDCs and under the more ambitious reduction targets for 2030, which are consistent with the 2 °C scenarios in the AR5 database [11]. The more stringent emissions reduction targets are associated with larger costs, making emissions trading important. We used the Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) model to achieve this goal.

[4] The financial mechanism in the context of supporting the least developed countries and technological transfer.

Materials and methods

Model

We used the AIM/CGE model. The CGE model used in this study is a recursive, dynamic, general equilibrium model that covers all regions of the world and is widely used in climate mitigation and impact studies [18–22]. There are other global CGE models that assess climate policy such as EPPA [23] and IMACLIM [24]. Among such CGE models, AIM/CGE has unique characteristics in its detailed representation of agriculture, land, and energy supply sectors. In addition, AIM/CGE has been used for Asian-specific analyses [20, 25, 26].

The main inputs of the model are the socioeconomic assumptions of drivers of GHG emissions such as population, gross domestic product (GDP), energy technology, and dietary preference. The production and consumption of all goods, and GHG emissions are the main outputs as the result of price equilibrium. Here, population and GDP assumptions under shared socioeconomic pathways [27] SSP2 were used as the basic drivers, and other technological assumptions were based on Fujimori, Hasegawa [28] (the energy technology is also follows this assumption). The model classifies the world into 17 geopolitical regions and 42 industrial classifications (see supporting information [SI] section 1 for a list of the regions and industries).

One characteristic of industrial classification is that energy sectors, including power sectors, are disaggregated in detail, because energy systems and technological descriptions are crucial for the purposes of this study. Moreover, to appropriately assess bioenergy and land-use competition appropriately, agricultural sectors are highly disaggregated [29]. Details of the model structure and its mathematical formulas are provided by Fujimori, Masui [30].

Production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions at each input price. Energy transformation sectors input energy and are value-added as a fixed coefficient, whereas energy end-use sectors have elasticities between energy and the value-added. They are treated in this manner to deal appropriately with energy conversion efficiency in the energy transformation sectors. Power generation from several energy sources is combined with a logit function [31], although a CES function is often used in other CGE models. We chose this method to consider energy balance because the CES function does not guarantee a material balance [32]. As discussed in Fujimori, Hasegawa [29], the material balance violation in the CES

Table 1. Scenario list.

Scenario name	Emissions target	Emissions trading	Global emissions
Baseline	None	None	
INDC_w/oET	Based on INDCs	without	Around 53GtCO_2eq in 2030 derived from INDCs
INDC_w/ET		with	
40Gt_CUMw/oET	Additional reductions to INDCs are based on cumulative emissions	without	Around 40GtCO_2eq in 2030 derived from 2°C goal
40Gt_CUMw/ET		with	
40Gt_GDPw/oET	Additional reductions to INDCs are based on GDP	without	
40Gt_GDPw/ET		with	
40Gt_POPw/oET	Additional reductions to INDCs are based on population	without	
40Gt_POPw/ET		with	
40Gt_EMIw/oET	Additional reductions to INDCs are based on baseline emissions	without	
40Gt_EMIw/ET		with	

would not be crucial if the share was similar to the calibrated information. In this study, climate mitigation should change the power generation mix when compared to that of the base year, therefore, this is a key treatment. The variable renewable energy cost assumption is shown in SI section 2. Household expenditures on each commodity are described by a linear expenditure system function. The saving ratio is endogenously determined to balance saving and investment, and capital formation for each item is determined by a fixed coefficient. The Armington assumption which assumes imperfect substitutability between domestically produced and traded goods [33] is used for trade, and the current account is assumed to be balanced.

In addition to energy-related CO_2 emissions, CO_2 from other sources, CH_4, and N_2O (including changes resulting from land use and non-energy related emissions), are included as GHG emissions in this model. Global warming potentials are used considering the emissions of the six gases stated in the Kyoto protocol.

Once an emission constraint is placed on a region, the carbon tax becomes a complementary variable to that constraint. This tax raises the price of fossil fuel goods when emissions are constrained, and promotes energy savings and the substitution of fossil fuels by energy sources with lower emissions. The emissions tax, called the GHG emission price, is an incentive to reduce non-energy-related emissions. The revenue from this tax is assumed to go to households.

If emissions trading is allowed, every region is assumed to import or export emission rights until each region's emission price reaches the international emissions price. This trading can be described by equation (1), which is treated as a part of the formula for the mixed complementarity problem.

$$\begin{aligned} ET^{imp}{}_r \geqslant 0 \perp PGHG_r \geqslant PET, \\ ET^{exp}{}_r \geqslant 0 \perp PET \geqslant PGHG_r, \end{aligned} \quad (1)$$

where $ET^{imp}{}_r$ is the net emission imports of region r, $ET^{exp}{}_r$ is the net emission exports of region r, and PET is the international emission price.

CGE models generally use a social accounting matrix (SAM) to calibrate the model parameters. To assess energy flow and GHG emissions more precisely and more realistically, the CGE model should account not only for the original SAM, but also for energy statistics. The Global Trade Analysis Project (GTAP) [34] and energy balance tables [35, 36] were used as the basis for the SAM and energy balance table, and data were reconciled with other international statistics, such as national account statistics [37]. The concept behind the reconciliation method is described by Fujimori and Matsuoka [38]. GHG and air pollutant emissions were calibrated to EDGAR4.2 [39]. For the land use and agriculture sectors, agricultural statistics [40], land use RCP data [41], and GTAP data [42] were used as physical data.

Scenario framework

In our model, the emissions targets as pledged in the INDCs bind the emissions in individual countries, and the carbon price works to achieve the targets. This, in turn, generates climate mitigation costs, which are measured by changes in macroeconomic indicators, such as GDP and consumption, compared to the baseline. We set eleven scenarios as shown in table 1. Baseline has no climate policy (carbon pricing policy), whereas the other scenarios do. INDC corresponds to the unconditional emissions targets submitted to the UNFCCC (the details of how to construct the emissions constraint in 2030 are shown in SI section 3). In addition, a more stringent climate policy scenario

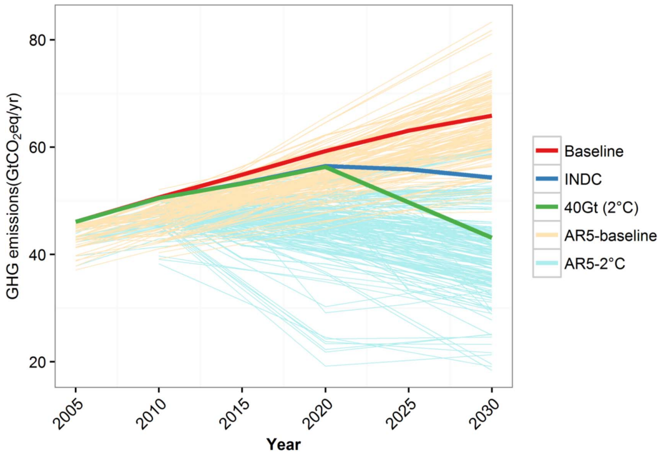

Figure 1. Overview of the global emissions trajectory. The baseline assumes the absence of a climate policy. INDC refers to a scenario meeting emissions derived from the intended nationally determined contributions (INDCs) (here the w/o scenario is shown, with global total emissions in the w/ and w/o emission trading [ET] scenarios being almost the same). Here, 40 Gt is a 40 $GtCO_2eq$ scenario, which corresponds to the least-cost 2 °C scenario addressed in the Paris Agreement (here 40Gt_CUMw/ET is shown as a representative, while other 40 Gt scenarios also had similar emissions trajectories). The AR5-baseline is the scenario without the climate policy taken from IPCC AR5 database [11] which includes multi-model and multi-scenario results. The AR5-2 degree is a scenario that approximately meets the 2 °C target in this century.

group of 40 Gt was prepared, as shown in figure 1, to limit the global total GHG emissions to about 40 $GtCO_2eq\ yr^{-1}$ in 2030, which in the Paris Agreement is regarded as a requirement to achieve the 2 °C goal in line with AR5 database [11]. The 40 Gt scenarios consisted of two dimensions, namely a burden-sharing scheme and the availability of emissions trading. The burden-sharing scheme is one of the key elements that determines the stringency of the mitigation target for an individual country. Four cases were used for the burden-sharing scheme. The basic idea was to distribute the 13 $GtCO_2eq$, which is the gap between the 40 Gt and INDC scenarios (see SI section 4), based on four indicators as shown below:

$$\mathrm{EC}_{r,b} = \mathrm{INDC}_r - \mathrm{GAP} \cdot \frac{I_{r,b}}{\sum_{rp \in R} I_{rp,b}}, \qquad (2)$$

where $r, rp \in R$ is a set of regions, $\mathrm{EC}_{r,b}$ is an emissions constraint in region r under a burden-sharing scheme b, INDC_r is the emissions target in region r pledged in the INDCs, GAP is the emissions gap in 2030 between the INDCs (53 Gt) and 40 Gt scenarios, and $I_{r,b}$ represents indicators in region r under burden-sharing scheme b.

The four indicators for burden sharing are cumulative emissions (from 1990 to 2030 in the baseline), GDP, population in 2030, and emissions in baseline 2030, which were referred to as CUM, GDP, POP, and EMI, respectively. We chose these four indicators with the consideration of concept of responsibility, capability, and equity as well as the simplicity of the model computation. CUM and GDP reflect the concept of responsibility, although their meanings for individual countries are different. Cumulative emissions are generally more severe in high-income countries that have emitted substantial amounts from 1990. The GDP indicator requires relatively large reductions for regions with a low emissions intensity (CO_2/GDP), which is most developing countries. POP and EMI are more related to the equality concept. EMI eventually causes the same additional reduction rate relative to the INDCs (20.0% = 13/65 = gap/baseline in 2030) for all regions. The emissions reduction percentages compared to the baseline for each scenario are presented in the SI section 5. We considered with (w/) and without (w/o) emissions trading (ET) options for all scenarios (e.g. w/ET and w/o ET). If emissions trading was allowed, every region was assumed to import or export emission rights freely until each region's emissions price reached the international level.

Results

Welfare change and mitigation cost under INDCs

Emissions trading significantly reduced global welfare loss (accounted for by Hicks' equivalent variation) in 2030 by 75% (equivalent to around US$220 billion), as shown in figure 2 (GDP loss is shown in SI section 6). The INDC w/o ET resulted in a 0.5% (0.47%) welfare loss in 2030 globally, but in the scenario w/ET the loss became 0.2% (0.16%). The OECD countries tended to have larger losses in the scenario w/o ET, whereas their losses substantially decreased in the scenario w/ ET. For example, Japan, the US, and EU had 0.6%, 0.8%, and 0.5% welfare loss in 2030, respectively, whereas emissions trading decreased their losses to −0.3%, 0.3%, and −0.0%, respectively (the negative value was due to changes in the international price and trade conditions). A similar trend was observed in the GDP loss rates.

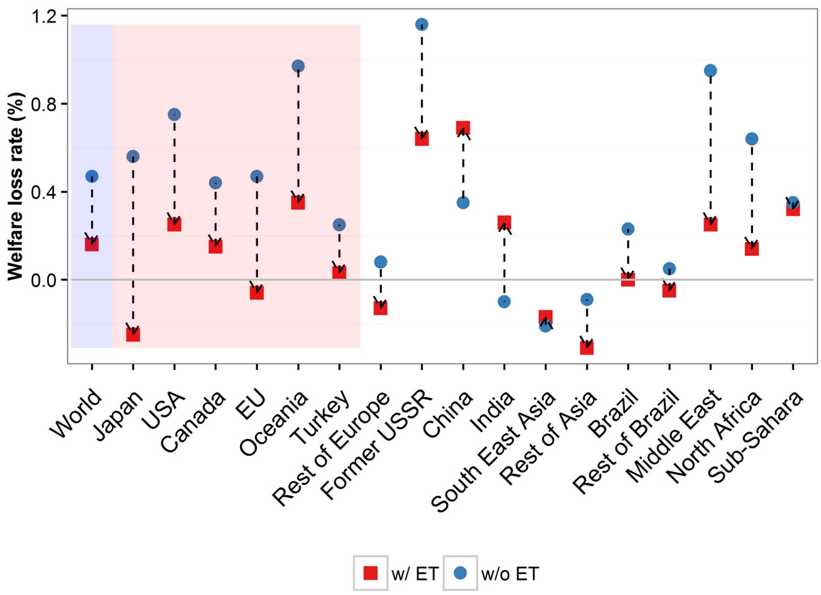

Figure 2. Welfare loss rates in the year 2030 compared to the baseline scenarios for all of the regions in the INDC_w/ET and INDC_w/o ET scenarios. The blue area is the global total and the red area is OECD countries.

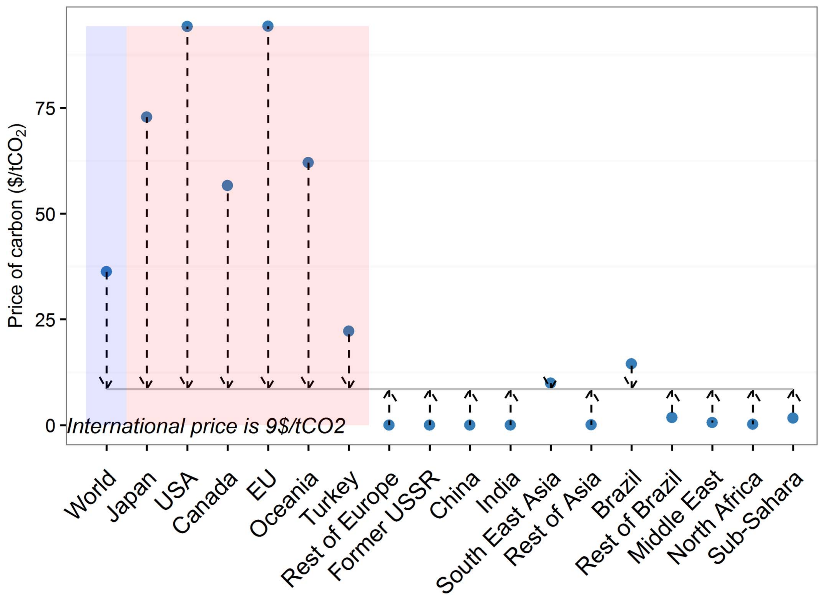

Figure 3. Carbon prices for all regions in the INDC_w/ET and INDC_w/o ET scenarios. The blue area is the global total and the red area is OECD countries.

In contrast, the situation varied in developing countries. For example, China and India would face a negative economic impact due to emissions trading, while Africa and South Asia would experience positive impacts. As shown in figure 3, the carbon prices in developing countries were low (almost negligible) in the w/o ET scenario. If the domestic carbon market were to be opened to the international market, the carbon prices in these regions would be elevated to 9 $/tCO_2$. While this is low compared to the values obtained in long-term stringent mitigation studies [43], there would still be some macroeconomic effects. It would decrease capital productivity and could result in these regions losing their international competitiveness, but this would depend on the energy mix and economic structure. In principle, in the scenario without emissions trading, OECD countries have a relatively high carbon price, which reduces international competitiveness in their export industries. Meanwhile, in the scenario with emissions trading, OECD countries regain their international competitiveness, and eventually the rest of the world loses with regard to exports. The results indicate that the effects of such trade conditions are much larger than the pure carbon

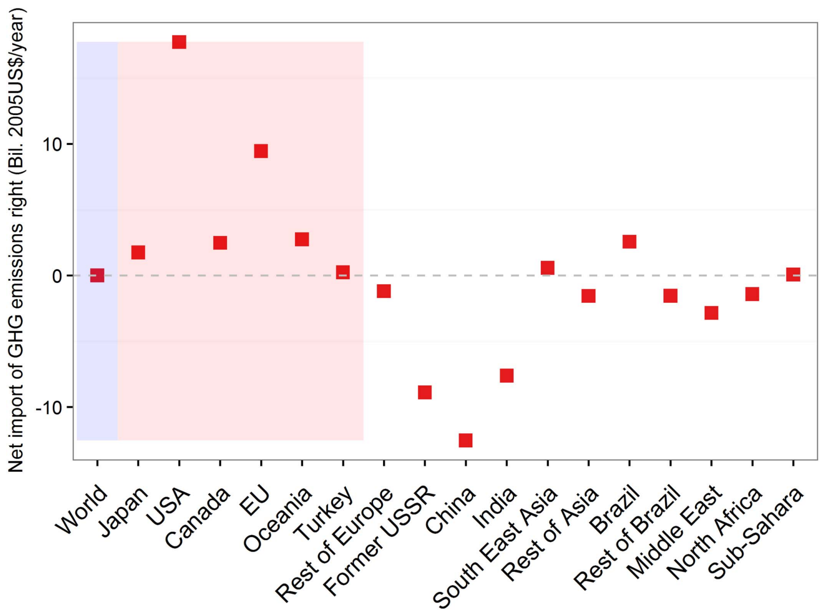

Figure 4. Monetary transfer associated with emissions trading in the INDC_w/ET scenario in 2030. The blue area is the global total and the red area is OECD countries.

emissions permit transfer effects in some countries (the total share of exports in GDP relative to the baseline scenario for each scenario is shown in SI section 6). The impacts would differ depending on the magnitude of the carbon price. For example, in countries with a high coal consumption there would be a relatively large impact on the economy at a certain carbon price. China and India are such examples (see SI in section 7 for the sources of primary energy supply and power generation in representative regions as well as other energy-related and land-related variables).

In terms of the financial flow associated with emissions trading, money was transferred from OECD to non-OECD countries because OECD countries imported emissions from non-OECD countries. These imports helped to reduce the mitigation cost in OECD countries. The global financial flows were about $38 billion in 2030. As shown previously, the carbon prices in OECD countries were high in the w/o ET scenario, and these countries faced relatively large challenges in meeting their emissions target. Hence, they purchased emissions rights from non-OECD countries. In OECD countries, the monetary flow in the w/ET scenario (figure 4) and the welfare loss rates in the w/o ET scenario in the US and EU were remarkably high (figure 2). The monetary flow in Japan was not as high, but there were large welfare losses in the w/o ET scenario (figure 2). This is because the scale of the economy (GDP) in the US and EU is 3.5 and 3.0 times larger than in Japan, respectively. In non-OECD countries, India, sub-Saharan Africa, and China were the main exporters. Their exported monetary amount ranged from US$5 to 10 billion yr^{-1}.

Some may think that China should be a high CO_2 emitter and importer of emissions permits. However, China has historically exhibited a strong energy and carbon intensity improvements, with an annual carbon intensity improvement rate of 3.0% from 1971 to 2010 (4% from 1990 to 2010). Meanwhile, the NDC commitment is a 60%–65% decrease over 25 years, equivalent to a 3.5% decrease per annum. Therefore, it is not surprising that China's carbon price in the INDC scenario is low, or that China becomes an exporter of permits. However, we it remains an uncertainty in this study.

Stringent emissions reduction targets and effectiveness of emissions trading

Figure 5 shows several factors regarding the welfare losses in stringent emissions reduction target scenarios. First, the mitigation costs under stringent climate targets were significantly larger than INDCs. Global welfare loss without emissions trading scenarios ranged from 1.4% to 3.4% (US$1020–2469 billion) depending on the exact burden-sharing scheme used. GDP loss also displayed a similar trend to welfare loss (see SI section 8).

Second, while the global welfare losses in the w/o ET scenarios differed, they converged to around 1.5% in the w/ET scenarios regardless of the burden-sharing scheme used. The welfare loss was dramatically reduced by emissions trading in most of the stringent climate target cases, ranging from 1.4% to 1.7%, which means emissions trading had an effectiveness of 0.1%–1.8% (equivalent to US$30–1240 billion). However, this was not the case for individual regions. For example, welfare losses in OECD regions ranged from 0.5% to 3.0% in w/ET scenarios, which implies that an initial allocation in the emissions allowance does

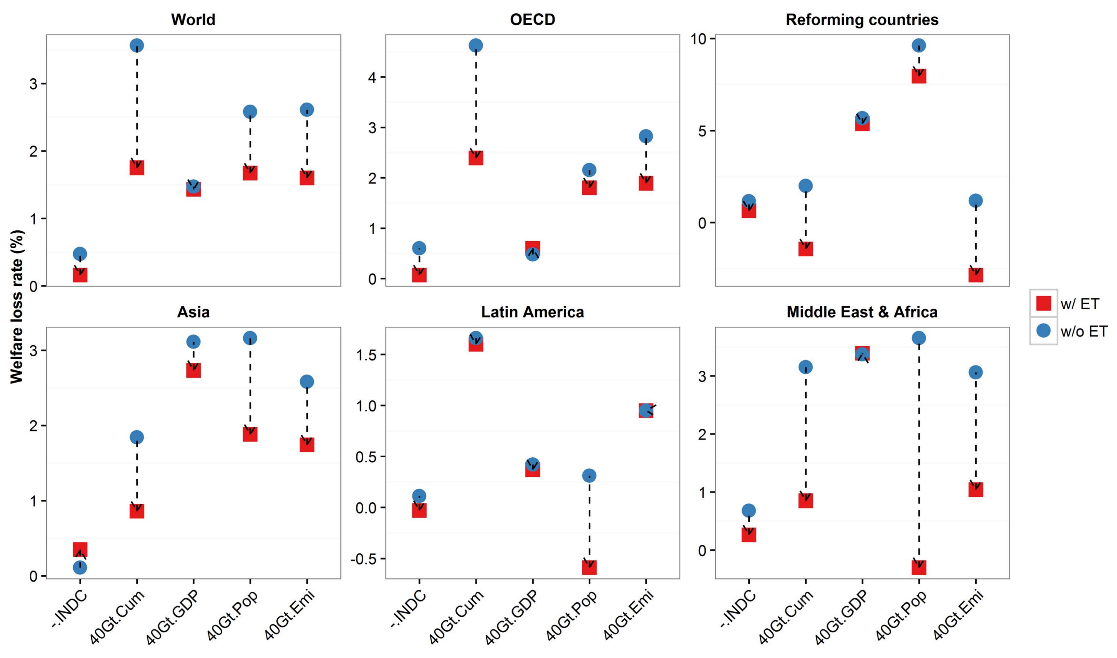

Figure 5. Welfare loss rates compared to baseline scenarios for five aggregated regions in the INDC and 40 GtCO$_2$eq scenarios in 2030. The horizontal axis represents burden-sharing differences.

matter for individual regions, even if emissions trading is available.

Third, there was a completely different situation across regions in the w/o ET scenarios depending on the burden-sharing scheme. In CUM, the OECD countries had the largest loss among the four burden-sharing schemes, and this loss dominated the global total GDP loss. This is because CUM is the most severe burden-sharing scheme for OECD countries, where an extremely high (more than \$500/tCO$_2$) carbon price is set (see SI section 8.3). In GDP case, the welfare loss in OECD countries was almost as low as in the INDCs scenario, whereas non-OECD countries experienced a large loss. This is because the emissions reduction in the GDP case was relatively modest for the OECD countries. CUM is the most severe case for OECD regions and causes the highest mitigation cost, whereas the GDP case required a large GHG reduction and resulted in the highest mitigation costs in non-OECD regions. This implies that OECD countries have a large share of the global economy and already face high costs in their INDC; therefore, the marginal cost increase caused by further emissions reductions is quite high in these regions. SI section 8.4 shows individual sectors' marginal abatement reduction rate curves, from which we can confirm that there is a flat trend in the low carbon price areas, but the steepness of the curves increases in the high carbon price areas.

Fourth, the net global benefits of emissions trading differed across the different burden-sharing schemes. Emissions trading generated most global benefits in the CUM case, mostly from the OECD countries (the absolute GDP difference is shown in SI section 8.2). In contrast, emissions trading generated very little benefit in the GDP case. This is probably because the carbon price variation in the GDP case was smaller than in other cases (see SI section 8.3). POP resulted in a global welfare benefit of 0.9% from emissions trading, mainly due to gains in Asian (India) and African regions (see SI section 8.1). Asia has a high population, and therefore the required reduction as well as the mitigation cost would increase in the POP w/o ET scenario, while emissions trading substantially reduced the costs. In EMI, all regions had to reduce the emissions by the same percentage from their individual INDCs, and therefore the benefits of emissions trading were shared among all regions.

Discussion and conclusion

We estimated the benefit of emissions trading under the current INDCs and more ambitious reduction targets in line with the 2 °C goal for 2030. The results indicated that emissions trading is a useful option for the international system to efficiently achieve the near-term climate target. The climate mitigation costs under current INDCs in OECD countries would reduce significantly with emissions trading. However, some regions would face negative economic impacts due to the high carbon price. In the more ambitious reduction target scenarios, emissions trading played an essential role. Without emissions trading, OECD countries could face significant macroeconomic losses and somewhat unrealistically high carbon prices in most burden sharing cases.

Emissions trading is an attractive measure to achieve the INDC targets efficiently, with the resulting carbon market being around US\$40 billion. However, there are at least three factors to consider. First, who will receive the benefit? The welfare loss rates in OECD countries decreased remarkably by implementing emissions trading, whereas this was not always the case for non-OECD countries. In some developing countries welfare would decrease despite the revenue obtained from exporting the carbon emissions. These phenomena imply that the market distortion induced by the carbon price is the primary factor in changing the macroeconomic performance rather than the monetary flow associated with emissions trading. While it is economically efficient globally, whether it is acceptable to implement the emissions trading system or not in the real world might be dependent to a large extent on the equity issue.

The second factor is that if we decide to adopt the 40 Gt pathways without emissions trading, OECD countries would face quite high carbon prices and macroeconomic losses in almost all cases (except for the GDP case). These pathways had a high carbon price (more than \$200 or \$300/tCO_2) in the near term in 2030. These values could be interpreted as being unrealistic. For example, implementing a Japanese carbon tax faced strong resistance, even at a carbon price of \$3, although many existing climate change mitigation studies have suggested hundreds of dollars as a reasonable target for a carbon price in long-term scenarios. This is absolutely critical when considering the reality of achieving such a stringent emissions reduction target. We must somehow implement the emissions trading system to achieve such a goal. Most regions would gain from the emissions trading system, with Sub-Saharan Africa receiving a remarkable benefit. On the other hand, the exact burden-sharing scheme used affected the distribution of the cost, even when emissions trading was available. The main conclusion obtained from the 40 Gt scenarios was that OECD countries already had strict emissions targets in their INDCs, and there was limited potential to further reduce emissions independently without emissions trading, with non-OECD countries also requiring a certain amount of emissions reduction. Therefore, non-OECD countries would have to reduce their emissions either through exporting their emission allowances to OECD countries (e.g., CUM w/ET) or intensifying their own emissions target (e.g., GDP w/o ET). The macroeconomic results imply that the emissions trading option is more attractive to non-OECD countries.

Third, for some regions, especially low-income countries, a large monetary flow could cause adverse effects (e.g., via Dutch disease) [44] (see the 40 Gt scenarios in SI section 8.5). The appreciated real exchange rate crowds out manufacturing exports and endogenous growth in the industrial sector. In addition, the volatility of carbon pricing may disrupt current balances. The financial flow creates rents, and that may spur unproductive rent-seeking activity. Policy makers must consider such possibilities. The quality of the institution involved seems to be instrumental in protecting against Dutch disease [45]. Moreover, if funds are distributed to technologies and sectors exhibiting productivity spillover, it could have a positive effect. Regarding price volatility, Jakob, Steckel [44] discussed permit allocation and price controls. Considering issues related to the abovementioned measures, they proposed a sovereign wealth fund, which could inter-temporally smooth the price.

Emissions trading may, in fact, be effective in reducing mitigation costs to achieve near-term NDC targets, but this is not a crucial step. However, in the long-term, mechanisms to ensure economic efficiency should be prioritized.

In addition to the model simulation, there are at least three factors to consider in terms of the international policy framework. The first factor is how to avoid the double counting of mitigation efforts. For example, the CDM should be accounted for as the developed countries' emissions reductions, but national emissions inventories are based on actual domestic emissions and could fail to attribute the reductions to the CDM. The second concern is whether a cooperative mechanism, such as a JCM or multilateral mechanism, should be adopted. Although the Paris Agreement includes a JCM, it is unknown whether a concrete political system, such as a certification system, would work and to what extent the credit would be transferred. The third factor references so called non-market-based approaches (NMAs), which encompass a wide range of development practices including contributions to sustainable development, poverty eradication, and adaptation measures. NMAs can imply emissions permit transfers, but this is hard to measure. International negotiations are required to establish the rules for these situations.

This study had several limitations. First, we deal with 17 aggregated regions in the modeling framework, although this implicitly assumes that emissions rights can be transferred under the aggregated regions and sectors. Therefore, the mitigation cost in the scenarios without emissions trading could actually be higher than the estimates in this study. Although it would be not so critically important to see the global overview, we should be careful to the specific aggregated region's results and regional aggregation may influence the results. A similar issue should be considered for the income loss distribution within each region (e.g., for each income class).

Second, one of the underlying assumptions was that advanced technologies can be accessible anywhere in the world. This assumption enables developing countries to reduce emissions at a low carbon price. This would sometimes be true because wages and many costs in developing countries are cheaper than in developed countries. However, the technology is only applicable with a certain skilled labor and access to such know-how. Therefore, as stated in the Paris Agreement, the transfer of technologies to developing countries is necessary.

Third, implementing emissions trading system can be costly, and we did not consider such transaction costs. One study presented opposing results [46]. However, they investigated cases in the EU and US, which may not be completely relevant to the current study, although it is still worthwhile to consider the implications. As we discussed earlier, MRV would be a major cost. The information obtained from this study should be interpreted as the maximum potential emissions trading benefit, if emissions trading works at its most efficient. Therefore, the results of this study should be considered compared to the cost of emissions trading (opportunity cost), and the final costs and benefits should be evaluated.

The fourth limitation is a more technical issue regarding the model. The revenues generated from GHG emission taxes and emissions trading exports are assumed to be received by a representative household. If the emission price is relatively high, as in this study, the amount of money generated by the emission tax becomes enormous. The saving and expenditure behavior of the institutional sectors receiving the tax revenue could then have a large influence on macroeconomic performance and GHG emission prices. If this revenue was used for green investments or investing in other energy technologies, different results would have been obtained. As discussed by Jakob, Chen [47], carbon pricing revenue can be used for to increase infrastructure access. Even if it were insufficient to promote ideal development, such options should be considered.

Fifth, we only discussed climate mitigation costs in this study, but climate change impacts risk must be reduced by specific mitigation efforts, which should be considered in decision making. Therefore, the results of this study should not be interpreted to suggest that climate change mitigation only generates costs. Climate change risks might not be obvious in 2030 because of internal climate variability, and while the short-term benefits would be small, there would be incredible long-term benefits.

Sixth, there is an uncertainty regarding the socioeconomic and technology assumptions. We conducted a sensitivity analysis for changes in the GDP and population assumptions (SSP1 and SSP3), as well as for oil price (GDP, population, and oil price are presented in the SI section 9). Although the numerical results slightly differ from the reference scenario, the main conclusion is robust, and we can conclude that emissions trading would be essential in the context of Paris Agreement. Technological assumptions could change regional relationships regarding cost advantages. Limiting technological assumptions, such as the Energy Modeling Forum 27 study, is desirable [48]. Furthermore, in this study, we did not reflect on each country's individual energy information, as was done in the International Energy Outlook [49] published by the US Energy Information Administration. Collecting information from all countries is difficult, but it would be worthwhile to collect data from major countries (i.e., major emitters). Such a treatment could affect the outcomes, and we propose this approach as a topic for further research.

Future studies are expected to follow three directions. One is to incorporate the 1.5 °C goal. This would require not only a 2030 but also a 2050 or century-scale assessment. After the Paris Agreement, this research topic has attracted much attention, but has not been sufficiently analyzed. The other direction would be to make a more realistic assessment of energy technologies and international cooperation.

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Author contribution

SF conceived the research; SF, IK and YH designed the research; SF performed all model simulation; IK designed policy institutional discussion; SF wrote the first draft; all authors contributed to the analysis and discussion of the results, as well as to writing the paper.

Competing interests

The authors have declared that no competing interests exist.

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