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Potential consequences of the international transfer of emission allowances under the updated national emissions targets by 2030

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ABSTRACT

All parties that signed the Paris Agreement are required to update their Nationally Determined Contributions (NDCs) every 5 years. The international transfer of emission allowances is a political instrument that has the potential to realize global emission reductions under the NDCs. This study conducted an economic assessment of the implementation of updated NDCs and quantified the effects of the international transfer of emission allowances using a global computable general equilibrium model. The results showed that updating NDCs increased gross domestic product (GDP) losses relative to the previous NDCs. The international transfer of emission allowances mitigated global GDP losses relative to baseline scenarios from 1.1 % to 0.7 % but there was an increase in some developing countries with relatively low emission reduction targets. While the international transfer of emission allowances could promote the reduction of global emissions in a cost-effective manner, it could also impose an economic burden on some developing countries through their linkages to the global carbon market. Thus, the results of this study indicate the importance of considering additional financial or technical support to developing countries.

1. Introduction

In 2015, the Conference of the Parties (COP) 21 to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement as a new international framework to combat climate change (UNFCCC, 2015). Parties to the Paris Agreement are required to prepare, communicate, and maintain Nationally Determined Contributions (NDCs), which are their post-2020 reduction targets, and to implement measures to achieve their NDCs. Parties are required to update their NDCs every 5 years, and each new NDC must be more ambitious than the previous one.

Most parties submitted Intended Nationally Determined Contributions (INDCs) prior to the adoption of the Paris Agreement, which became the first NDCs after the ratification of the agreement. While this represents an important milestone to enforce climate change mitigation actions, it is accepted that the first NDCs are insufficient in terms of emission reductions to achieve the long-term 1.5 °C and 2 °C temperature increase targets(UNEP, 2020). Several studies have analyzed the impact of implementing NDCs on the economy and energy system, followed by emission reductions in line with the 1.5 °C and 2 °C targets (Iyer et al., 2015; Fujimori et al., 2016c; Vandyck et al., 2016; Rogelj et al., 2017; van Soest et al., 2017; Luderer et al., 2018). They have shown that strengthening NDCs will reduce the negative impact on the economy and smooth the transformation of the energy system.

The parties submitted updated NDCs around 2020–2021. According to the Emissions Gap Report 2022(United Nations Environment Programme, 2022), 166 parties have submitted new or updated NDCs to the UNFCCC, (2022). Emissions from countries that submitted updated NDCs accounted for 91 % of global greenhouse gas (GHG) emissions in 2019. According to Ou et al. (2021), the updated NDCs will result in 15 % stricter CO_2 emission reductions from energy and industrial processes in 2030 compared to the NDCs submitted in 2015. However, the updated NDCs will still be insufficient to achieve the 1.5 °C target(Ou et al., 2021; Robiou du Pont and Meinshausen, 2018; Meinshausen et al., 2022).

The updated NDCs will necessitate a much larger GHG emission reduction than the previous NDCs. The international transfer of emission allowances could achieve updated NDCs in a cost-efficient manner. The

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international transfer of emission allowances is a system in which emissions are capped in the form of allowances. These allowances are traded on the market between entities that emit more than their allowances and entities that emit less than their allowances. Article 6 of the Paris Agreement refers to the international transfer of emission allowances as a means to achieve NDCs. The international transfer of emission allowances has rarely been attempted, but it is expected to be introduced in the future after the COP26 in 2021 agreed on implementation guidelines under the Paris Agreement(2022).

The advantage of the international transfer of emission allowances is that the marginal abatement cost can theoretically be equalized among emitters through trading allowances, thus enabling cost-effective emission reductions in the economy(Montgomery, 1972; Tietenberg, 1985; Weyant, 1999; Böhringer and Welsch, 2004; Carbone et al., 2009; Fujimori et al., 2015; Zhang et al., 2017). Several studies have analyzed the effects of the international transfer of emission allowances when implementing NDCs(Fujimori et al., 2016b; Hof et al., 2017; Edmonds et al., 2021; Böhringer et al., 2021). The consensus at this stage is that the international transfer of emission allowances will significantly reduce the global abatement costs of implementing NDCs. Other studies have analyzed the economic effects of the international transfer of emission allowances implemented at the cross-regional level when implementing NDCs(Li and Duan, 2021; Khabbazan and von Hirschhausen, 2021).

Most of these previous studies analyzed the impact of NDCs submitted in 2015. No study has attempted to analyze the global economic impact of updated NDCs, or to analyze the effects of the international transfer of emission allowances under updated NDCs. If, as Fujimori et al. (2015) speculated, the international transfer of emission allowances is more effective in reducing economic losses under more stringent climate targets, then it may play a vital role in mitigating the global impacts of implementing updated NDCs.

Here, we estimated the economic and energy implications under the updated NDCs and the effects of the international transfer of emission allowances. The international transfer of emission allowances here includes mechanisms that enable international transactions of carbon credits, such as the cooperative mechanism established by Article 6, paragraph 4, of the Paris Agreement(2023) To achieve this goal, we collected information on updated NDCs and processed it for input into a model. Then, we used a computable general equilibrium (CGE) model, Asia-Pacific Integrated Model-Hub (AIM-Hub), to estimate mitigation costs under the updated NDCs for the entire world by 2030, and the effects of the international transfer of emission allowances. We designated four scenarios: baseline, 2015NDC_w/oET, 2015NDC_w/ET, 2020NDC_w/oET, and 2020NDC_w/ET. Each region reduced their emissions based on the initial NDCs and updated NDCs. We considered options with (w/) and without (w/o) the international transfer of emission allowances (ET) for each scenario (i.e., w/ET and w/oET). The socioeconomic assumptions behind the scenarios were based on the Shared Socioeconomic Pathway 2 (SSP2).

This study built on the findings of previous studies by analyzing the effects of the international transfer of emission allowances under updated NDCs, when the international transfer of emission allowances could be a more important option. Additionally, this study analyzed the value-added changes across sectors, which were not considered in Fujimori et al. (2016b), and the effects of the international transfer of emission allowances were analyzed by sector. This study's novelty lies in its consideration of the most recent historical statistics in the simulation, which have the potential to inform the realism of current NDCs and the challenges they face. This study also analyzed the external effects of climate change mitigation measures such as changes in air pollutant emissions and food prices.

2. Methods

2.1. Overview

This study had two main parts. First, information on updated NDCs was collected and processed so that these data, which differed by country in terms of the reference year and target gases, could be input into the model. Then, the processed information was incorporated into the AIM-Hub model to estimate mitigation costs under the updated NDCs for the entire world by 2030, as well as the effect of the international transfer of emission allowances. The period covered by the calculations was from 2005 (base year) to 2030. The AIM-Hub model uses the SSP2(O'Neill et al., 2014; Riahi et al., 2017) as the underlying socioeconomic assumption. We determined the emissions constraints by 2030, which were exogenously based on the initial NDC and updated NDC information. Based on the results of the AIM-Hub model, we assessed the economic impacts when implementing updated NDCs, and the effects of the international transfer of emission allowances.

2.2. AIM-Hub model

The AIM-Hub model used in this study is a recursive, dynamic CGE model developed by Fujimori et al.(Fujimori et al., 2017) and is widely used in climate mitigation and impact studies(Hasegawa et al., 2014, 2015, Hasegawa et al., 2016; Fujimori et al., 2014; Mittal et al., 2016). The model described as a mixed complementarity problem, and equilibrium solutions in a perfectly competitive market were obtained for each year, with 2005 as the base year. The model features detailed descriptions of the agriculture, land, and energy supply sectors, and covered a total of 48 industrial sectors. Each sector had its own capital stock, investing every year and depleting by 4 % per year. The value of 4 % per year has commonly been used in previous studies(Aguiar, 2015). New capital is distinguished from capital deployed in the previous year and once deployed is fixed in the sector. The location and amount of new capital deployed are assumed to be determined by a single market (one price per country).

The CGE models generally use a social accounting matrix (SAM) to calibrate the model parameters. We calibrated the model using data from the Global Trade Analysis Project (GTAP)(Dimaran, 2006) and energy balance tables, and data were reconciled with other international statistics, such as national account statistics for 2005 as the base year of the model(Fujimori and Matsuoka, 2011). To evaluate energy flows and GHG emissions more accurately and realistically, it was necessary to consider not only the original SAM but also energy statistics. In this model, the period from 2005 to 2023 was selected as the period to be calibrated using the Energy Balance Table (IEA, 2024), where energy consumption by fuel, sector, and share of electricity generation were given as exogenous conditions (see the SI for the comparison of simulation results and the observations for main energy-related parameters). The parameters in the model, such as coefficients representing household consumption propensity, industrial sector energy consumption efficiency and fuel source share, were adjusted endogenously. For a discussion of parameter setting through calibration, see Fujimori et al. (2016a), in which model results are compared with historical observations.

The main inputs of the model were the future socioeconomic assumptions that contributed to GHG emissions, such as population, GDP, energy efficiency improvements with technological development, and changes in dietary preferences with economic growth. The production and consumption of all goods and GHG emissions were the main outputs as the result of price equilibrium. Production sectors maximized profit under a multi-nested constant elasticity substitution (CES) function at each input price. Energy transformation sectors input energy and were value added as a fixed coefficient. In contrast, energy end-use sectors had elasticities between the input energy and value added. This was due to the appropriate treatment of energy conversion efficiency in the energy transformation sector. Power generation from several energy sources was combined in a logit function(Clarke and Edmonds, 1993). Household expenditures on each commodity were described by a linear expenditure system (LES) function. The savings ratio was determined endogenously to balance savings and investment, and capital formation for each good was determined by a fixed coefficient. The Armington assumption of imperfect substitutability between domestically produced and traded goods(Armington, 1969) was used for trade, and the current account was assumed to be in balance.

In addition to energy-related CO_2 emissions, CO_2 from other sources, CH_4, and N_2O (including land-use changes and non-energy-related emissions) were included as GHG emissions in this model. When an emission constraint was imposed in the model, the carbon price was endogenously determined to meet the given emission constraints and the carbon price is treated as explicit carbon tax which is conventional way how to deal with the carbon price in CGE models. The carbon price increased the price of fossil fuel goods and promoted energy savings and the substitution of fossil fuels by less emission-intensive energy sources. The revenue generated by the carbon price was assumed to be returned to households. For calculations, we divided the world into 17 regions based on geographic and economic considerations (see SI).

When the international transfer of emission allowances was allowed in the model, each region was assumed to import or export emission allowances until its carbon price reached the international carbon price. This was described by Eqs. (1) and (2) as a part of the formula for the mixed complementarity problem:

$$ETIMP_r \geq 0 \perp PGHG_r \geq PET \tag{1}$$

$$ETEXP_r \geq 0 \perp PET \geq PGHG_r \tag{2}$$

where $ETIMP_r$ is the net emission imports of region r, $ETEXP_r$is the net emission exports of region r, $PGHG_r$ is the carbon price in region r, and PET is the international carbon price. All countries traded emission allowances for GHGs. The revenue generated by the international transfer of emission allowances was assumed to be returned to households. The initial allocation of emission allowances was set based on the NDC; emissions were imported when they were above the NDC and exported when they were below the NDC.

2.3. Scenario framework

The details of the five scenarios used in the study are given in Table 1. The baseline scenario reflects the current policy or trend of the energy system, to a certain extent, through IEA statistics until 2022. The 2015NDC_w/ET and 2015NDC_w/oET scenarios were based on the emissions derived from the initial NDCs with and without the international transfer of emission allowances, respectively. The 2020NDC_w/ET and 2020NDC_w/oET scenarios were based on the emissions derived from the updated NDCs with and without the international transfer of emission allowances, respectively. The details of how the emission constraints in 2030 were set under the initial NDCs and updated NDCs are given in the SI. Note that as of July 2025, the United States has withdrawn from the Paris Agreement, and the NDC is no longer valid. Although the US may not return immediately due to the political situation, this analysis assumes that the NDC remains in effect.

Table 1
Scenario list.

Scenario name	Emissions target	International transfer of emission allowances
Baseline	None	None
2015NDC_w/oET	Initial NDC	without
2015NDC_w/ET	Initial NDC	with
2020NDC_w/oET	Updated NDC	without
2020NDC_w/ET	Updated NDC	with

3. Results

3.1. Greenhouse gas emissions

The global GHG emissions in 2030 were 56.9 $GtCO_2eq$ for the baseline, 54.2 $GtCO_2eq$ for the initial NDCs, and 48.5 $GtCO_2eq$ for the updated NDCs, as shown in Fig. 1 (see the supplementary information [SI] for the absolute emissions in representative regions). The emission reduction rates were significantly higher for the updated NDCs than for the initial NDCs, especially in developed countries (Fig. 2). The reduction rates were lower in some regions in the 2020NDC_w/oET scenario compared to the 2015NDC_w/oET scenario. This was because the initial NDC scenario used the emissions in the baseline scenario in the AIM-Hub model for countries that submitted NDCs with emission reduction targets relative to the baseline scenario, while the updated NDC scenario used the specified emissions for countries that specified baseline emissions in their NDCs (see the SI). The baseline emissions specified in the NDCs were often higher than the emissions in the baseline scenario in the AIM-Hub model. The international transfer of emission allowances reduced the differences in emission reduction rates between regions.

3.2. The carbon price

Under the updated NDCs, the carbon price increased compared to under the initial NDCs, with increases in emission reductions in many countries (Fig. 3). The carbon price was higher in countries with higher emission reduction rates, such as Japan, the United States (USA), the European Union as of 2005 (EU25), Brazil, and Rest of Africa, where it increased to about 100–150 US2005$/$tCO_2$ under the 2020NDC_w/oET scenario.

In the 2020NDC_w/ET scenario, the carbon price was the same (14.6 US2005$/$tCO_2$) in all countries due to the international transfer of emission allowances. The carbon price decreased in Japan, Canada, USA, EU25, Brazil, and rest of Africa due to the international transfer of emission allowances.

3.3. Primary energy supply

In the 2020NDC_w/oET scenario, the primary energy supply decreased significantly in Organization for Economic Co-operation and Development (OECD) countries with high emission reduction rates (Fig. 4). In OECD countries, the use of renewable energy, biomass, and carbon capture and storage (CCS) increased and the use of fossil fuels, mainly oil, decreased as the reduction targets were enhanced under the updated NDCs.

In the absence of the international transfer of emission allowances, the global supply of oil and coal decreased, but the international transfer of emission allowances led to a global increase in oil under the updated NDCs. The international transfer of emission allowances also led to increases in the oil and primary energy supply in OECD countries, while in non-OECD countries there were decreases in the coal and primary energy supply.

3.4. Economic impacts

Global gross domestic product (GDP) loss was 0.21 % in the 2015NDC_w/oET scenario compared to 1.1 % in the 2020NDC_w/oET scenario (Fig. 5). The GDP losses increased in many countries and tended to be higher in countries with higher emission reduction rates. In the Rest of South America, Middle East, and North Africa, emission reduction rates and carbon prices were low, but GDP loss rates were relatively high. The international transfer of emission allowances reduced the global GDP loss from 1.1 % to 0.7 % under the updated NDCs. In the initial NDC scenario, the international transfer of emission allowances

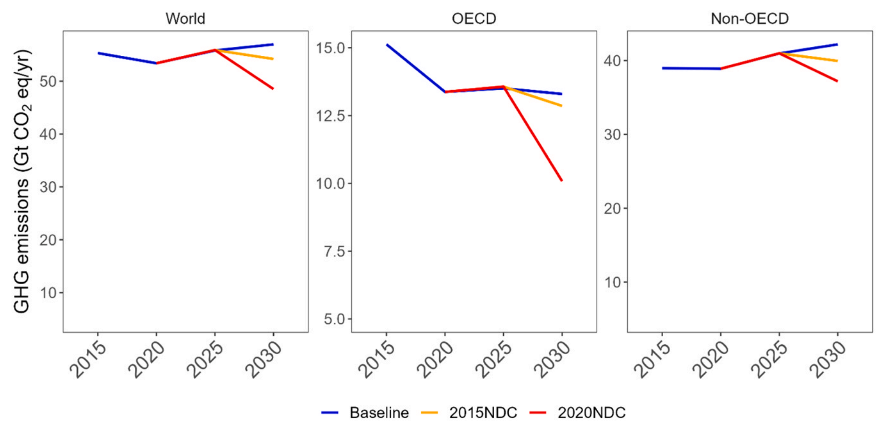

Fig. 1. Greenhouse gas (GHG) emission trajectories from 2015 to 2030 for each scenario.

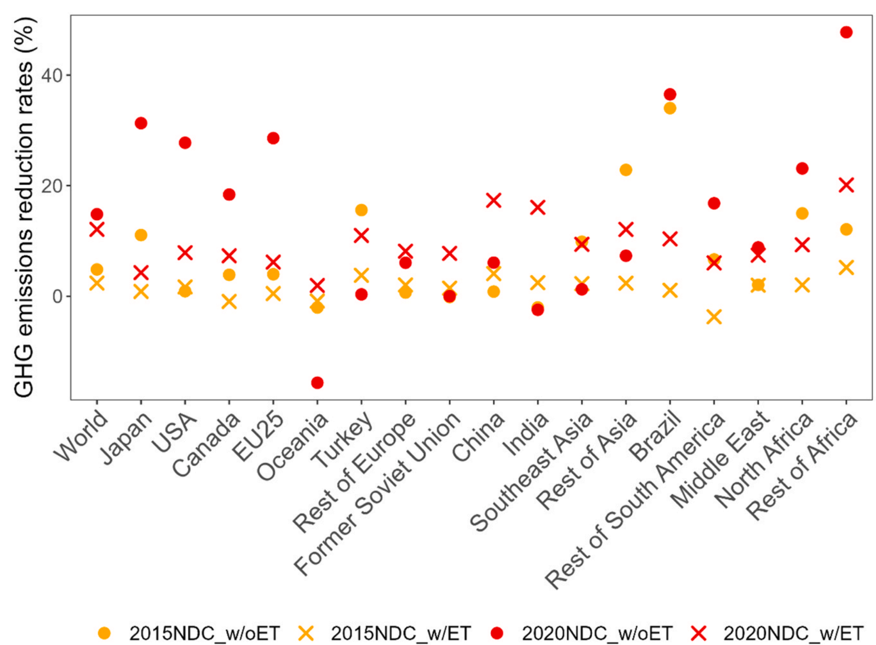

Fig. 2. Greenhouse gas (GHG) emission reduction rates relative to the baseline scenario in 2030.

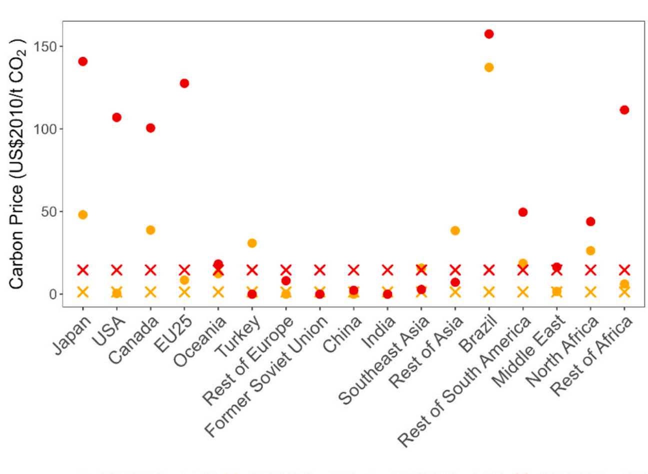

Fig. 3. Carbon prices for all regions in 2030.

reduced the global GDP loss from 0.21 % to 0.005 %; therefore, the international transfer of emission allowances reduced the global GDP loss rate more significantly in the updated NDC scenario than in the initial NDC scenario.

The international transfer of emission allowances reduced GDP loss under the updated NDCs, mainly in the countries that imported emission allowances. In contrast, GDP losses increased with the international transfer of emission allowances in some regions that exported emission allowances under the updated NDCs, such as the Former Soviet Union, China, and India.

In OECD countries, the value added tended to decrease significantly in the service (SER) sector because of the decrease in output (Fig. 6). The value added increased in the manufacturing and construction (IND) sector because of the value-added productivity increase and in the power (PWR) sector because of the increased output. Compared to the 2015NDC w/oET scenario, these trends were stronger in the 2020NDC w/oET scenario.

The international transfer of emission allowances increased the value added in the SER sector and decreased it in the PWR sector in developed countries that imported emission allowances.

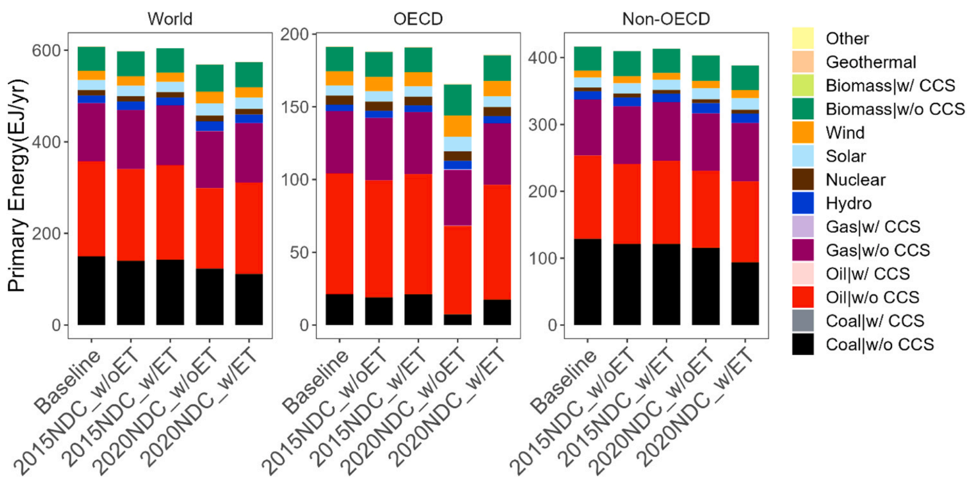

Fig. 4. Primary energy supply in 2030.

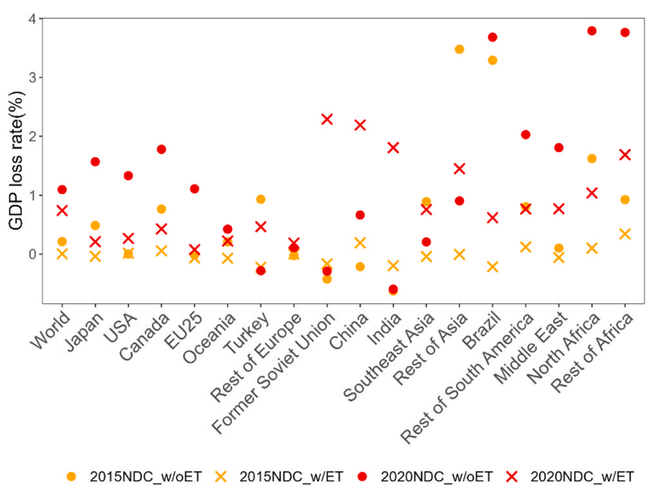

Fig. 5. GDP loss rates relative to the baseline scenario for all regions in 2030.

3.5. *Monetary transfers associated with the international transfer of emission allowances*

The global monetary flows in 2030 were 1.6 billion US 2005$ in the 2015NDC_w/ET scenario and 45.7 billion US 2005$ in the 2020NDC_w/ET scenario; therefore, the monetary flows under the updated NDCs were about 28 times higher than those under the initial NDCs (Table 2). In most developed countries, the monetary transfer expressed as a percentage of GDP was almost negligible in the 2015NDC_w/ET and the 2020NDC_w/ET scenario less than 0.1 %. In some non-OECD countries, such as the Former Soviet Union and India, the monetary transfer was high, with values of −0.28 % in the Former Soviet Union and −0.37 % in India. These countries also had a high monetary transfer as a percentage of trade, with values of −0.16 % in the Former Soviet Union and −0.48 % in India.

4. Discussion

4.1. *Comparison with earlier studies*

We compared the present results with those of other studies. In the present study, the carbon price in 2030 was 1.4 US2005$/t$CO_2$ when the international transfer of emission allowances was introduced under the initial NDCs, intermediate between the carbon prices reported in Fujimori et al. (2016b) and Edmonds et al. (2021) of 9 US2005$/t$CO_2$ and 22 US2015$/t$CO_2$, respectively. The money transfer associated with the international transfer of emission allowances in 2030 in these two studies was approximately 38 billion US2005$ and 100 billion US2015 $, respectively, and the 1.6 billion US2005$ reported in this study was smaller than these values. The possible main reason why the carbon price is so lower than earlier studies would be that this study incorporates most updated energy and emissions situation which reflects recent strong trend in renewable energy penetration. They are shown in Supplementary figures 10–12.

4.2. *Impacts of updated NDCs*

The United Nations Environment Programme (UNEP) estimated the median of global GHG emissions in 2030 for updated NDCs to be 52 GtCO_2eq for unconditional NDCs (i.e., regardless of the realization of financial and technical assistance or other factors) and 50 GtCO_2eq for conditional NDCs (i.e., conditional on financial and technical assistance or other factors)(UNEP, 2021). The Intergovernmental Panel on Climate Change (IPCC) projected the median annual global GHG emissions in 2030 under NDCs (C3b scenarios) to be 52 GtCO_2eq(Riahi et al., 2022). In this study, the global GHG emissions in 2030 were 48.5 GtCO_2eq for the updated NDCs, which was close to the UNEP and IPCC estimates (UNEP, 2021; Riahi et al., 2022). According to the UNEP (2021) and IPCC (Riahi et al., 2022), the median estimated global GHG emissions in 2030 limiting warming to 2 °C (> 67 %) are 39 and 44 GtCO_2eq, respectively. Therefore, the emissions in 2030 for the updated NDCs in this study were not sufficient to meet the 2 °C target.

Carbon prices and GDP losses increased under the updated NDCs compared to the initial NDCs. The primary energy supply also changed significantly from the baseline scenario, indicating that a rapid transformation of the energy system would be required. The supply of oil as a primary energy resource decreased significantly, which was attributed to a decrease in the consumption of liquid fuels in the industrial and transportation sectors (see the SI for the final energy consumption by sector and fuel in representative regions). Furthermore, the value added decreased in the energy-related industries and service sectors, while it increased in the power generation and transportation sectors. These results suggest that the impact of the updated NDCs on the economies, energy systems, and industries of developed countries will be significant. Additionally, developing countries have not enhanced their NDCs as much as developed countries, which increased the difference in the impact between developed and developing countries.

The carbon price indicated in this study may not correspond to the current market prices or tax levels. For instance, certain European Union (EU) countries have already implemented carbon taxes in excess of $100 per ton of CO_2. In contrast, other EU countries and other OECD countries

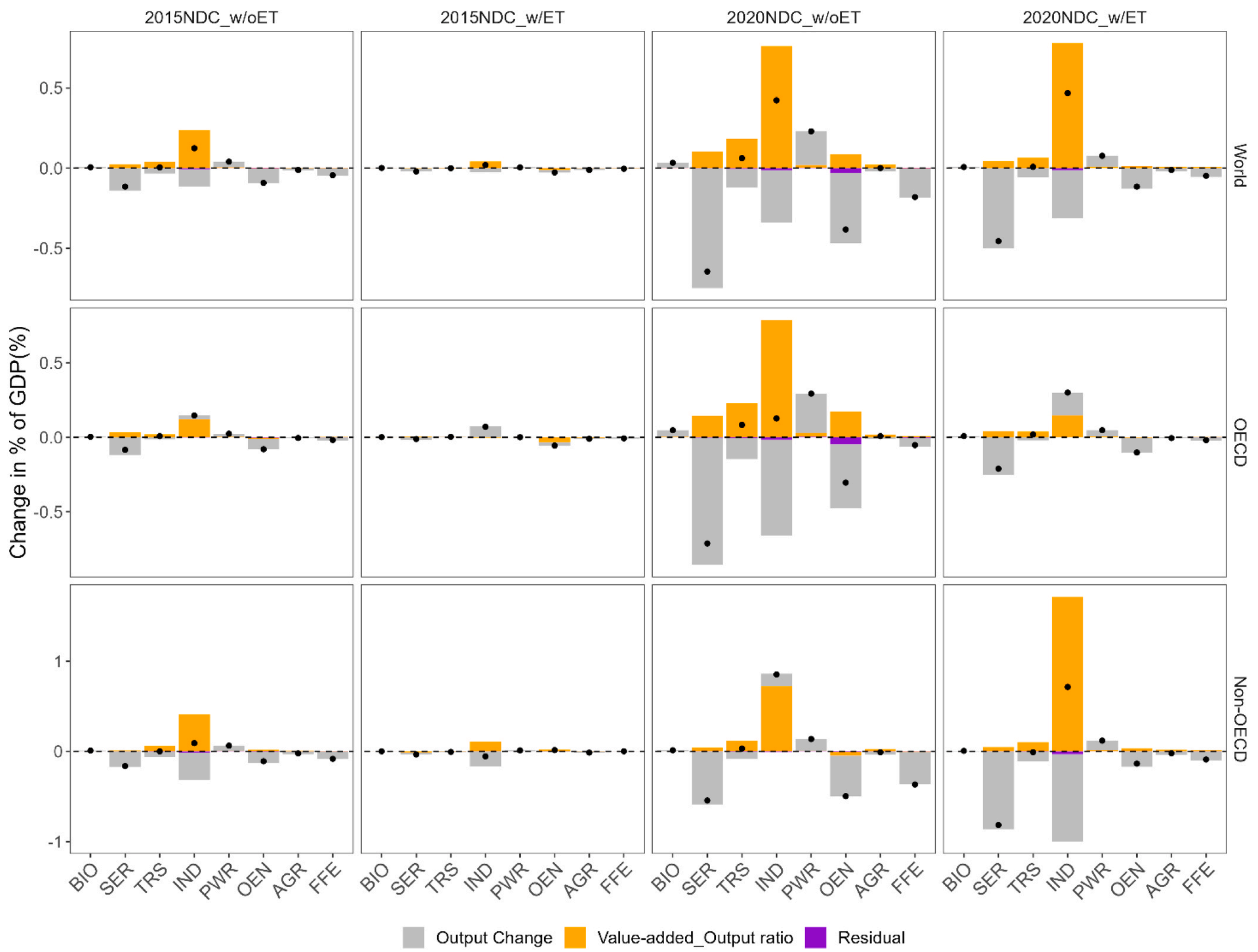

Fig. 6. Decomposition analysis of GDP changes across sectors. Value-added changes relative to the baseline scenario are expressed as a percentage of the GDP. Output change, Value-added_output ratio, and Residual refer to output changes, value-added productivity changes (value added per output), and residuals, respectively. The sectors are bioenergy industry (BIO), service (SER), transportation (TRA), manufacturing and construction (IND), power (PWR), other energy supply (OEN), agriculture (AGR), and fossil fuel extraction (FFE).

Table 2
Monetary transfer associated with the international transfer of emission allowances in the 2015NDC_w/ET and 2020NDC_w/ET scenarios in 2030. Negative values indicate the export of emission allowances. The global imports are zero because the amount of emission allowances exported equals the amount of emission allowances imported for the world. Now, trade is calculated as the mean of exports and imports.

	Monetary transfer (billion US2005$)		Monetary transfer in % of GDP (%)		Monetary transfer in % of trade (%)	
Region	2015NDC_w/ET	2020NDC_w/ET	2015NDC_w/ET	2020NDC_w/ET	2015NDC_w/ET	2020NDC_w/ET
Japan	0.163	4.75	0.0032	0.093	0.0061	0.18
USA	−0.0372	15.8	−0.00019	0.083	−0.0014	0.59
Canada	0.0250	0.845	0.0015	0.051	0.00093	0.031
EU25	0.140	11.2	0.00078	0.063	0.0052	0.42
Oceania	0.0269	0.124	0.0017	0.0079	0.0010	0.0046
Turkey	0.0729	−0.652	0.0067	−0.060	0.0027	−0.024
Rest of Europe	−0.0271	−0.0987	−0.0018	−0.0065	−0.0010	−0.0037
Former Soviet Union	−0.178	−4.31	−0.011	−0.28	−0.0066	−0.16
China	−0.843	−22.7	−0.0070	−0.19	−0.031	−0.84
India	−0.595	−12.7	−0.017	−0.37	−0.022	−0.47
Southeast Asia	0.349	−5.07	0.0060	−0.088	0.013	−0.19
Rest of Asia	0.149	−0.305	0.019	−0.040	0.0055	−0.011
Brazil	0.338	3.16	0.025	0.24	0.013	0.12
Rest of South America	0.169	2.68	0.0053	0.084	0.0063	0.10
Middle East	−0.00296	0.260	−0.00013	0.012	−0.00011	0.0097
North Africa	0.127	1.48	0.016	0.19	0.0047	0.055
Rest of Africa	0.123	5.44	0.0079	0.35	0.0046	0.20

have considerably lower carbon prices. As demonstrated, the implementation of a carbon tax would present significant challenges in the decision-making process for policy makers. However, it is crucial to acknowledge the necessity of additional measures that would need to be implemented to achieve the objectives of the NDC target. These supplementary actions should be designed to align with the level of carbon tax proposed.

4.3. Effectiveness of the international transfer of emission allowances

The international transfer of emission allowances reduced the differences in emission reduction rates among regions under the updated NDCs. This indicates that the marginal abatement cost in each region did not differ significantly around emission reduction rates under the updated NDCs. Additionally, the international transfer of emission allowances reduced global GDP losses and changed the primary energy supply without changing global emission reductions. This is because the international transfer of emission allowances has resulted in emission reductions in regions where emission reductions can be achieved at low cost. The oil supply as a primary energy resource increased and the coal supply decreased due to the international transfer of emission allowances. This was attributed to the emission reductions from coal combustion, which is a low-cost option for emission reductions. Additionally, while it is difficult for developed countries to rapidly change their energy systems because they have already completed the capital investment in their formation, it is relatively easy for developing countries to grow their economies while building low-carbon energy systems. The international transfer of emission allowances increased the value added in the SER sector and decreased value added in the PWR sector, mainly in the developed countries that imported emission allowances. This was because the amount of capital input decreased in the PWR sector, which required capital inputs to reduce emissions (see the SI for the power generation in representative regions), while the amount of capital input increased in the SER sector.

The international transfer of emission allowances reduced climate mitigation costs in developed countries in terms of GDP loss rates (see the SI for the consumption loss rates). It also reduced the changes in primary energy supply from the baseline scenario in developed countries. This suggests that the international transfer of emission allowances can reduce the need to make rapid changes to the energy systems of developed countries. Furthermore, the international transfer of emission allowances reduced the rapid changes in value-added in developed countries. These results suggest that the international transfer of emission allowances can reduce the impact of emission reductions on the economy and energy system in developed countries. Developed countries might be able to further increase their emission reductions using the gains associated with the international transfer of emission allowances.

Edmonds et al. (2021) estimated that an additional reduction of 9 $GtCO_2$/year could be achieved in 2030 if the costs of implementing the NDCs were reduced by the international transfer of emission allowances and the savings were then reinvested in additional emissions mitigation measures. These additional emission reductions would be possible if developed countries were willing to accept the same level of mitigation costs for implementing updated NDCs with the international transfer of emission allowances as those required without the international transfer of emission allowances.

The reduction in global GDP loss rates due to the international transfer of emission allowances was higher for the updated NDCs than for the initial NDCs. Additionally, the money transfer associated with the international transfer of emission allowances was more than 28 times higher under the updated NDCs than under the initial NDCs. This suggests that the international transfer of emission allowances played an important role in reducing the global mitigation cost by expanding the size of the international transfer of emission allowances market under the updated NDCs compared to the initial NDCs.

Conversely, GDP losses increased significantly in the Former Soviet Union, India, and China. The international transfer of emission allowances imposed domestic carbon prices equivalent to the international markets in export permits, which resulted in abatement and negative economic burdens in all sectors. The macroeconomic impact was dependent on whether the macroeconomic mitigation costs or the benefits from the export of emission allowances were higher. In the Former Soviet Union, India, and China, the macroeconomic mitigation costs were higher and were considered to have a negative impact on the macroeconomy. When implementing the international transfer of emissions allowances, developed countries recover their competitiveness in the global trade market, although some developing countries lose exports(Flachsland et al., 2009; Alexeeva and Anger, 2016; Fujimori et al., 2016b; Li and Duan, 2021; Böhringer et al., 2021) (see the SI). This occurred because the international transfer of emission allowances assumed the optimization of the microeconomic aspect, i.e., the carbon price was the same worldwide, and the cost of emission reduction was minimized and did not assume the optimization of the macroeconomic aspect.

It is relatively easy for developing countries to grow their economies while building low-carbon energy systems. Once built, these low-carbon energy systems will enable emission reductions after 2030. To achieve the 1.5°C and 2°C targets, developing countries will eventually need to reduce their emissions, and sharing emission reductions by transferring emission allowances at the present time may facilitate future reductions. Furthermore, emissions reduction brings co-benefits such as air pollution reduction for developing countries(Cheng et al., 2015), which is one of the serious problems for developing countries (see the SI for NO_x and SO_2 emissions). By contrast, emissions reductions increase food prices in developing countries, which should be noted from a food security perspective (see the SI for the food price changes) However, this is small compared to the increase in food prices in developed countries in the 2020NDC_w/oET scenario.

The Former Soviet Union and India have small emission reduction targets in their NDCs, and the international transfer of emission allowances will therefore greatly increase their emission reductions. If these countries are willing to reduce emissions, they are likely to share the burden of emission reductions in developed countries through the international transfer of emission allowances. However, if they are reluctant to reduce emissions, they may not participate in the international transfer of emission allowances, which would cause significant economic losses in their own countries. Therefore, it is necessary to consider the type of system that these countries would be willing to participate in. For example, developed countries could provide additional financial and technological support in addition to payments through the international transfer of emission allowances. The Copenhagen Accord, adopted at COP15 in 2009, called for developed countries to transfer $100 billion per year by 2020 to help developing countries adapt to and mitigate climate change(2010). As an important form of aid from developed countries to developing countries, Official Development Assistance (ODA) amounted to about $150 billion in 2018(OECD, 2019). In this study, the monetary transfer associated with the international transfer of emission allowances under the updated NDCs was 158 billion US2005$, i.e., more than the target in the Copenhagen Accord and the actual amount of ODA. Therefore, more support than that envisaged in the Copenhagen Accord and provided by ODA may be required to mitigate the negative economic impact of emission reductions in developing countries. However, the realization of such transfers could take time and needs unprecedented international movement. However, the role of this study is not just to show realistic numbers but, rather, to inform policy makers so they can more fully understand “what if” under the economic rationale conditions.

4.4. Policy implications of the international transfer of emission allowances

The international transfer of emission allowances reduced emission reductions in developed countries because emission reductions were implemented in a manner that minimized abatement costs worldwide. As a result, GDP losses in developed countries were smaller than those in developing countries. From a macroeconomic perspective this might not be acceptable for developing countries in terms of the principle of equity. In this study, the amount of emission allowances exported by developing countries increased under the updated NDCs compared to the initial NDCs. If the monetary flow to developing countries was high, negative effects such as Dutch disease (see (Jakob et al., 2015)) may occur in developing countries, preventing them from growing their industries and balancing emission reductions and economic growth. In addition to the model simulation, policy makers must consider such possibilities. Developing countries with higher GDP losses tended to have much lower reduction rates relative to the baseline scenario than other countries. One possible reason for this large increase in GDP losses with the international transfer of emission allowances was that the reduction targets were much lower than those in developed countries. The existence of regions with increased GDP losses due to the international transfer of emission allowances presents a challenge for the international transfer of emission allowances, but it may be necessary for these developing countries to increase their emission reduction targets to some extent.

A cooperative mechanism established by Article 6, paragraph 4, of the Paris Agreement (2023) could be adopted when implementing NDCs. Care must be taken when designing such a system, because if the system is not designed to function properly, the effects of the international transfer of emission allowances estimated in this study may not be achieved. Additionally, the non-market-based approaches covered by Article 6.8 of the Paris Agreement include a wide range of development actions, including contributions to sustainable development, poverty eradication, and adaptation measures, which are difficult to measure as emission allowances and international rules will therefore need to be established.

4.5. Limitations of this study

In this study, when implementing NDCs into the model, various assumptions were made, such as NDCs in countries whose baseline emissions were not specified in their NDCs and the interpretation of conditional and unconditional NDCs. Rogelj et al. (2017) analyzed the uncertainty of emission estimates for 2030 when implementing the previous NDCs. Their study showed that the global estimated emissions for 2030 under NDCs ranged from 47.1 to 62.9 $GtCO_2eq$. Of the uncertainties, 7.1–11.3 $GtCO_2eq$ were due to socioeconomic baseline variation, and 1.0–2.7 $GtCO_2eq$ were due to the conditionality of NDCs. The study also found that uncertainties were larger in developing countries than in developed countries. Although our study produced estimates under updated NDCs, it is necessary to consider the likely uncertainties as indicated in Rogelj et al. (2017). For example, the impacts of the updated NDCs in developing countries could change over time, and the monetary transfers associated with the international transfer of emission allowances could also change as emissions are reduced in developing countries, which will then result in changes to the export emissions allowance.

The present study also did not consider the sector specific targets of each country, such as renewable energy targets. Therefore, the results of this study for primary energy supply and electricity generation may differ from the targets of each country. For example, it was estimated that power generation with CCS accounted for about 20 % of power generation in Japan in 2030 (see the SI for the power generation). However, Japan's 6th Strategic Energy Plan(METI, 2021) aimed for the commercialization of CCS by 2030, and was not expected to introduce the same amount of CCS as estimated in this study. If the amount of CCS implemented is lower than estimated in this study, more costly abatement options will have to be adopted, which will result in a higher negative impact on the economy. Therefore, it should be noted that the estimated negative economic impact of emission reductions and the effects of the international transfer of emission allowances may differ from those estimated in this study if the targets for renewable energy and other factors are considered.

The base year for the AIM-Hub model is 2005, which may not capture the latest information that could affect emission reductions. It is possible to incorporate current topics into the model to an extent, but this is not always desirable as it can include extreme events, such as COVID-19 and the Russia-Ukraine conflict, and bias the results. Other models used for scenario assessment in the IPCC Six Assessment Report also set their base year to 2005–2015(Pedro, 2016; Emmerling et al., 2016; Krey et al., 2020; Baumstark et al., 2021), so this is one of the limitations of our study, but is not a critical issue.

In this study, the international transfer of emission allowances increased GDP losses in some developing countries, and they tended to be higher than the GDP losses in developed countries. Thus, the international transfer of emission allowances may cause negative macroeconomic impacts in some countries. This suggests that these countries may decide not to participate in the international transfer of emission allowances and the monetary transfers associated with the international transfer of emission allowances may therefore be lower than the results in this study. To address these issues, it is necessary to establish a scenario in which countries such as the Former Soviet Union, India, and China do not participate or only partly participate in the international transfer of emission allowances.

Additionally, because each country submits its own emission reduction targets under the NDCs, countries that are not willing to reduce emissions can submit easily achievable emission reduction targets and then gain from the international transfer of emission allowances. Under these situations, an international transfer of emission allowances in which all countries participate could not be implemented, or a cap would be set on the amount of emission allowances, with the result that the amount of emission allowances traded would be lower than estimated in this study.

The international transfer of emission allowances also has some disadvantages. The price of allowances in the market is unstable; monitoring, reporting, and verification of the emission reductions are required, and a market for the international transfer of emission allowances needs to be established. These issues are beyond the scope of this study, but they should be considered by policy makers.

5. Conclusions

We estimated the economic and energy implications when countries implement initial NDCs and updated NDCs and the effectiveness of the international transfer of emission allowances using the AIM-Hub model. The results showed that global GDP losses would increase from 0.21 % to 1.1 % under the updated NDCs compared to the initial NDCs. Large GDP losses were in developed countries with strict emission reduction targets and where there is a need for rapid transformation of the energy system. The international transfer of emission allowances reduced global GDP losses from 1.1 % to 0.7 % compared to a case without the international transfer of emission allowances. It also reduced the negative economic impact and contributed to lowering the risks associated with a rapid energy transition, especially in developed countries. Furthermore, the reduction in the GDP loss rates due to the international transfer of emission allowances was higher for the updated NDCs than for the initial NDCs. The money transfer associated with the international transfer of emission allowances was also higher under the updated NDCs than under the initial NDCs. This study indicated that the international transfer of emission allowances is a useful option for developed countries in terms of reducing their economic losses and providing more time for the transformation of their energy systems. However, some developing countries faced greater GDP losses than developed countries when the international transfer of emission allowances was introduced, and it will therefore be necessary to consider how to support such countries, including the provision of financial and technical support in addition to payments through the international transfer of emission allowances, and to consider how to share emission reductions.

This study only considered emission reduction targets by 2030. If emission reductions after 2030 are based on the net zero targets proposed by each country, the international transfer of emission allowances by 2030 may facilitate the achievement of the net zero targets in developing countries. However, this study did not estimate such a scenario, and it is therefore necessary to estimate the effect of the international transfer of emission allowances on emission reductions based on net zero targets after implementing the NDCs.

Contributions

T.T. and S.F. conceived the study and designed the scenarios; all authors contributed to the methodology, software preparation, and model construction; T.T. prepared material, collected data, carried out the analysis of modeling results, created figures, and drafted the paper; and all authors contributed to the writing of the entire paper.

CRediT authorship contribution statement

Ken Oshiro: Writing – review & editing. **Shinichiro Fujimori:** Writing – review & editing, Software, Funding acquisition, Conceptualization. **Osamu Nishiura:** Writing – review & editing, Software, Methodology. **Toshiki Tsutsui:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

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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Ethics declaration

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecadv.2025.100022.

Data availability

Data will be made available on request.

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