Adjusting Net Zero Emissions Pledges Under Global Permit Trade – Implications to Welfare and Consumption-based Emissions Pledges

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Adjusting net zero emissions pledges under global permit trade – implications to welfare and consumption-based emissions pledges

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Abstract

Many countries have made net zero emissions pledges (NZEPs). Who have made the most stringent pledges, and how to improve equity and efficiency of global mitigation efforts? We developed a dynamic computable general equilibrium (CGE) model to analyze these questions. We fitted the model with a new, endogenous CCS modelling mechanism, a new renewable power generation nesting structure, and an energy-specific base-case. Using this model, we build three scenarios up to 2050, namely 1) a 'business-as-usual' scenario, 2) a 'net zero emissions pledges' scenario (with two variants: with and without global permit trade), and 3) an 'adjusted emissions pledges' scenario, in which the existing NZEPs are adjusted in pursuit of improved equity under global permit trade. Our results show that without global permit trade, the developed regions would suffer more economically and import more emissions for their final use. By forming global permit trade, the world would enjoy higher mitigation efficiency, with the developed regions yielding most of these benefits, leaving some less developed regions to be worse off, while hurting global welfare (when higher inequality reduces global welfare). We demonstrated that, by making the more developed regions to pledge to even stronger abatement targets, it is possible to achieve a Pareto Improvement condition, in which no region is worse off because of permit trade. This would not only improve global welfare but also reduce the net transfer of carbon from developing to developed regions through trade. Our results lead to one important policy recommendation. Countries should work together to facilitate global permit trade and to ask the more developed regions to pledge to even lower, if not negative, emissions levels than their current NZEPs.

Key words: Paris agreement, net zero emissions pledges, permit trade, equity, efficiency, welfare, CGE, GVC, trade-embodied emissions

JEL classification: C68; Q4; R13

Keywords: carbon neutrality, permit trade, CGE, GVC, welfare.

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Table of Contents

1. Introduction

The Paris Agreement aims to limit global temperature rise by 1.5 degrees Celsius above the pre-industrial revolution level. Towards this goal, more than 70 countries have made net zero emissions pledges (NZEPs). Developed countries typically set earlier net zero emissions dates. The United States (U.S.), the Europe Union (E.U.), and Japan, have pledged to reach net zero emissions by 2050. China and Russia set the date to 2060, while India set the date to 2070. The NZEPs have covered about 70% of the global emissions, they showcase countries' willingness to sacrifice a degree of economic growth in return for a lesser risk of catastrophic climate events.

How countries achieve their NZEPs are important. Mitigation efforts are generally regarded as costs, as environmental externalities are internalized, costs are expected to rise. Such costs can be non-negligible to the global economy (Kompas et al., 2018). The costs are unlikely to be equally distributed, too. The developed countries typically face steeper marginal abatement curves (MACs) and have generally set earlier net zero emissions targets. If countries pursue their NZEPs on their own, the developed countries are expected to make larger economic setbacks than developing countries (Aldy et al., 2016). In addition, higher domestic production costs may shift carbon-intensive activities abroad, creating a competitive disadvantage to developed countries and induce carbon leakage. The prospect of disproportionately large economic setback and carbon leakage have invoked some developed regions, notably the EU, to consider border carbon adjustment mechanisms (CBAMs) (Fouré et al., 2016, Zhong and Pei, 2022). By erecting higher trade barriers, developed countries may restore some trade competitiveness and reduce the extent of carbon leakage. The higher tariff rates, however, would also create further efficiency losses.

Should countries trade emissions permits globally, though, the global mitigation efforts would be more efficient (Flachsland et al., 2009). This is because more mitigation tasks can be shouldered by the less developed world, who tends to have flatter MACs (Morris et al., 2012). The challenge of this approach, however, is that the poorer regions may suffer larger economic setbacks than the richer ones as their costs of livings and productions raise because of higher carbon costs (Babiker et al., 2004). If one constructs a global welfare index, such as the Atkinson (1970)'s, that includes both people's like for efficiency and their dislike for inequality, this widening gap could potentially reduce global welfare despite enhanced economic efficiency. It is possible, however, that with certain allocations of global mitigation responsibilities, global permit trading could lead to gains in global welfare when both equity and efficiency and considered. In addition, it is also possible that no regions would be worse off compared to no permit trade situations, i.e., achieving a Pareto Improvement condition. Feng et al. (2018) demonstrated, using the example of China's regional emissions trading system (ETS) pilots, that giving more stringent mitigation responsibilities to the richer regions would help to achieve these conditions.

It is worth noting that the existing NZEPs, which can be seen as countries' committed mitigation responsibilities, are production-based pledges. They target emissions produced within countries' borders but are not necessarily consumed within. There may be many emissions that are embodied in a country's trade. These emissions can be embodied in trade in both final goods and intermediate goods and can cross borders several times before finally being consumed. The committed emissions from a consumption-based perspective are therefore the production-based pledges plus the imported emissions that are consumed within their borders and minus those that are exported and eventually consumed outside their borders. Meng et al. (2018) calculated such trade-embodied emissions and found that developing countries tend to have a larger share of emissions induced by foreign final demand. With global emissions permit trade, as developing countries internalize more mitigation costs, their carbon intensive activities may loose global competitiveness and thus reduce the level of emissions transfer from developed regions to the developing regions.

There could be many ways to engage in permit trade. Countries can form a uniformed global emissions trading system, link their individual ETSs[4], or purchase emissions reduction certificates[5] from abroad. It has been hard to convince the poorer regions to link with the richer ones also because they have not committed to absolute emissions targets. China and India, for example, have only committed to emissions intensity targets – such targets are hard to be translated into emissions caps. Now that many developing countries have made NZEPs, and they can be seen as de-facto emissions caps. Another opportunity for global permit trade is that the NZEPs pose much harder emissions constraints, especially towards the 2050s, and that the opportunity cost of not trading, in terms of economic efficiency, could be too big to ignore.

The current study thus asks four important questions, First, what are the economic implications to different countries should they achieve their NZEPs without permit trade. Second, how would these implications change when they engage in global permit trade. Third, would it be possible to make no regions to be worse-off from permit trade and if the existing NZEPs shall be adjusted, and how. Fourth, what are countries' mitigation pledges from the consumption-based perspective under existing and adjusted pledges. We answer these questions by combining dynamic computable general equilibrium (CGE) modelling with global value chain (GVC) analysis and welfare analysis using Atkinson (1970)'s welfare index. Section 2 is a literature review. Section 3 details data and analytical methods. Section 4 discusses modelling results. Section 5 makes concluding remarks.

2. Literature Review

The go-to method for analyzing economic implications of NZEPs is by using CGE models. There has been a large body of literature using CGE models to evaluate economic implications of climate policies (Cao et al., 2021, Babiker et al., 2003, Böhringer and Löschel, 2006, Cui et al., 2020, Dai et al., 2017, Lin and Jia, 2018, Liu and Lu, 2015, Qi et al., 2014, Zhang, 2000, Zhang et al., 2016, Wu et al., 2022a, Babatunde et al., 2017, Fraser and Waschik, 2013, Liu et al., 2017). In this tradition, many have used global CGE models to compare economic implications of climate policies across countries (Böhringer, 2000, Viguier et al., 2003, Lu and Stern, 2016, Fragkos et al., 2018, Vandyck et al., 2016, Aldy et al., 2016, Thube et al., 2022). Since the rectify of the Paris Agreement in 2009, many studies have focused on the economic implications of countries' nationally determined contributions (NDCs) with the end of the simulation year set to 2030. Results from these studies generally show that developed countries' NDCs would lead to greater economic costs than the developing countries.

The release of the NZEPs have provided new opportunities for similar studies to be conducted, with the end year being set at 2050 or later. There are challenges, however, that are involved with setting

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[4] Many regional ETSs have already been created, such as the EU ETS, the California's cap and trade program, and China's national ETS.

[5] Based on the Clean Development Mechanism (CDM) under the Kyoto Protocol, for example, companies can use Certified Emissions Reductions (CERs) to fulfill their mitigation obligations.

a later date. First, most dynamic CGE analysis requires developing business-as-usual scenarios. Most studies lay down the macroeconomic fundamentals for the future, using forecasts for labor force, TFP, and so forth. In addition, some also set predicted carbon price levels in base cases. Dixon and Rimmer (2013) show that for sectors' future growth trajectories that might deviate largely from the past trends, accurate long-term forecasting requires sector-specific controls. However, few studies have set up specific energy development paths for each type of fossil fuel use and power generation in building a base-case for CGE models. Failing to do so risk having unrealistic base-case scenarios for energy composition, and therefore misleading economic implications.

Another challenge in CGE modelling of longer scenarios has been the treatment of new technologies, most notably renewable power generation and carbon capture and storage (CCS). Regarding renewable power, the challenge is to design a nesting strategy which models user's optimization behaviors for choosing between different power sources. A nesting strategy contains two aspects, namely nesting structure, and elasticity parameters. The GTAP-E-Power model offers a reference for both (Peters, 2016a). However, one needs to design different renewable power generation nesting strategies based on their chosen power sector classifications. Since our model has a different classification to theirs, we need to design a new one. Regarding CCS, a few attempts have incorporated CCS and related technologies into economy-wide mitigation costs analysis using CGE models (Huang et al., 2020, Li et al., 2017, Vennemo et al., 2014). No studies have yet expanded such mechanisms to a global-scaled analysis for the NZEPs.

CGE models are also useful in investigating global emissions-sharing patterns – most notably, issues regarding carbon leakage. Many studies have used CGE models to test whether unilateral mitigation policies would lead to carbon leakage, domestically and internationally (Elliott et al., 2010, Elliott and Fullerton, 2014, Zhang et al., 2020a, Gerlagh and Kuik, 2014, Babiker, 2005, Balistreri and Rutherford, 2012, Burniaux and Oliveira Martins, 2012). Many have also tested ways to curb them (Boeters and Bollen, 2012, Li and Zhang, 2012, Böhringer et al., 2012, Winchester et al., 2011). It is interesting to notice that the existence of carbon leakage is not confirmed in all such ex-ante studies, and that the extent of leakages are usually small. While an ex post study also failed to find sufficient evidence for the EU ETS to have caused carbon leakage (Naegele and Zaklan, 2019).

One potential limitation of these studies has been a systematic accounting for emissions that are embodied in trade. Indeed, a body of literature has been devoted to estimate consumption-based emissions – emissions that are not necessarily produced but are ultimately consumed within the border (Peters, 2008, Davis et al., 2011, Su and Ang, 2010, Su and Ang, 2014, Pan et al., 2008). In recent years a new accounting framework, pioneered by Koopman et al. (2014), has been developed to trace the origins and destinations of value added through global value chains (GVCs). Such methods have the advantage of detailing forward- and back-linkages, as well as overcoming the double-counting problems. The trade-embodied emissions literature has quickly absorbed this new framework and was able to trace historical emissions using similar techniques (Meng et al., 2018, Chen et al., 2020, Zhang et al., 2017, Zhang et al., 2020b, Xu et al., 2020).

Since input-output (IO) models and CGE models can produce perturbed IO tables under different scenarios for different years in the future, the perturbed IO tables can then be used in the GVC accounting framework for *ex ante* studies. Xiao and Feng (2019) and Zhou and Zhang (2019) applied this line of thought to analyze the impacts of U.S.-China trade frictions and Trump's tax reform to global trade in value-added. Tian et al. (2022) combined input-output modelling with GVC analysis to study the impact of the Regional Comprehensive Economic Partnership (RCEP) to global emissions sharing. Tan et al. (2018) and Wu et al. (2022b) combined CGE modeling with GVC and structural decomposition analysis to investigate the severity and sources of carbon leakage. Combining these techniques, studies generally found that developed regions tend to be net emissions importers – emissions embodied in their imports exceed those in their exports.

Table 1: Selected global analyses on implications of long-term mitigation policies to welfare and trade-embodied emissions

Study	Global permit trade	Energy-specific base-case	renewable power generation disaggregation and nesting	Explicit modelling of CCS	GVC analysis of Trade-embodied emissions	Equity-adjusted global welfare	Mitigation policy	End year
Lanzi et al. (2012)	√	X	X	X	X	X	Kyoto	2020
Springmann (2012)	√	X	X	X	X	X	Non-specific	2020
Antimiani et al. (2016)	√	X	X	X	X	X	450ppm	2050
(Qi and Weng, 2016)	√	X	√	√	X	X	NDCs	2030
(Li and Duan, 2020)	√	X	√	√	X	X	NDCs	2030
Siriwardana and Nong (2021)	√	X	X	X	X	X	NDCs	2030
Zhong and Pei (2022)	X	X	X	X	√	X	EU CBAM	Non-specific
Wu et al. (2022b)	X	X	√	X	√	X	NDCs	2030
This study	√	√	√	√	√	√	NZEPs	2050

Engaging in international permit trade is a mechanism that has been merited for both containing carbon leakage and reducing economic losses (Qi and Weng, 2016, Li et al., 2019). The key challenge is to ensure that the poorer regions are not worse off compared to no-trade scenarios. As discussed, Feng et al. (2018) demonstrated - using China's regional carbon markets linking as an example - that setting more stringent mitigation targets for the richer regions could indeed lead to a Pareto-improvement. No studies have examined if Pareto improvement could be achieved for the NZEPs. From a global perspective, allowing international permit trade can enhance overall efficiency but may harm global income equality. If a widening income gap is viewed as a loss to global welfare, then a welfare index should take into the consideration of changes in both equity and efficiency. Feng et al. (2018) applied Atkinson (1970)'s welfare index, which weighs both equity and efficiency, and found that asking the richer regions to commit more abatement responsibilities could improve overall welfare.

Clearly the literature is rich in applying CGE modelling, welfare analysis and GVC analysis in studying climate policies and long-term low carbon development strategies. We list a small sample of them in Table 1. This small sample nevertheless shows that although there have been important development and utilization of analytical techniques and frameworks, there is still room for them to be combined and employed to answer different questions.

The current study contributes to the literature in five aspects: First, we develop an energy-specific base-case, with endogenous CCS mechanisms and a new renewable power generation nesting strategy in dynamic CGE modelling, up to 2050; and on top of this, we model NZEP scenarios and evaluate their economic implications. Second, we compare the economic implications of countries achieving their NZEPs with and without having global emissions permit trade. Third, we adjusted the existing NZEPs in search of Pareto improvement conditions as countries open to global permit trade. Fourth, we use Atkinson (1970)'s welfare index to conduct welfare analysis for the world by weighing both equity and efficiency. Fifth, we use GVC analysis to calculate countries consumption-based emissions pledges.

3. Data and methods

3.1 Base-data and update

We use a recursive dynamic CGE model to conduct the simulations. The model builds on the standard GTAP-E model (Burniaux and Truong, 2002), with international emissions permit trading module built-in. Our data is compiled from the GTAP-power version 10 data base (Chepeliev, 2020, Peters, 2016b). The data base year is 2014. It is important to rely on a database like GTAP-power, which has a detailed representation of 11 different power generation technologies (sectors).

Table 2: aggregated regions, sectors, and factors

Region (11)	Sector (24)	
1. Utd States of America (USA)	1. Agriculture (agr)	13. Other manufacturing (omf)
2. Central South America (CSA)	2. Coal (coa)	14. Power transmission distribution (tnd)
3. European Union (EUR)	3. Oil (oil)	15. Solar power (slp)
4. Africa (AFR)	4. Gas (gas)	16. Wind power (wdp)
5. Mid-East (MDE)	5. Other mining (oxt)	17. Nuclear hydropower (nhp)
6. Russia (RUS)	6. Petroleum products (p_c)	18. Other power (otp)
7. China (CHN)	7. Chemical rubber plastic (crp)	19. Coal-fired power (cfp)
8. India (IND)	8. Non-metallic mineral (nmm)	20. Gas-fired power (gfp)
9. Japan (JPN)	9. Iron steel (i_s)	21. Oil-fired power (ofp)
10. Southeast Asia (SEA)	10. Non-ferrous metal (nfm)	22. Construction (cns)
11. Rest of the World (ROW)	11. Electronics (ele)	23. Transport (tsp)
	12. Motor vehicle and part (mvh)	24. Services (srv)
Factors (2)	1. Labour 2. Capital	

We aggregate the original 141 regions, 76 sectors, and 8 factors into 11, 24 and 2, respectively (see Table 2). The aggregated region classification is consistent with that of IEA (2021), which, as will be shown later, is an important source of data input for our scenarios design. The aggregated sector classification maps the power generation classification between GTAP-power and IEA (2021). Noticeably, we aggregated the peak load and base load power generation sectors due to the lack of their individual projection levels in future scenarios. The non-power sectors classifications leave enough differentiations between energy intensive sectors (e.g., crp and i_s) and GVC-related sectors (e.g., ele and mvh), while maintaining a tractable size. The factor is aggregated into two broad categories, namely labour and capital, for simplicity.

Using historical data, we update each region's macroeconomic and energy data from 2014 to 2020. Historical data for gross domestic product (GDP), population, household consumption, and investment are taken from the World Development Indicators (The Wold Bank, 2022). Historical data for energy consumption by fuel and electricity generation by technology are taken from the World Energy Outlook 2021 (IEA, 2021).

3.2 A multi-layer power generation nesting system in production

We incorporate a new power generation nesting structure of production into our model. Our higher-level production nests and the non-electricity energy nests have similar nesting structures and constant elasticity of substitution (CES) parameters as the GTAP-E model. Given that we have different power generation sector specification to neither the GTAP-E model nor the GTAP-E-power model (Peters, 2016a), however, we need a new power generation nesting structure with new CES parameters (see Figure 1). Ours is a special structure such that we have a 'main substitution' bundle, which is a CES combination between a fossil fuel power bundle and a wind and solar bundle. This allows specific replacement of the former by the latter. Such a mechanism is critical to the transformation of the power generation structure in modelling long-term decarbonization scenarios. Failing to do so might risk deriving unrealistic energy compositions in long-term CGE simulations.

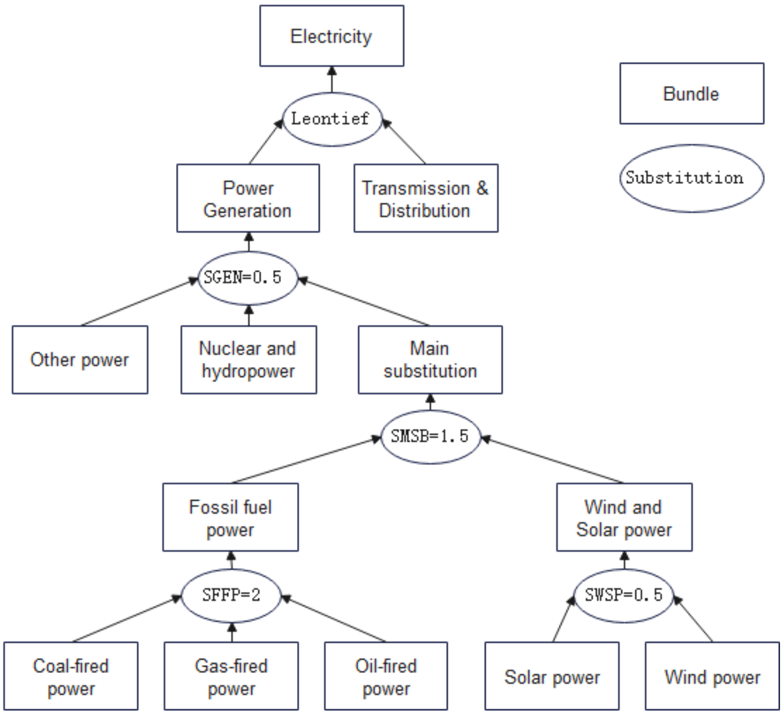


Figure 1: Electricity nesting structure in production

The CES substitution rate of the main substitution bundle (SMSB=1.5) is set to be more elastic than that of the 'fossil fuel power' bundle (SFFP=2) and more elastic than that of the 'wind and solar' bundle

(SWSP=0.5) and the power generation bundle (SGEN=0.5), reflecting the relative easiness of technological switch at each level. These CES values are not obtained from econometrics analyses – such efforts warrant devoted studies on their own – they are nevertheless within the generally accepted boundary of CES parameters. A systematic sensitivity analysis is performed with regard to these parameters (see Section 4.8).

3.3 A carbon capture and storage modelling mechanism

We incorporate an explicit, endogenous way of modelling CCS in our model. We set up an explicit, negative emissions account, FCCS(f,u,r), to represent the amount of CO_2 emissions captured by CCS from the use of fuel f (f∈[coa, oil, gas}] by user u (u∈[crp, nmm, i_s, cfp, gfp, ofp}) in region r (r∈all regions). We can obtain FCCS(f,u,r) endogenously by controlling the CCS coverage rate, FCCSCOV(f,u,r), such that:

$$FCCS(f,u,r) = -FCCSCOV(f,u,r) \times CO_2(f,u,r), \quad 0<FFCCSCOV<1, \qquad \text{Equation (1)}$$

where CO_2(f,u,r) is the amount of emissions released before CCS is used. Net emissions of region r, $NetCO_2$(r), can thus be expressed as the sum of CO2 emissions and CCS removals, such that:

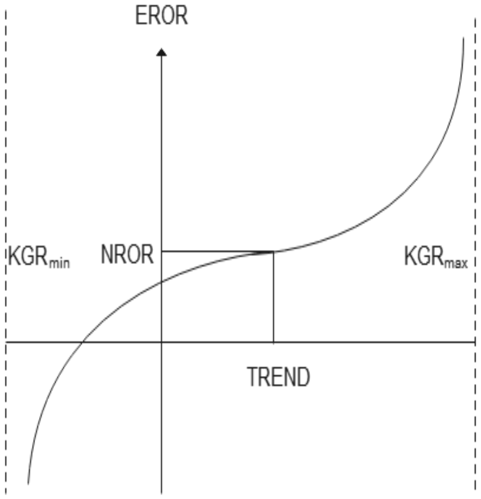
$$NetCO_2(r) = \sum_{f,u} CO_2(f,u,r) + \sum_{f,u} FCCS(f,u,r) + OCCS, \qquad \text{Equation (2)}$$

Where OCCS is a negative emissions account for emissions removed by other CCS technologies (such as bioenergy CCS (BECCS) and direct air capture (DAC)).

There are three important advantages of this CCS modelling mechanism. The first is that by controlling CCS coverage rate for different CCS users, it helps to see how much emissions can be removed by each type of CCS users by using each type of fuels. Second, this helps to calculate the net emissions of each CCS users. CCS users can thus endogenously adjust their output levels by considering CCS costs and carbon pricing levels. Third, this helps to prevent possible mismatch between CO_2 emissions and CCS removals levels, as without tying these two by controlling the coverage rate there exists the risk that CCS removals are so high that they may exceed the amount of emissions produced.

3.4 Incorporating MONASH-styled dynamisms into GTAP-E

We incorporate the MONASH-style dynamisms into the generic GTAP-E model. The generic GTAP-E model is a static model. The MONASH-style dynamisms are documented in Dixon and Rimmer (2002) and have been widely applied worldwide (Dixon et al., 2013, Adams et al., 1994, Nong et al., 2017, Choi et al., 2017, Bohlmann et al., 2016, Dixon et al., 2017, Cao et al., 2021). Following these, we use an inverted logistic capital supply curve (see Equation 3 and Figure 2) to establish a relationship between capital growth rates ($KGR_{j,r}$) and expected rate of return to capital ($EROR_{j,r}$) for industry j in region r,



$$
\begin{aligned}
&EROR_{j,r} = NROR_{j,r} \\
&+\left(1/C_{j,r}\right)\times\left[l\,\mathrm{n}\left(KGR_{j,r}-KGR_{\min j,r}\right)-\ln\left(KGR_{\max j,r}-KGR_{j,r}\right)\right. \\
&\left.-\ln\left(TREND_{j,r}-KGR_{\min j,r}\right)+\ln\left(KGR_{\max j,r}-TREND_{j,r}\right)\right]
\end{aligned}
$$

Equation (3)

Figure 2: inverted logistic capital supply curve: expected rate of return and capital growth

where NROR represents a normal capital return rate, and TREND is the associated capital growth rate; KGR$_{MAX}$ and KGR$_{MIN}$ are maximum and minimum capital growth rates, respectively, and C is a parameter denoting the sensitivity of capital growth to variations in expected rate of return. We form expected rates of return using static expectation, such that in changes in next period's capital return and capital costs are the same as this period's, adjusted by real interest rates, which, in turn, are nominal interest rates deflated by inflation. A key advantage of this setup is that it prevents unrealistically large changes in sectoral capital growth, which can often cause problems in long-term, dynamic CGE modelling.

3.5 Scenarios setting

We have two main scenarios and one alternative scenario. The two main scenarios are the BAU and the NZEP. The NZEP is a grouped scenario with two variants, they are 1) a scenario for countries achieving their NZEPS with no international permit trade (NZEP_NT), and 2) a scenario for all countries achieving their NZEPs with international permit trade (NZEP_TR). The alternative scenario is called the adjusted emissions pledges (AEP) scenario. It uses an alternative distribution of emissions pledges so that all regions will benefit from permit trade. This subsection introduces the BAU and the NZEP scenarios. Since the design of the AEP depends on the results of the BAU and the NZEP scenarios, we will show its design in Section 4.3. Table 3 summarizes these four scenarios.

Table 3: Summary of simulation scenarios

Name	Main aim	Referenced scenarios
BAU	Business as usual	STEPS (IEA, 2021)
NZEP_NT	Net zero emissions pledges without global permit trade	APS (IEA, 2021)
NZEP_TR	Net zero emissions pledges with global permit trade	APS (IEA, 2021)
AEP	Adjusted emissions pledges for achieving Pareto Improvement through global permit trade	Author's assumption

- BAU scenario

Developing a BAU scenario is very important in long-term CGE modelling as future economic structures, especially in many developing economies, can be very different to the status quo. In a study like ours, incorporating a reasonable energy outlook is essential. Indeed, much renewable energy development would happen even without the NZEPs being implemented. Failing to incorporate these changes might require stronger policy interventions and thus risk overestimating economic losses. Table 4 shows our macroeconomic and energy development outlook for our BAU.

Table 4: BAU scenario design

	GDP (CAAGR%)			POP (CAAGR%)			Fossil Fuel (PJ)						Net CO_2 ($mtCO_2$)	
							coal		oil		gas			
	2021-25	2026-30	2031-50	2021-25	2026-30	2031-50	2020	2050	2020	2050	2020	2050	2020	2050
USA	3.3	2.2	1.9	0.6	0.5	0.4	9329	1361	29590	25041	30427	27936	4207	2938
CSA	3.1	2.7	2.6	0.8	0.7	0.4	1295	1437	9618	12093	5230	6714	1010	1220
EUR	3.0	2.0	1.3	0.0	-0.1	-0.2	5976	1393	17706	7879	13642	10119	2355	1085
AFR	4.0	4.2	4.2	2.3	2.2	1.9	4560	4657	7308	16164	5702	11085	1176	2000
MDE	2.9	2.7	3.1	1.1	0.9	0.6	129	449	12434	18036	19429	29249	1732	2480
RUS	2.6	2.1	1.1	-0.1	-0.2	-0.3	4911	4300	5873	5903	16631	18398	1536	1532
CHN	5.8	5.1	2.9	0.3	0.1	-0.2	87501	58019	27595	25494	11138	17414	10009	7385
IND	7.4	6.9	4.4	0.9	0.8	0.4	16323	20254	9021	17848	2290	7465	2140	3359
JPN	1.7	1.0	0.7	-0.4	-0.5	-0.7	4475	2106	6021	3569	3682	2208	961	483
SEA	4.9	4.9	3.2	0.9	0.8	0.4	7535	11451	9268	14869	5703	11633	1544	2511
ROW	3.8	3.5	2.7	1.2	1.1	0.8	13766	12296	36966	51355	25226	33331	4949	6214

	Power generation (TWH)													
	slp		wdp		nhp		otp		cfp		gfp		ofp	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
USA	117	1300	340	1178	1116	877	92	210	858	42	1676	1558	38	7
CSA	22	346	78	392	719	1229	76	200	66	21	242	234	73	11
EUR	142	540	398	1363	1028	936	194	357	386	15	556	356	47	5
AFR	10	370	17	271	149	588	10	211	241	175	329	707	69	62
MDE	11	445	2	261	20	141	0	128	3	29	844	1583	308	188
RUS	1	19	1	99	405	490	3	99	167	127	471	653	8	1
CHN	270	3147	471	2632	1701	2901	146	667	4958	3338	230	545	11	1
IND	64	2108	68	916	220	679	55	179	1127	948	69	172	7	1
JPN	79	188	8	205	127	293	62	143	316	65	366	140	26	2
SEA	18	348	7	201	164	371	66	224	479	822	360	858	17	11
ROW	97	861	205	1281	1390	1950	112	415	867	628	1115	1639	112	20

Source: GDP growth numbers for 2021-25 are taken from World Economic Outlook (IMF, 2021), and those for 2026-50 are taken from IEA (2021). Population forecasts are taken from the World Population Prospects 2019 (United Nations, 2019). Fossil fuel consumption, power generation and CO_2 emissions are taken from the STEPS scenario, World Energy outlook 2021 (IEA, 2021). *Note:* CAAGR stands for compounded average annual growth rate; PJ stands for peta-joule; $MtCO_2$ stands for million tonnes of carbon dioxide emissions, and TWH stands for terra-watt hour. CO_2 emissions only account for those from fossil fuel combustion.

We relied on the Stated Policy Scenario (STEPS) of World Energy Outlook 2021 (IEA, 2021) to construct the BAU scenario for energy. The STEPS is composed by a sector-by-sector assessment of the specific policies that are already in place, as well as those that have been announced. These, based on the emissions numbers shown in Table 3, are far from the pledged targets. The STEPS thus serves as a very important baseline for evaluating impacts of the additional efforts made toward to the NZEPs.

Energy-using efficiency for coal, oil, and gas, as well as productivity for all power generation technologies are endogenized to facilitate the control in fossil fuel consumption and power generation, respectively. We also assume little CCS technologies have been utilized in the BAU.

- NZEP scenarios

For NZEP scenarios, we control countries' net emissions commitments and CCS coverage rates (see Table 5). These values are taken from the Announced Pledges Scenario (APS) of World Energy Outlook 2021 (IEA, 2021). The APS assumes all climate commitments made by governments around the world, including the NDCs and the longer-term net zero targets, will be met in full and on time (IEA, 2021, p.27)[6]. The emissions and CCS coverage projections in the APS thus serve as important land posts in our NZEP scenarios. The deviations from the BAU to the NZEPs can be interpreted as the additional efforts needed to achieve the NDCs and the longer-term net zero goals (*i.e.*, the NZEPs). Carbon prices are endogenized in the NZEP scenarios to facilitate the lower emissions targets. Energy-using efficiency for coal, oil, and gas, as well as productivity for all power generation technologies are kept the same as in the BAU. Unit CCS abatement is assumed to increase energy consumption by 10% to power the CCS operation. Notice that our NZEPs are not identical replications of the APS. A critical difference is that our scenarios are driven by economic forces under general equilibrium conditions, and that GDP can deviate from the BAU under the NZEPs whereas they are fixed at the BAU levels in the APS.

Table 5: net emissions commitments and CCS coverage rates in NZEP scenarios.

	Net emissions commitments (mtCO$_2$)							CCS coverage rate (%)						
	2020	2025	2030	2035	2040	2045	2050	2020	2025	2030	2035	2040	2045	2050
USA	4207	3496	2786	1697	1068	678	426	0.00	0.04	0.08	0.51	0.84	0.92	0.97
CSA	1010	973	937	907	880	848	795	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EUR	2354	1859	1363	854	463	240	123	0.00	0.00	0.00	0.08	0.54	0.98	0.99
AFR	1176	1270	1364	1408	1460	1595	1757	0.00	0.00	0.00	0.00	0.02	0.02	0.02
MDE	1732	1875	2019	2202	2312	2439	2477	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RUS	1536	1583	1630	1603	1582	1552	1512	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHN	10008	9912	9815	7809	5887	3621	1781	0.00	0.00	0.00	0.11	0.20	0.35	0.65
IND	2140	2603	3066	3383	3499	3449	3330	0.00	0.00	0.00	0.00	0.00	0.00	0.00
JPN	961	801	641	452	291	155	87	0.00	0.04	0.08	0.51	0.84	0.92	0.97
SEA	1544	1818	2092	2314	2414	2494	2518	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROW	4949	5021	5093	4971	4950	4960	4970	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WLD	31617	31211	30806	27600	24806	22031	19776							

Source: APS, World Energy Outlook 2021 (IEA, 2021)

Regions' commitments are varied. We show cumulative emissions between 2021 and 2050 between the BAU and the NZEPs commitments in Table 6. USA, EUR and JPN's commitments lead to the largest percentage reduction – 45%, 38% and 32%, respectively. China's commitments imply the largest absolute reduction – 59 billion tonnes (btCO$_2$). MDE, IND, and SEA, however, commit to little extra abatement.

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[6] Notice that although the USA, EUR and JPN have committed to net zero emissions by 2050, they are not zero our NZEP scenarios. This is because other negative emissions methods, such as forest carbon sink, are assumed to have been used to remove the remaining emissions.

Table 6: cumulative emissions in BAU and NZEPs commitments, 2021-50.

Cumulative, 2021-50	USA	CSA	EUR	AFR	MDE	RUS	CHN	IND	JPN	SEA	ROW	WLD
BAU ($btCO_2$)	107	34	47	48	65	48	270	94	20	66	173	971
NZEP (btCO2)	58	27	29	43	65	47	211	94	14	66	150	805
NZEP-BAU (btCO2)	-48	-7	-18	-4	0	0	-59	0	-7	0	-23	-166
NZEP-BAU (rate)	-45%	-20%	-38%	-9%	0.1%	-1%	-22%	0.2%	-32%	0.4%	-13%	-17%

As discussed, our NZEP has two variants. In the NZEP_NT variant, countries achieve their commitments by mitigation efforts of their own and do not engage in any form of international permit trade. In the NZEP_TR variant, we allow international permit trade while retaining regions' commitments. Permit trading mechanisms are implemented using the method described in Burniaux and Truong (2002). Net permit trading revenues are accrued to regional income (which equals to regional expenditure, which contains private expenditure, government expenditure, and savings). All scenarios are implemented and solved by using the GEMPACK economic modelling software (Horridge et al., 2018).

3.6 Calculating equity-adjusted welfare of the world

We use results from CGE simulation to calculate equity-adjusted welfare of the world. Following Atkinson (1970), we use an isoelastic function (Equation (4)) to define welfare of region r in scenario s as Ur,s, such that

$$U_{r,s} = \frac{1}{1-\varepsilon} C_{r,s}^{1-\varepsilon}, \quad \varepsilon \neq 1$$
$$U_{r,s} = \ln\left(C_{r,s}\right), \quad \varepsilon = 1$$

Equation (4)

Where ε is an aversion to inequality parameter. The higher the value of ε, the more the world discounts welfare due to higher inequality. C is the per capita real household consumption. The combined equity-adjusted welfare of the world under scenario s is thus Ws, such that:

$$W_s = \frac{\sum_r \left(POP_r \times U_{r,s}\right)}{\sum_r POP_r}$$

Equation (5)

Where POP is population. In order to understand the welfare changes between different scenarios, we use the equally distributed income (EDI) factor e_K[7] to search for the percentage change in real household consumption that is needed to equate welfare in different scenarios, such that

$$W_{NT\_TR}\left(\left(1+e_{NT\_TR}/100\right) \times C_{r,NZEP-NT}\right) = W_{NZEP-TR}\left(C_{r,NZEP-TR}\right)$$
$$W_{NT\_PI}\left(\left(1+e_{NT\_AP}/100\right) \times C_{r,NZEP-NT}\right) = W_{NZEP-PI}\left(C_{r,NZEP-PI}\right)$$

Equation (6)

Where W_{NT_TR} and W_{NT_PI} are welfare levels using real per capita household consumption levels in the no trade scenario adjusted by the EDI factors, where e_{NT_TR} and e_{NT_AP} denote the percentage change in per capita household consumption levels in the no global permit trade scenario needed to reach those in trade scenarios. Solving for values of e_K, a positive e_K implies that moving from no-trade to trade leads to overall welfare improvement for the world when both equity and efficiency are

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[7] k∈[NT_TR, NT_PI] denotes the transition, where subscript NT_TR denotes moving from NZEP-NT scenario to NZEP-TR scenario, and subscript NT_PI denotes moving from NZEP-NT scenario to NZEP-PI scenario.

considered.

3.7 Consumption-based emissions pledges (CBPs)

We use CGE modelling results to calculate embodied carbon emissions. The CGE modelling results are shown in the GTAP database structure, where export of good i from country s to country r does not have user-specific details in country r. Thus, similar to Zhou and Zhang (2019), we distributed country r's imports among its users by using each good's domestic sales structure. The derived database has the same structure as the World Input-output Database (WIOD), which can then be used to calculate embodied emissions.

We use the method introduced in Meng et al. (2018) to account for the Embodied Carbon Emissions Exports (ECX). ECX represents the emissions that are produced by one country and finally consumed by others. ECX from country s to country r can be decomposed into three parts:

$$ECX^{sr} = F\sum_{t}^{G} B^{st}Y^{tr} \qquad \text{Equation (7)}$$

Where B is the Leontief inverse matrix. Y is the final demand vector. The superscripts in B^{sr} and Y^{sr} mean s is the producing country, r is the destination country. F^{s} is the direct carbon emission intensity vector of country s, the direct carbon emission intensity of sector i in country s $f_i^s = e_i^s/x_i^s$, e_i^s is the emissions of sector i in country s, x_i^s is the output of sector i in country s.

Matrices F, B, and Y can all be found in our derived database from CGE simulation results.

From Equation 7, we can obtain the embodied carbon emissions exports (ECX), embodied carbon emissions imports (ECI) and net carbon emissions transfer[8] (NCT) of country s, also as defined by Meng et al. (2018) :

$$ECX^{s} = \textstyle\sum_{r\neq s}^{G} ECX^{sr}$$

$$ECI^{s} = \textstyle\sum_{s\neq r}^{G} ECX^{rs} \qquad \text{Equation (8)}$$

$$NCT^{s} = ECX^{s} - ECI^{s}$$

Based on the consumption principle, a country should be responsible for all carbon emissions caused by its final demand, under which we can get a comprehensive understanding of the international transfer of mitigation responsibility and the mitigation pledges countries have made. According to the calculation of consumption-based carbon emissions defined in Meng et al. (2018), we define consumption-based pledges (CBPs) of country s as:

$$CBPs^{s} = PBPs^{s} + ECI^{s} - ECX^{s} = PBPs^{s} - NCT^{s} \qquad \text{Equation (9)}$$

Where $PBPs^{s}$ denote production-based pledges of country s. Thus $PBPs = NZEPs$ under NZEP scenarios and $PBPs = AEPs$ under the AEP scenario. The CBPs are thus arguably the more appropriate measurements of countries' long-term mitigation targets.

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[8] A positive net carbon emissions transfer thus means transferring domestically produced carbon to be used by other countries' final demand. A country with a positive NCT is also a net emissions exporter.

4. Results and discussion

4.1 Energy, emissions, and CCS results

We first show results for energy, emissions, and CCS. These results are important as they correspond to our economic results. It is worth noting that, and as discussed in Section 3.5, although we rely on IEA's projections for the emissions levels in NZEPs, ours are not replications of their APS scenario. The key difference lies in the underlying energy structure and CCS utilization. We show primary energy consumption levels, cumulative between 2021 and 2050, in Table 7. Global energy consumption is 6.1% and 5.6% lower than BAU levels in NZEP_NT and NZEP_TR, respectively. From NZEP_NT to NZEP_TR, fossil fuel energy consumption increases 329 EJ, non-fossil fuel energy decreases 228 EJ. This is because permit trade allows more energy production in the developed countries, who rely on more CCS to remove CO_2 emissions from fossil fuel energy. The overall global energy composition is similar between NZEP_NT and NZEP_TR, with fossil fuel energy accounting for 75% and 76%, respectively.

Table 7: primary energy consumption (exajoule), cumulative between 2021 and 2050.

	Primary energy consumption (Exajoule, 10^{18} joule, EJ), cumulative 2021-50														
	BAU					NZEP_NT					NZEP_TR				
	coal	oil	gas	NFF	Total	coal	oil	gas	NFF	Total	coal	oil	gas	NFF	Total
USA	124	858	905	595	2482	100	692	610	730	2131	119	839	847	609	2414
CSA	39	340	178	257	813	25	307	148	286	765	33	331	168	265	798
EUR	74	369	367	496	1307	42	308	197	578	1125	69	365	347	501	1282
AFR	139	346	248	98	831	125	344	243	103	815	116	329	236	106	786
MDE	10	470	748	155	1383	10	486	754	159	1409	8	447	698	169	1323
RUS	139	189	550	106	984	134	185	552	106	978	109	182	517	106	914
CHN	2240	856	470	1279	4845	1851	825	399	1358	4434	1851	835	395	1334	4416
IND	627	453	167	359	1607	626	457	167	358	1608	521	439	159	371	1489
JPN	94	145	81	99	419	82	139	72	101	394	89	144	78	100	411
SEA	312	403	265	56	1036	324	413	268	56	1061	214	394	265	57	929
ROW	384	1414	878	609	3284	312	1329	820	645	3106	335	1359	836	634	3164
WLD	4182	5843	4856	4111	18991	3631	5486	4229	4480	17826	3465	5664	4546	4252	17927

Source: authors' simulations.

We show electricity generation levels, cumulative between 2021 and 2050, in Table 8. Global electricity generation is 6% and 0.5% higher than BAU levels in NZEP_NT and NZEP_TR, respectively. From NZEP_NT to NZEP_TR, global power output falls by 552 PWH. This is mainly due to the fall in renewable power generation in the developed regions as they face much less stringent need to develop clean energy. The overall global energy composition is also similar between NZEP_NT and NZEP_TR, with fossil fuel power accounting for 41% of total global power output in both variants.

Table 8: electricity generation (petawatt-hour), cumulative between 2021 and 2050.

	Electricity generation (Petawatt-hour, 10^{15} watt-hour, PWH), cumulative 2021-50														
	BAU					NZEP_NT					NZEP_TR				
	slp	wdp	aop	ffp	Total	slp	wdp	aop	ffp	Total	slp	wdp	aop	ffp	Total
USA	21	24	34	60	139	32	29	34	58	152	22	25	34	60	141
CSA	6	7	33	9	55	7	8	36	8	59	6	7	34	9	56
EUR	13	30	37	17	97	17	39	37	14	106	13	31	37	17	98
AFR	5	4	13	23	45	6	4	14	23	47	5	5	14	22	45
MDE	5	3	4	46	59	6	3	6	48	62	6	3	4	44	57
RUS	0.3	1	15	23	39	0.3	1	15	23	40	0.3	1	15	21	38
CHN	54	51	84	138	328	62	54	84	153	354	56	53	84	143	336
IND	28	12	17	41	98	28	12	17	41	97	29	13	17	40	99
JPN	4	2	11	12	30	5	3	11	12	30	4	2	11	12	30
SEA	5	3	12	40	60	5	3	13	41	62	5	3	13	33	54
ROW	14	23	59	64	160	16	25	63	60	165	15	24	60	62	161
WLD	155	161	318	475	1109	181	182	330	481	1174	163	168	322	462	1115

Source: authors' simulations.

We show CCS removals and permit trade volumes, cumulative between 2021 and 2050, in Table 9. Globally, CCS remove 3% of total cumulative emissions in both NZEP_NT and NZEP_TR. These are much lower than the removal rates (CCS/CO2T) in developed countries. Under NZEP_TR, USA, CSA, EUR, JPN and ROW are net permit importers. The USA and EUR are two largest net permit importers, importing 28 and 14 btCO$_2$ over the 30 years, respectively. Net permit import account for 32% of net total emissions (PI/NTTE) in both regions. AFR, MDE, RUS, CHN, IND and SEA are net permit exporters. SEA, IND and MDE are the three largest permit exporters, exporting 18, 13 and 11 btCO$_2$, respectively. Net permit export account for 36%, 16% and 21% of their net total emissions, respectively. The cumulative global permit trade volume is 52 btCO$_2$, amounting to 7% of net total emissions globally.

Table 9: CCS removals and permit trade (billion tonnes of CO$_2$), cumulative between 2021 and 2050.

	Cumulative emissions 2021-50, btCO$_2$												
	NZEP_NT					NZEP_TR							
	CO2T	FCCS	OCCS	CCS/ CO2T	NTTE	CO2T	FCCS	OCCS	CCS/ CO2T	NTTE	Permit import	PI/NTTE
USA	66	-5.0	-2.9	-12%	58	96	-6.9	-2.9	-10%	86	28	32%
CSA	27	0.0	0.0	0%	27	31	0.0	0.0	0%	31	4	13%
EUR	30	-1.0	-0.2	-4%	29	45	-2.3	-0.2	-5%	43	14	32%
AFR	43	-0.2	-0.1	-1%	43	40	-0.2	-0.1	-1%	40	-3	-7%
MDE	65	0.0	0.0	0%	65	54	0.0	0.0	0%	54	-11	-21%
RUS	47	0.0	0.0	0%	47	42	0.0	0.0	0%	42	-5	-12%
CHN	221	-7.0	-3.5	-5%	211	219	-7.6	-3.5	-5%	208	-3	-1%
IND	94	0.0	0.0	0%	94	81	0.0	0.0	0%	81	-13	-16%
JPN	18	-3.6	-0.6	-23%	14	20	-3.9	-0.6	-23%	15	1	8%
SEA	66	0.0	0.0	0%	66	49	0.0	0.0	0%	49	-18	-36%
ROW	150	0.0	0.0	0%	150	156	0	0	0%	156	6	4%
WLD	829	-17	-7	-3%	805	833	-21	-7	-3%	805	0	0%

Source: authors' simulations.

Note: CO2T denotes total CO2 emissions before being removed by CCS; FCCS denote emissions removed by fossil fuel-based CCS; OCCS denotes emissions removed by non-fossil fuel-based CCS (BECCS and DAC); NTTE denotes net total emissions, such that NTTE = CO2T – FCCS – OCCS (see also Equation (2)).

4.2 Macroeconomic results

We show results for carbon price, real GDP, and equivalent variations in Table 10. Under NZEP_NT, carbon price levels are generally below 100 USD/tCO_2 by 2030. These are broadly in line with the simulation results of similar studies. By 2050, however, the carbon price level in EUR becomes very high – reaching 2700 USD/tCO2. We have not found similar levels of modelling outcomes in the literature. That said, we have not found modelling attempts trying to analyze mitigation costs for reach NZEPs either. Our results indicate that compared to BAU, without significant improvement in energy efficiency or strong changes in users' preference for cleaner energy, reaching EUR's NZEPs without global permit trade may induce alarmingly high levels of mitigation cost at the margin toward the middle of the 21st century.

Under NZEP_NT, by 2050, EUR, USA, MDE and RUS have the largest negative cumulative deviations in real GDP from BAU – the deviations are -4.8%, -3.2%, -2.9% and -2.6%, respectively. EUR and USA's lower GDP results are mainly due to high carbon price levels causing high living and production costs in their own economies. MDE and RUS's lower GDP results are mainly due to reduction in fossil fuel demand – especially reduction in demand for their fossil fuel export. By 2050, nearly all regions are worse off in terms of equivalent variation (EV), except for IND and SEA. Having pledged to less stringent mitigation goals, these two regions benefit from low domestic carbon prices.

Under NZEP_TR, when regions can trade emissions permits while retaining their NZEPs, global carbon prices converge to uniformed levels. They become 6 USD/tCO_2 and 46 USD/tCO_2 in 2030 and 2050, respectively. For EUR and USA, these are significantly lower than their NZEP_NT prices. Lower carbon costs are stimulus to their economies, by 2050, their cumulative real GDP deviations from BAU become -0.27% and -0.54%, respectively. RUS suffers the largest setback in terms of real GDP due to global permit trade. They endure higher carbon prices as well as lower fossil fuel demand.

Table 10: Carbon price, real GDP, and equivalent variation results

	Carbon price (USD/tCO_2)				Real GDP, cumulative (%) deviation from BAU				Equivalent variation, cumulative (bUSD) deviation from BAU			Equivalent variation, USD per capita, cumulative deviation from BAU		
	NZEP_NT		NZEP_TR		NZEP_NT		NZEP_TR		NT	TR	NT-TR	NT	TR	NT-TR
	2030	2050	2030	2050	2030	2050	2030	2050	2050	2050	2050	2050	2050	2050
USA	51	653	6	46	-0.51	-3.20	-0.06	-0.54	-1172	-190	981	-3098	-503	2594
CSA	31	140	6	46	-0.35	-1.69	-0.07	-0.70	-133	-55	78	-218	-90	128
EUR	104	2692	6	46	-0.63	-4.78	-0.03	-0.27	-1081	-49	1032	-2548	-117	2431
AFR	5	14	6	46	-0.15	-0.87	-0.15	-1.14	-19	-59	-40	-8	-25	-17
MDE	0	5	6	46	-0.10	-2.94	-0.22	-1.60	-75	-81	-6	-239	-260	-20
RUS	1	7	6	46	-0.52	-2.58	-0.25	-3.54	-58	-57	1	-430	-422	8
CHN	1	190	6	46	0.02	-1.51	-0.12	-0.59	-172	-51	122	-125	-37	88
IND	0	1	6	46	0.05	-0.09	-0.18	-1.91	96	-24	-120	59	-14	-73
JPN	35	297	6	46	-0.30	-1.49	-0.05	-0.34	-121	-15	107	-1155	-140	1015
SEA	0	1	6	46	-0.01	-0.23	-0.16	-1.14	28	-3	-31	36	-3	-39
ROW	16	44	6	46	-0.28	-1.05	-0.10	-0.93	-145	-172	-27	-96	-114	-18
WLD			6	46	-0.29	-2.06	-0.09	-0.77	-2852	-755	2098	-295	-78	217

Source: authors' simulations.

Moving from NZEP_NT to NZEP_TR, reduction in global GDP becomes smaller. By 2050, real GDP deviations from BAU are -2.1% and -0.8% in NZEP_NT and NZEP_TR, respectively. Compared to NZEP_NT, global EV by 2050 is also higher by 2098 billion USD in NZEP_TR. These gains, however, are not equally distributed. Three developed regions reap most of the benefits. By 2050, the cumulative benefits of USA, EUR, and JPN, in terms of EV, are 2594, 2431 and 1015 USD per capita, respectively. Five regions, namely AFR, MDE, IND, SEA, and ROW are worse off due to permit trade. These results demonstrate the concern raised in the literature, that global permit trade may hurt the less developed regions of the world.

4.3 Adjusted emissions pledges (AEPs) scenario

In order to address the concern of unequal distribution of gains from permit trade, we adjusted regions' emissions pledges by assigning more stringent emissions targets for more developed regions. Moving from NZEP to AEP, we redistributed a total of 155 billion tonnes[9] of CO_2 (btCO_2) mitigation pledges from three more developed regions (USA, EUR, JPN) to four less developed regions (AFR, IND, SEA and SOW) throughout the 30 years (2021-50) (see Table 11). Total world emissions levels are the same between NZEP and AEP. The 155 btCO2 are distributed proportionate to countries' population. The population ratio for USA, EUR, and JPN over the 30 years is 39:48:13, hence, compared to NZEP, their additional mitigation pledges in AEP are 61, 75 and 20 btCO_2, respectively (see bottom line in Table 11). Similarly, AFR, IND, SEA, and ROW would pledge to 52, 44, 21 and 38 btCO_2 less mitigation, respectively.

Table 11: Cumulative emission pledges in AEP, 2021-50

Cumulative, 2021-50	USA	CSA	EUR	AFR	MDE	RUS	CHN	IND	JPN	SEA	ROW	WLD
AEP (btCO2)	-2	27	-46	96	65	47	211	138	-6	87	188	805
AEP-BAU (btCO2)	-109	-7	-93	48	0	0	-59	44	-26	21	15	-166
AEP-BAU (rate)	-102%	-20%	-197%	101%	0.1%	-1%	-22%	46%	-128%	32%	9%	-17%
AEP-NZEP (btCO2)	-61	0	-75	52	0	0	0	44	-20	21	38	0

Source: authors' assumptions and calculations.

By assigning more generous targets to the four less developed regions, they also get to enjoy the benefit, in term of EV, of joining global permit trade. While the three more developed regions would still enjoy higher EV than no-trade. Table 12 compares permit trading revenues and EV results between NZEP_NT, NZEP_TR, and AEP. By 2050, in AEP, compared pared to NZEP_TR, AFR, IND, SEA and ROW's permit trading revenues increase by 154, 128, 62 and 111 billion USD, respectively. As a result, compared to NZEP_NT, their per capita EV increase by 90, 47, 69 and 103 USD. Therefore, under AEP, no region would be worse off by moving from no permit trade to global permit trade, while achieving the same global emissions level more efficiently. Thus, the AEP is an example of a scenario in which a Pareto Improvement can be achieved by adjusting emissions pledges around the world.

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[9] This level is obtained by trial-and-error. This is just one of the values to achieve a Pareto Improvement condition.

Table 12: Permit trading revenues and EV results

Cumulative deviations from BAU by 2050								
	Permit trade revenues (billion USD)		EV (billion USD)		EV differences (billion USD)		Per capita EV differences (USD)	
	NZEP_TR	AEP	NZEP_TR	AEP	TR-NT	AEP-NT	TR-NT	AEP-NT
USA	-60	-238	-190	-472	981	700	2594	1850
CSA	-9	-9	-55	-50	78	83	128	136
EUR	-29	-248	-49	-361	1032	720	2431	1697
AFR	15	169	-59	196	-40	216	-17	90
MDE	38	38	-81	-71	-6	4	-20	12
RUS	16	16	-57	-51	1	7	8	52
CHN	-74	-74	-51	-31	122	141	88	103
IND	52	179	-24	174	-120	78	-73	47
JPN	-4	-62	-15	-88	107	33	1015	315
SEA	52	114	-3	83	-31	55	-39	69
ROW	4	115	-172	12	-27	156	-18	103

Source: authors' simulations.

4.4 Global welfare

Using results from our CGE simulations and applying Atkinson (1970)'s welfare index, we calculate the values of equally distributed income (e) for two cases: 1) moving from NZEP_NT to NZEP_TR, and 2) moving from NZEP_NT to AEP. To calculate these values, we need to choose the 'aversion to inequality' parameters. In our calculation for each case, we choose three values for the parameter eps, namely 0 (implying no dislike for inequality), 1 (as used by Stern (2008)), and 2 (as used by Nordhaus (2008)). The higher the value of eps is, the more aversive people are toward inequality. We show our calculation results in Table 13.

Moving from NZEP_NT to NZEP_TR, if there is no aversion to inequality (ε=0), the values of e increase overtime. By 2050, e_{NT_TR}=1.0, implying global welfare improves by 1.0% by forming global permit trade. Such improvements in welfare are solely derived from gains in efficiency. When ε=1, and aversion to inequality is being considered, however, the values of e become much smaller. By 2050, e_{NT_TR}=0.1, it suggests that efficiency improvements are almost entirely offset by worsening inequality. When ε=2, e_{NT_TR} becomes negative in 2021 and keeps falling overtime. By 2050, e_{NT_TR}=-0.7, it means that the worsening inequality harms global welfare despite higher efficiency. These results demonstrate again the need for the developed world to make more ambitious emissions reduction targets.

Under the hypothetical scenario of AEP, the developed world takes on more mitigation responsibilities. Moving from NZEP_NT to AEP, the values of e_{NT_AP} increase over time across all three different parameter settings. Under ε=0 and ε=1, e_{NT_AP} become 1.1 and 1.0, by 2050, respectively. When ε=2, the value of e_{NT_AP} reaches 1.4 in 2050. This value is higher than all other cases - suggesting improved global equality by 2050.

Table 13: calculated values of e

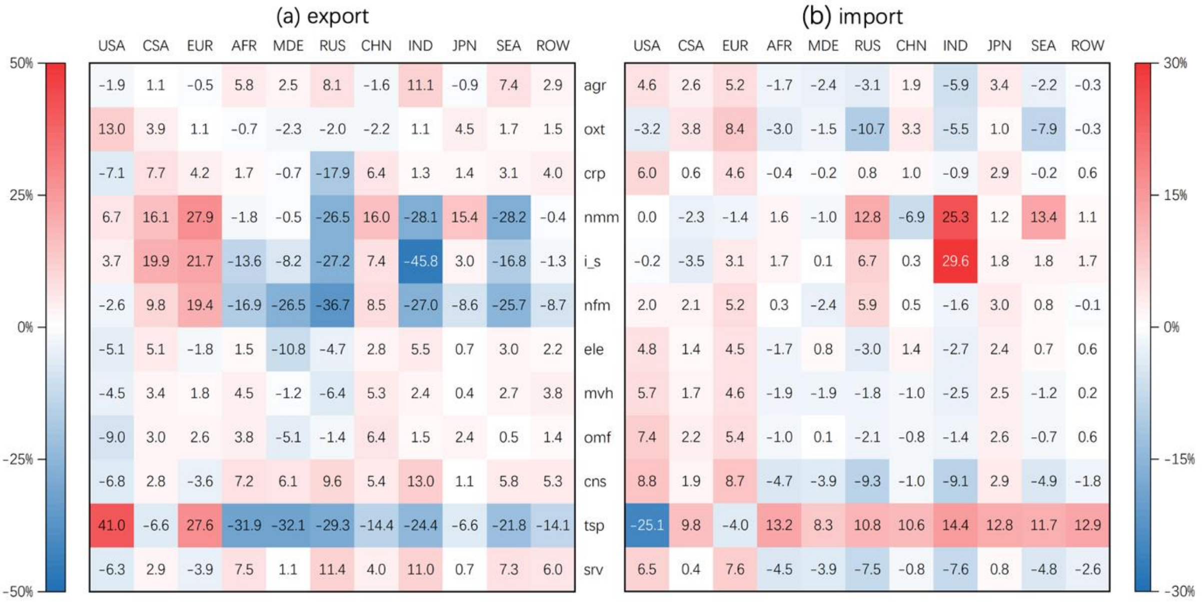
Values of e (equally distributed income)							
	From NZEP_NT to NZEP_TR (e_{NT_TR})						
ε	2021	2025	2030	2035	2040	2045	2050
0	0.0	0.1	0.2	0.4	0.6	0.8	1.0
1	0.0	0.0	0.0	0.0	0.1	0.1	0.1
2	0.0	0.0	-0.1	-0.1	-0.1	-0.2	-0.7
	From NZEP_NT to AEP (e_{NT_AP})						
ε	2021	2025	2030	2035	2040	2045	2050
0	0.0	0.1	0.2	0.4	0.6	0.9	1.1
1	0.0	0.0	0.1	0.2	0.4	0.7	1.0
2	0.0	0.0	0.1	0.3	0.6	1.0	1.4

Source: authors' simulations.

4.5 Trade flow

International trade would change if permit trade is allowed. Table 14 presents cumulative deviations in sectors' trade volumes from NZEP_NT to NZEP_TR by 2050. As discussed in section 4.2, permit trade reduces carbon price levels, including export prices, in developed countries, so their exports, especially carbon-intensive exports, rise. For the opposite reason, higher carbon prices drive up costs of carbon-intensive activities in less-developed regions, who, thus, tend to export less carbon intensive goods. Nmm, i_s, and nfm best illustrate such changes. AFR, MDE, RUS, IND, and SEA all experience higher carbon prices and they export less of these goods, whereas CSA, EUR, and CHN all experience lower carbon prices, and they export more. A large portion of the global supply of these goods thus shift from net permit exporters (*e.g.*, IND) to net permit importers (*e.g.*, EUR).

Table 14: Cumulative deviations in trade volumes from BAU by 2050, NZEP_TR-NZEP_NT(%). The commodity classification is same as in Table 2.



(a) export

	USA	CSA	EUR	AFR	MDE	RUS	CHN	IND	JPN	SEA	ROW
agr	-1.9	1.1	-0.5	5.8	2.5	8.1	-1.6	11.1	-0.9	7.4	2.9
oxt	13.0	3.9	1.1	-0.7	-2.3	-2.0	-2.2	1.1	4.5	1.7	1.5
crp	-7.1	7.7	4.2	1.7	-0.7	-17.9	6.4	1.3	1.4	3.1	4.0
nmm	6.7	16.1	27.9	-1.8	-0.5	-26.5	16.0	-28.1	15.4	-28.2	-0.4
i_s	3.7	19.9	21.7	-13.6	-8.2	-27.2	7.4	-45.8	3.0	-16.8	-1.3
nfm	-2.6	9.8	19.4	-16.9	-26.5	-36.7	8.5	-27.0	-8.6	-25.7	-8.7
ele	-5.1	5.1	-1.8	1.5	-10.8	-4.7	2.8	5.5	0.7	3.0	2.2
mvh	-4.5	3.4	1.8	4.5	-1.2	-6.4	5.3	2.4	0.4	2.7	3.8
omf	-9.0	3.0	2.6	3.8	-5.1	-1.4	6.4	1.5	2.4	0.5	1.4
cns	-6.8	2.8	-3.6	7.2	6.1	9.6	5.4	13.0	1.1	5.8	5.3
tsp	41.0	-6.6	27.6	-31.9	-32.1	-29.3	-14.4	-24.4	-6.6	-21.8	-14.1
srv	-6.3	2.9	-3.9	7.5	1.1	11.4	4.0	11.0	0.7	7.3	6.0

(b) import

	USA	CSA	EUR	AFR	MDE	RUS	CHN	IND	JPN	SEA	ROW
agr	4.6	2.6	5.2	-1.7	-2.4	-3.1	1.9	-5.9	3.4	-2.2	-0.3
oxt	-3.2	3.8	8.4	-3.0	-1.5	-10.7	3.3	-5.5	1.0	-7.9	-0.3
crp	6.0	0.6	4.6	-0.4	-0.2	0.8	1.0	-0.9	2.9	-0.2	0.6
nmm	0.0	-2.3	-1.4	1.6	-1.0	12.8	-6.9	25.3	1.2	13.4	1.1
i_s	-0.2	-3.5	3.1	1.7	0.1	6.7	0.3	29.6	1.8	1.8	1.7
nfm	2.0	2.1	5.2	0.3	-2.4	5.9	0.5	-1.6	3.0	0.8	-0.1
ele	4.8	1.4	4.5	-1.7	0.8	-3.0	1.4	-2.7	2.4	0.7	0.6
mvh	5.7	1.7	4.6	-1.9	-1.9	-1.8	-1.0	-2.5	2.5	-1.2	0.2
omf	7.4	2.2	5.4	-1.0	0.1	-2.1	-0.8	-1.4	2.6	-0.7	0.6
cns	8.8	1.9	8.7	-4.7	-3.9	-9.3	-1.0	-9.1	2.9	-4.9	-1.8
tsp	-25.1	9.8	-4.0	13.2	8.3	10.8	10.6	14.4	12.8	11.7	12.9
srv	6.5	0.4	7.6	-4.5	-3.9	-7.5	-0.8	-7.6	0.8	-4.8	-2.6

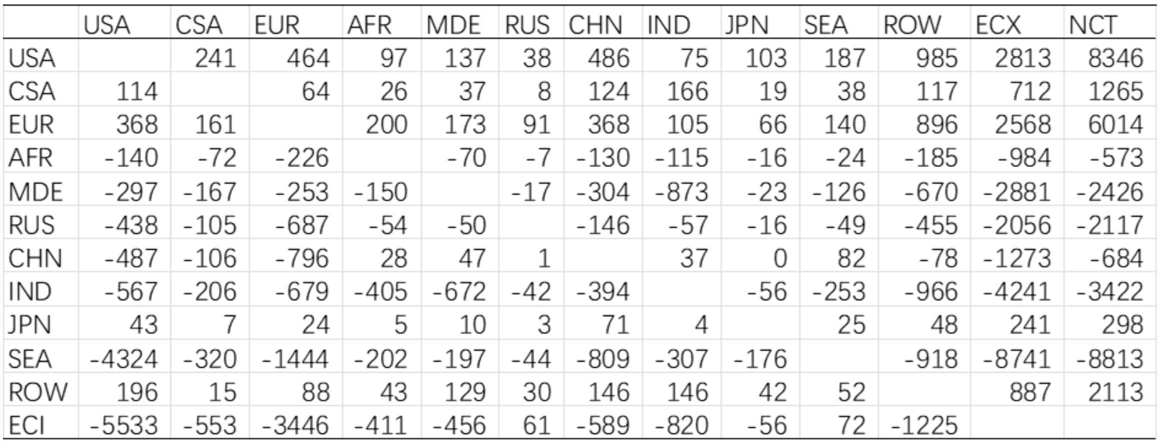
Source: authors' simulations.

4.6 Consumption-based emissions pledges (CBPs)

We use the method described in Section 3.7 to calculate the cumulative changes in bilateral carbon emissions flows (denoted by ΔECIs and ΔECXs) by 2050. Table 15 shows these changes in moving from no permit trade to permit trade (NZEP_NT to NZEP_TR)[10].The regions on the left-hand side of the table are carbon emissions exporters and the regions on the top of the table are carbon emissions importers. Our results show that, as carbon prices (see Table 10) decrease in some more developed regions (*e.g.*, USA, EUR, and JPN) and increase in some less developed regions (*e.g.*, AFR, IND, and SEA), the ΔECXs of the former rise (*e.g.*, ΔECX^{USA}=2813, ΔECX^{USA}=2568) and that of the latter fall (*e.g.*, ΔECX^{IND}=-4241, ΔECX^{SEA}=-8741). At the same time, the ECIs of the more developed regions decrease. Such changing patterns are consistent with changes in the trade flow of carbon intensive goods.

We show the ΔNCT results in the last column of Table 15. The developed regions were large net emissions exporters. The fact that their ΔNCTs are large and positive means the over the years they take more carbon-intensive productions back domestically. It is thus shown that opening to global permit trade reduces the global emissions trade. The production and consumption of carbon-intensive goods become more geographically aligned – they are more likely to happen within, rather than across, borders.

Table 15: Cumulative change in bilateral carbon flow from NZEP_NT to NZEP_TR, 2021-50 (MtCO$_2$)



	USA	CSA	EUR	AFR	MDE	RUS	CHN	IND	JPN	SEA	ROW	ECX	NCT
USA		241	464	97	137	38	486	75	103	187	985	2813	8346
CSA	114		64	26	37	8	124	166	19	38	117	712	1265
EUR	368	161		200	173	91	368	105	66	140	896	2568	6014
AFR	-140	-72	-226		-70	-7	-130	-115	-16	-24	-185	-984	-573
MDE	-297	-167	-253	-150		-17	-304	-873	-23	-126	-670	-2881	-2426
RUS	-438	-105	-687	-54	-50		-146	-57	-16	-49	-455	-2056	-2117
CHN	-487	-106	-796	28	47	1		37	0	82	-78	-1273	-684
IND	-567	-206	-679	-405	-672	-42	-394		-56	-253	-966	-4241	-3422
JPN	43	7	24	5	10	3	71	4		25	48	241	298
SEA	-4324	-320	-1444	-202	-197	-44	-809	-307	-176		-918	-8741	-8813
ROW	196	15	88	43	129	30	146	146	42	52		887	2113
ECI	-5533	-553	-3446	-411	-456	61	-589	-820	-56	72	-1225		

Source: authors' simulations and calculations.

Table 16 shows cumulative CBP results by adding CBP results for years between 2021-50. These levels are important because they show different regions' overall contribution to global climate change. Under BAU, CHN and USA are two biggest carbon emitting countries. USA is a big net emissions importer, its CBP is 32% higher than its PBP. CHN, is a big net emissions exporter, its CBP is 15% lower than its CBP. CHN's pledged emissions are 153% higher than that of the USA's by PBP whereas they are 63% higher than USA's by CBP.

Moving to NZEP scenarios, USA's pledged emissions are 58 btCO$_2$ – a reduction of 45% from its BAU level. A larger share of its consumption-based emissions relies on imports – the (-NCT/PBPs) ratio rises to 60% in NZEP_NT and 45% in NZEP_TR. The latter ratio is lower than the former one because under global permit trade, USA does not need to exert the same level of carbon prices as when there

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[10] Changes in carbon flows from NZEP_NT to AEP are similar to that from NZEP_NT to NZEP_TR, as on-going carbon prices are similar between NZEP_NT and AEP, hence we only show the differences for the changes from NZEP_NT to NZEP_TR.

is no permit trade, so a larger portion of their emissions can be satisfied by their domestic production. Similarly, EUR and JPN, who have also made strong mitigation pledges, also see their (-NCT/PBPs) ratios rise. CHN’s pledged emissions are 211 btCO_2– a reduction of 22% from its BAU level. CHN’s (-NC/PBPs) ratio does not change much – it continues to be a net emissions exporter, with total NCTs accounting for 14%-15% of total PBPs across all scenarios. IND’s CBP under NZEP_TR become larger than that of the USA’s, making it the second largest carbon emitting country if permit trade is allowed.

Table 16: Cumulative PBPs, CBPs and NCT/pledges, 2021-50 (btCO_2)

	BAU			NZEP_NT			NZEP_TR			AEP		
	PBPs	-NCT/PBPs	CBPs	PBPs	-NCT/PBPs	CBPs	PBPs	-NCT/PBPs	CBPs	PBPs	-NCT/PBPs	CBPs
USA	107	32%	140	58	60%	93	58	45%	85	-2	-1076%	24
CSA	34	17%	40	27	20%	33	27	16%	31	27	15%	31
EUR	47	58%	74	29	102%	58	29	81%	52	-46	-51%	-23
AFR	48	1%	48	43	-2%	42	43	-1%	43	96	0%	96
MDE	65	-4%	63	65	-9%	59	65	-6%	61	65	-6%	61
RUS	48	-29%	34	47	-33%	32	47	-29%	34	47	-28%	34
CHN	270	-15%	229	211	-14%	181	211	-14%	181	211	-14%	181
IND	94	-10%	85	94	-10%	84	94	-7%	88	138	-4%	132
JPN	20	22%	25	14	36%	19	14	34%	19	-6	-80%	-1
SEA	66	-16%	55	66	-23%	51	66	-10%	60	87	-7%	81
ROW	173	3%	177	150	2%	153	150	1%	151	188	1%	189

Source: authors’ simulations and calculations.

Note: -NCT/PBPs denote the negative of the ratio of NCTs to PBPs. Since a positive NCT denotes net emissions export, we have PBPs×(1-NCT/PBPs)=CBPs.

Under AEP, because of large negative emissions pledges in the later years, USA, EUR, and JPN all have overall negative PBPs. That said, cumulated over 30 years, they are still net emissions importers and their CBPs are still higher than their PBPs. AFR, IND, and SEA’s pledged emissions, by both PBP and CBP, all become larger than their BAU levels. CHN, however, still remains the biggest carbon emitting country by all accounting methods.

4.7 Emissions intensity and emissions per capita

We calculate regions’ emissions intensity and emissions per capita using emissions levels inferred by their pledges. We compare countries’ emissions intensity levels and changes in Table 17. Energy exporting regions, especially RUS and MDE, have the highest emissions intensity across the scenarios. Richer countries tend to have lower emissions intensities thanks to higher income levels. The world average cumulative emissions intensity (total emissions over total income) under consumption-based net zero emissions pledges, between 2021 and 2050, is 0.19 tCO_2/USD. USA’s is about half of this value, and CHN’s is slightly (0.02 percentage points) higher than this value. Under NZEP, all regions’ emissions intensity fall, and the richer countries’ generally fall faster. CHN is the only developing country whose emissions intensity fall at a comparable rate to that of the developed countries. Under NZEP_TR and using CBPs, CHN would have the largest reduction in emissions intensity.

Table 17: Emissions intensity (pledged carbon dioxide emissions per unit of regional income), cumulative levels

and changes

	Cumulative, CO_2/Y 2021-50 (tCO_2/USD)								Change CO_2/Y 2021-50							
	PBP				CBP				PBP				CBP			
	BAU	NZEP _NT	NZEP _TR	AEP	BAU	NZEP _NT	NZEP_ TR	AEP	BAU	NZEP _NT	NZEP _TR	AEP	BAU	NZEP _NT	NZEP _TR	AEP
USA	0.12	0.07	0.07	0.00	0.16	0.11	0.10	0.03	-68%	-95%	-95%	-143%	-58%	-80%	-87%	-127%
CSA	0.14	0.11	0.11	0.11	0.17	0.14	0.13	0.13	-56%	-70%	-71%	-71%	-54%	-68%	-71%	-71%
EUR	0.08	0.05	0.05	-0.07	0.12	0.10	0.08	-0.04	-72%	-96%	-97%	-240%	-62%	-78%	-85%	-189%
AFR	0.27	0.25	0.25	0.54	0.28	0.24	0.25	0.54	-60%	-66%	-65%	-11%	-64%	-72%	-70%	-17%
MDE	0.55	0.55	0.55	0.55	0.53	0.50	0.52	0.52	-52%	-52%	-51%	-52%	-61%	-66%	-61%	-61%
RUS	0.73	0.74	0.74	0.74	0.52	0.50	0.53	0.53	-26%	-24%	-23%	-24%	-44%	-50%	-39%	-40%
CHN	0.31	0.24	0.24	0.24	0.27	0.21	0.21	0.21	-76%	-94%	-94%	-94%	-74%	-91%	-93%	-93%
IND	0.43	0.42	0.43	0.62	0.39	0.38	0.40	0.59	-67%	-68%	-67%	-44%	-70%	-71%	-67%	-41%
JPN	0.15	0.10	0.10	-0.04	0.18	0.14	0.14	-0.01	-60%	-92%	-92%	-211%	-59%	-85%	-87%	-186%
SEA	0.36	0.35	0.36	0.47	0.30	0.27	0.32	0.43	-57%	-58%	-58%	-38%	-67%	-74%	-60%	-38%
ROW	0.23	0.20	0.20	0.25	0.24	0.20	0.20	0.25	-57%	-66%	-65%	-50%	-56%	-66%	-66%	-50%
WLD	0.23	0.19	0.19	0.19	0.23	0.19	0.19	0.19	-61%	-75%	-75%	-75%	-61%	-75%	-75%	-75%

Source: authors' simulations and calculations.

Table 18: emissions per capita

	Cumulative, CO_2/Pop 2021-50 (tCO_2/person)								Change CO_2/Pop 2021-50 (%)							
	PBP				CBP				PBP				CBP			
	BAU	NZEP_ NT	NZEP _TR	AEP	BAU	NZEP _NT	NZEP _TR	AEP	BAU	NZEP _NT	NZEP _TR	AEP	BAU	NZEP _NT	NZEP _TR	AEP
USA	9.65	5.28	5.28	-0.22	12.72	8.43	7.67	2.13	-39%	-91%	-91%	-178%	-21%	-65%	-76%	-149%
CSA	1.88	1.51	1.51	1.51	2.21	1.81	1.74	1.74	5%	-31%	-31%	-31%	9%	-26%	-32%	-32%
EUR	3.46	2.13	2.13	-3.35	5.47	4.30	3.85	-1.66	-51%	-94%	-94%	-336%	-34%	-65%	-75%	-250%
AFR	0.83	0.76	0.76	1.67	0.84	0.74	0.75	1.67	-4%	-17%	-17%	123%	-13%	-31%	-27%	108%
MDE	7.32	7.33	7.33	7.33	7.06	6.64	6.92	6.91	16%	15%	15%	15%	-6%	-19%	-8%	-8%
RUS	11.03	10.96	10.96	10.96	7.87	7.35	7.84	7.84	6%	5%	5%	5%	-20%	-31%	-17%	-17%
CHN	6.14	4.79	4.79	4.79	5.22	4.11	4.13	4.12	-25%	-82%	-82%	-82%	-20%	-73%	-79%	-79%
IND	1.98	1.98	1.98	2.89	1.78	1.77	1.84	2.77	28%	27%	27%	124%	18%	15%	29%	139%
JPN	5.67	3.86	3.86	-1.61	6.91	5.26	5.18	-0.32	-41%	-89%	-89%	-259%	-40%	-79%	-80%	-223%
SEA	2.87	2.88	2.88	3.79	2.40	2.22	2.60	3.52	34%	34%	34%	100%	3%	-16%	26%	97%
ROW	4.16	3.61	3.61	4.53	4.27	3.69	3.64	4.55	-5%	-23%	-23%	13%	-3%	-23%	-25%	11%
WLD	3.56	2.95	2.95	2.95	3.56	2.95	2.95	2.95	-21%	-49%	-49%	-49%	-21%	-49%	-49%	-49%

Source: authors' simulations and calculations.

We show regions' emissions per capita in Table 18. Using production-based emissions pledges, RUS has the highest per capita emissions levels across the regions. Using consumption-based emissions pledges, however, USA has the highest emissions per capita under BAU and NZEP_NT. The world average cumulative emissions per capita (total emissions over total population) under consumption-based net zero emissions pledges, between 2021 and 2050, is 2.95 tCO_2/person. USA's is nearly 3 times of this value, and CHN's is 1.4 times of this value. AFR has the lowest per capita emissions under BAU and NZEPs. All regions experience reduction in emissions per capita under NZEPs and AEP, using CBP, except for IND, whose emissions per capita levels increased, but are still lower than the world average. JPN would experience the biggest percentage reducitno in emissions per capita under consumption-baesd emissions peldges.

4.8 Systematic sensitivity analysis

As discussed in Section 3.2, our choices of the four CES parameter values (SMSB=1.5, SFFP=2, SWSP=0.5, and SGEN=0.5) are somewhat arbitrary. We therefore perform a systematic sensitivity analysis (SSA) to learn how sensitive our results are with respect to changes in these parameter values. We set each of these parameter values to vary by 50% from their initial values for all sectors uniformly and for each region individually. Hence, with four parameters in eleven regions each having two variations (plus or minus 50%), a total of 4×11×2=88 simulations were performed. To reduce the required number of simulations, we only performed the SSA for the NZEP_NT scenario.

Table 19: Systematic sensitivity analysis results

	Cumulative % deviation in real GDP from BAU, 2050					Cumulative change in EV (mUSD) from BAU, 2050				
	NZEP_NT	SSA_M	SSA_SD	93.75% C.I.		NZEP_NT	SSA_M	SSA_SD	93.75% C.I.	
				lower	upper				lower	upper
USA	-3.20	-3.17	0.03	-3.28	-3.06	-1172	-1161	22	-1247	-1074
CSA	-1.69	-1.67	0.19	-2.43	-0.91	-133	-132	10	-170	-93
EUR	-4.78	-4.75	0.05	-4.93	-4.57	-1081	-1077	7	-1107	-1048
AFR	-0.87	-0.87	0.05	-1.06	-0.68	-19	-19	3	-31	-6
MDE	-2.94	-2.96	0.12	-3.42	-2.49	-75	-74	4	-88	-60
RUS	-2.58	-2.61	0.08	-2.92	-2.31	-58	-58	2	-66	-49
CHN	-1.51	-1.51	0.01	-1.56	-1.46	-172	-173	5	-194	-152
IND	-0.09	-0.09	0.03	-0.21	0.03	96	95	5	77	114
JPN	-1.49	-1.49	0.04	-1.67	-1.32	-121	-121	2	-128	-115
SEA	-0.23	-0.24	0.02	-0.32	-0.15	28	29	1	24	33
ROW	-1.05	-1.05	0.05	-1.23	-0.86	-145	-145	13	-195	-94
WLD	-2.06	-2.05	0.01	-2.09	-2.01	-2852	-2836	21	-2922	-2750

Source: authors' simulations and calculations.

Note: SSA_M and SSA_SD denote mean and standard deviation from SSA results, respectively. C.I. denotes confidence interval. A 93.75% confidence interval, according to Chebyshevs Inequality, implies that the true value lies within 4 standards deviations from the mean, regardless of the distribution (Hogg and Craig, 1970).

We show our SSA results for real GDP and EV in Table 19. Results show that given 50% variations in the tested CES parameters, the SSA means are close to their original solutions, and that the standard deviations are all small. The confidence intervals (C.I.) are therefore reasonably small and comfortably encompass all the initial solutions.

5. Concluding remarks

We developed a global, dynamic CGE model with an energy-specific base-case, endogenous CCS mechanisms, and a new renewable power generation nesting strategy. We build three scenarios up to 2050, namely 1) BAU, 2) NZEP (with two variants: NZEP_NT and NZEP_TR), and 3) AEP.

We show that, under the NZEP_NT scenario with no global permit trade, the developed regions (USA, EUR, and JPN) would suffer more economically and import more emissions for their final use.

By forming global permit trade and aligning international carbon prices, as the NZEP_TR scenarios shows, the world as a whole would enjoy higher mitigation efficiency, and the developed regions would yield most of these benefits, leaving some less developed regions to be worse off, while hurting global welfare (when higher inequality reduces global welfare).

We demonstrated that, in the AEP scenario, by making the more developed regions to pledge to even lower emissions levels, it is possible to achieve a Pareto Improvement condition, in which no region is worse off because of permit trade. This would not only improve global welfare but also reduce the net transfer of carbon from developing to developed regions through trade.

Our results also show that, using consumption-based emissions pledges, between 2021 and 2050, China would have the biggest percentage reduction in emissions intensity, and Japan would have the biggest percentage reduction in emissions per captia. Cumulated over these 30 years, and also using consumption-based net zero emissions pledges, China is about twice as emissions-intensive as the United States, whilst the former's emissions per capita is about half of the latter's.

These results lead to one important policy recommendation. Countries should work together to facilitate global permit trade and to ask the more developed regions to pledge to even lower, if not negative, emissions levels than their current NZEPs.

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