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Limited Trading of Emissions Permits as a Climate Cooperation Mechanism? US-China and EU-China Examples

Claire Gavard, Niven Winchester & Sergey Paltsev

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Limited trading of emissions permits as a climate cooperation mechanism? US–China and EU–China examples

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Claire Gavard [a,c,*], Niven Winchester [b], Sergey Paltsev [b]

[a] Centre for European Economic Research (ZEW), L7, 1, D-68161 Mannheim, Germany
[b] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, 77 Massachusetts Ave, E19-411, Cambridge, MA 02139-4307, USA
[c] Centre d'Économie de la Sorbonne, Université Paris 1 Panthéon-Sorbonne, 106-112 Boulevard de l'Hôpital, 75013 Paris, France

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ABSTRACT

Recent multilateral climate negotiations have underlined the importance of international cooperation and the need for support from developed to developing countries to address climate change. This raises the question of whether carbon market linkages could be used as a cooperation mechanism. Policy discussions surrounding such linkages have indicated that, should they operate, a limit would be set on the amount of carbon permits that could be imported by developed regions from developing countries. This paper analyzes the impact of limited carbon trading between an ETS in the EU or the US and a carbon market covering Chinese electricity and energy intensive sectors using a global economy-wide model. We find that the limit results in different carbon prices between China and Europe or the US. Although the impact on low-carbon technologies in China is moderate, global emission reductions are deeper than in the absence of international trading due to reduced carbon leakage. If China captures the rents associated with limited permit trading, we show that it is possible to find a limit threshold that makes both regions better off relative to carbon markets operating in isolation.

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1. Introduction

Carbon markets are being developed around the world as policy instruments to reduce greenhouse gas emissions. For example, national or subnational carbon markets are operating in Europe, Japan, New Zealand, California, the Northeastern United States and Eastern Canada (Trotignon et al., 2011).[1] Additionally, pilot schemes have been launched in several Chinese provinces and cities with the intention of implementing a national emission trading system.[2] Some interconnections between carbon markets already exist (e.g., between California and Québec) and these linkages may expand in the future.

In parallel, the Paris Agreement adopted at the 21st Conference of the Parties (COP21) of the United Nation Framework Convention on Climate Change (UNFCCC) stressed the importance of international cooperation, and in particular the need for support from developed to developed countries to address climate change. One mechanism that meets the dual objectives of cooperation and assistance is the linking of carbon markets in developed and developing regions.[3]

To date, developing countries have been involved in carbon markets through the Clean Development Mechanism (CDM) defined in Article 12 of the Kyoto Protocol (UN, 1998). For each project approved by the

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* Corresponding author. Tel.: +49 621 1235 208; fax: +49 621 1235 226.
  E-mail addresses: gavard@zew.de (C. Gavard), niven@mit.edu (N. Winchester), paltsev@mit.edu (S. Paltsev).
  [1] The EU ETS has been extensively analyzed. Among others, Ellerman and Buchner (2007) evaluated the first phase of the ETS. Ellerman and Buchner (2008) examine the extent of over-allocation of permit and emissions abatement that took place in the first phase of the scheme, and Hepburn et al. (2006) discusses the options for introducing auctioning in the second phase. More recently, Martin et al. (2014) analyze compensation rules aimed at reducing carbon leakage in trade exposed sectors. In the US, Chen et al. (2011) and Caron et al. (2015) examine the California's cap-and-trade program, and Sue Wing and Kolodziej (2008) examine leakage from the Regional Greenhouse Gas Initiative in the Northeastern. At the national level, Paltsev et al. (2009) estimate the impact of a potential carbon market on the US economy.

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[2] Chinese pilot markets currently operate in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen.
[3] While "emission trading" is not explicitly mentioned in the Paris Agreement, it calls for "internationally transferred mitigation outcomes".

CDM Executive Board, a certain amount of credits, called Certified Emission Reductions (CER) are issued.[4] Many of these projects are renewable energy projects in India or China, e.g., the Huadian Fuqing Niutouwei wind power project in China. These CERs can be traded and sold in the carbon markets developed by more industrialized countries. Among these carbon markets, the EU Emissions Trading Scheme (ETS), launched in 2005, has been the largest one to accept CERs for compliance. Similarly, under the Joint Implementation mechanism (JI) defined in Article 6 of the Kyoto Protocol, Emission Reduction Units (ERUs) can be earned for projects occurring in Annex B countries and traded in other Annex B countries.[5]

In earlier UNFCCC sessions, new market mechanisms have been considered to move away from the CDM to a wider approach. In the Durban COP in 2011, sectoral trading was one alternative mechanism proposed (EU, 2009). This instrument involves including a sector or sectors from one nation in the cap-and-trade system of another nation or group of nations (IEA, 2009b). For example, electricity sectors in China or India could be linked to the EU ETS. Such approaches have been widely discussed (Baron et al., 2008, 2009; CCAP, 2008; Bradley et al., 2007; ICC, 2008; IEA, 2006a, 2006b, 2007). Although they are less efficient than a global cap-and-trade system (Tirole, 2009), they are seen as a way to encourage participation in an international climate agreement (Sawa, 2010). As emission reductions achieved through the CDM have been criticized (Schneider, 2007), there is a hope that a sectoral mechanism would achieve greater environmental benefits (IEA, 2005a, 2005b, 2006a, 2006b; Schneider and Cames, 2009a, 2009b; Sterk, 2008) and take advantage of a wider set of abatement opportunities (CCAP, 2010).

Several previous studies have investigated the impact of sectoral trading. Hamdi-Cherif et al. (2010) analyzed sectoral trading between all developed countries and the electricity sector of developing countries. Gavard et al. (2011a) looked at the hypothetical US–China case, with trading between a national policy in the US and an electricity cap in China. These studies showed that, with unlimited sectoral trading, carbon prices in the two systems are equalized and a large proportion of the emission reductions specified in the developed country are implemented in the developing country. Hence carbon price decreases in the developed country resulted in a partial reversal of the technological changes induced by carbon policies in the absence of sectoral trading. Conversely, sectoral trading induces greater adoption of low-carbon technologies in emerging regions. Previous studies also show that such policies lead to carbon leakage to the rest of the emerging country economy due to a reduction in fossil fuel prices. Gavard et al. (2011b) show that the European carbon price would decrease by more than 75% if there were unlimited sectoral trading between the EU ETS and Chinese electricity sector. This suggests that policy makers would limit the amount of permits that could be traded if such mechanisms were adopted, in the same way that caps are imposed on the volume of CERs and ERUs accepted for compliance in the EU ETS.[6]

The purpose of this paper is to quantify the emissions, energy and economic impacts of limited carbon trading between a developed and a developing country. Given the US–China joint statements on climate change (White House, 2014, 2015), and the EU ETS experience in accepting international credits, this paper evaluates, coupling between (1) a (hypothetical) US ETS and a carbon market covering electricity and energy intensive sectors in China, and (2) the EU ETS and the same partial carbon market in China, and (3) a trilateral US–EU–China carbon market. The analysis considers the time period 2020–2030 in three further sections. Section 2 describes relevant policies, the modeling

framework and the scenarios considered. Section 3 presents the results. Section 4 concludes.

2. Modeling framework

The analysis in this paper extends the MIT Emissions Prediction and Policy Analysis (EPPA) model. Policies represented in this model include national ETSs, the use of offsets through the CDM, and sectoral trading.

2.1. The EPPA model

The EPPA model is a recursive–dynamic, multi-region computable general equilibrium model (Paltsev et al., 2005). The model is designed to assess the impact of energy and environmental policies on emissions and economic activity. Version 5 of the model is calibrated to 2004 economic data and is solved through time by specifying exogenous population and labor productivity increases, for 2005 and for five-year increments thereafter. As indicated in Table 1, 16 countries or regions are represented. For each country or region, fourteen production sectors are defined: five energy sectors (coal, crude oil, refined oil, gas and electricity), three agricultural sectors (crops, livestock and forestry), and five other non-energy sectors (energy-intensive industry, transport, food products, services and other industries). Factors of production include capital, labor, land and resources specific to energy production. There is a single representative utility-maximizing agent in each region that derives income from factor payments and emissions permits and allocates expenditures across goods and investment. A government sector collects revenue from taxes and purchases goods and services. Government deficits and surpluses are passed to consumers as lump sum transfers. Final demand separately identifies household transportation and other household demand.

Production sectors are represented by nested constant elasticity of substitution production functions. Production sector inputs include primary factors (labor, capital and energy resources) and intermediate inputs. Goods are traded internationally and differentiated by region of origin following an Armington assumption (Armington, 1969), except crude oil which is considered as a homogenous good.

In the model, electricity can be generated from traditional technologies (coal, gas, oil, refined oil, hydro and nuclear) and advanced technologies. Advanced technologies include solar, wind, biomass, natural gas combined cycle, natural gas with carbon capture, integrated gasification combined cycle with carbon capture, advanced nuclear, wind with biomass backup, and wind with gas backup. There also are four technologies that produce substitutes for energy commodities: shale oil and hydrogen are substitutes for crude oil, synthetic gas from coal is a substitute for natural gas and liquids from biomass is a substitute for refined oil. The period in which advanced technologies become available reflects assumptions about technological developments. When available, advanced technologies compete with traditional energy technologies on an economic basis.

The model projects emissions of GHGs (carbon dioxide, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulfur hexafluoride) and urban gases that also impact climate (sulfur dioxide, carbon monoxide, nitrogen oxides, non-methane volatile organic compounds, ammonia, black carbon and organic carbon).

Version 5 of the EPPA model is calibrated using economic data from Version 7 of the Global Trade Analysis Project (GTAP) database (Narayanan and Walmsley, 2008) and energy data from the International Energy Agency. The model is coded using the General Algebraic Modeling System (GAMS) and the Mathematical Programming System for General Equilibrium analysis (MPSGE) modeling language (Rutherford, 1995).

2.2. Limited sectoral trading of emissions permits

Climate policy instruments in EPPA include emission constraints, carbon taxes, energy taxes and technology regulations such as

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[4] Lecocq and Ambrosi (2007) presents the process through which CER units are issued and the sectors and developing countries in which most CDM projects take place.
[5] Annex B countries are countries with emissions reductions or limitation commitments under the Kyoto Protocol (UN, 1998).
[6] In related literature, Massetti and Tavoni (2012) analyze the potential response of Asian economies to global or regional cap-and-trade schemes.

Table 1
EPPA model aggregation.

Countries or regions	Sectors	Factors
Developed countries	*Non-energy sectors*	Capital
United States (USA)	Crops (CROP)	Labor
Canada (CAN)	Livestock (LIVE)	Crude oil resources
Japan (JPN)	Forestry (FORS)	Natural gas resources
Australia–New Zealand (ANZ)	Food products (FOOD)	Coal resources
European Union (EUR)	Energy-intensive industry (EINT)	Shale oil resources
	Transport (TRAN)	Nuclear resources
Developing countries	Services (SERV)	Hydro resources
Mexico (MEX)	Other industry (OTHR)	Wind resources
Rest of Europe and Central Asia (ROE)		Solar resources
East Asia (ASI)	*Energy supply and conversion*	Land
China (CHN)	Electric generation (ELEC)	
India (IND)	Conventional fossil	
Brazil (BRA)	Hydro	
Africa (AFR)	Nuclear	
Middle East (MES)	Wind	
Rest of Latin America (LAM)	Solar	
Rest of Asia (REA)	Biomass (BIO)	
Russia (RUS)	Advanced gas (NGCC)	
	Advanced gas with CCS (NGCAP)	
	Advanced coal with CCS (IGCAP)	
	Advanced nuclear (ADV-NUCL)	
	Wind with biomass backup (WINDBIO)	
	Wind with gas backup (WINDGAS)	
	Fuels	
	Coal (COAL)	
	Crude oil (OIL), refined oil (ROIL)	
	Natural gas (GAS),	
	Shale Oil (SYNF-OIL)	
	Gas from coal (SYNF-GAS)	
	Liquids from biomass (BIO-OIL)	
	Hydrogen (H_2)	

renewable portfolio standards. When there are emission constraints under existing model functionality, permits may be either: (i) not tradable across sectors or regions, resulting in sector-specific permit prices in each region, (ii) tradable across sectors within regions but not across regions, resulting in region-specific permit prices, or (iii) tradable across sectors and regions, resulting in an international permit price. Modeling limited sectoral trading requires extending the model to allow trade between international permits and sector-specific permits an including an option to cap the amount of permits that can be traded.

A trade certificate system is introduced to set the limit on the amount of sectoral permits that can be imported from the developing country (e.g., China) to more industrialized countries (e.g., the EU ETS). The number of certificates issued is a fraction, α, of the total amount of permits allocated in developed countries' carbon markets. Each permit exported from developing to developed regions requires a trade certificate, which limits the number of permits imported to α multiplied by the number of permits issued in developed regions. The revenue from the certificates is distributed either to the importer or exporter of permits, and will ultimately depend on how the policy is designed. In the model, alternative revenue allocations are considered by endowing certificates to either China or the developed region that it is trading with. As a consequence, the impact of the carbon market linkage on the welfare in the countries involved depends on this allocation choice, as discussed in the results presented in Section 3.

2.3. Emission trading schemes and long-term mitigation objectives in Europe, China and the US

For the COP21 in Paris, Europe, China and the US reaffirmed their long-term emission reduction objectives in their respective Intended Nationally Determined Contributions (INDC).[7] The US announced target is a 26 to 28% reduction of greenhouse gas emissions by 2025 below the 2005 level. For China, the goal for 2030 is a 60 to 65% reduction in carbon intensity below 2005 its level.[8] Among the measures taken to achieve this objective, the development of an ETS at the national level that would likely cover electricity and energy-intensive industries was explicitly mentioned. In Europe, the 2030 aim is a 40% emission reduction below 1990 levels, as decided under the 2030 climate and energy framework and in line with the longer term 80% reduction objective stated in the 2050 roadmap.

The EU ETS is a key instrument for reducing European industrial greenhouse gas emissions. Started in 2005, it now covers more than 11,000 power stations and industrial plants in 31 countries.[9] Credits from CDM and JI are accepted for compliance in the EU ETS under a specific limit. For Phase II of the scheme (2008–2012), this limit was 13% of the total amount of EU allowances. Some organizations estimate that 1.6 to 1.7 billion tons of credits could be used in Phases II and III combined (ICAP, 2016). Banking and borrowing are allowed within each phase.

It is currently uncertain how the US will meet its INDC pledged at the Paris agreement. The Clean Power Plan (EPA, 2015), the current centerpiece of climate policy in the US, was put on hold by the Supreme Court in February 2016. Furthermore, the Clean Power Plan is only a first step in abating emissions. To meet its Paris commitments, it is highly likely that the US will have to implement policies on the electricity and other energy-intensive industries. In China, as the objective is expressed in terms of emissions intensity, there remains some uncertainty on the exact emissions path that this corresponds to.

In this analysis, the EU ETS is modeled as a carbon market covering the EU electricity and energy-intensive sectors. The emission constraint imposed on these sectors is in line with the official EU ETS objectives: a

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[7] After Paris Agreement INDCs are converted to Nationally Determined Contributions (NDC). We keep the abbreviation INDC in our study to reflect the contributions.

[8] Zhang et al. (2014) examines the feasibility of emissions reduction pathways for China for the 2020–2050 timeframe.

[9] In addition to the EU Member States, Iceland, Norway and Liechtenstein also participate in the EU ETS.

Table 2
Scenarios summary.

Scenarios	Carbon constraint on emissions from electricity and energy-intensive sectors	International carbon trading
NO-POLICY	None	None
CHN-ETS	17% reduction in 2020 and 25% in 2030 compared to the NO-POLICY scenario	None
EU-ETS	21% reduction by 2020 and 43% by 2030 compared to 2005 levels	None
US-ETS	16% reduction by 2020 and 29% by 2030 compared to 2005 levels	None
EU–CHN-Trade	As in CHN-ETS for China and EU-ETS for the EU	Unlimited between China and the EU
EU–CHN-LIMIT	As in CHN-ETS for China and EU-ETS for the EU	Limited between China to the EU
US–CHN-TRADE	As in CHN-ETS for China and US-ETS for the US	Unlimited between China and the US
US–CHN-LIMIT	As in CHN-ETS for China and US-ETS for the US	Limited between China and the US
EU–US–CHN-TRADE	As in CHN-ETS for China, US-ETS for the US, and EU-ETS for the EU	Unlimited between China, the EU and the US

21% reduction by 2020 below 2005, and a 43% reduction by 2030. Banking of allowances is modeled by specifying a carbon price in the base period that grows at an assumed discount rate of 5% per year.[10] The base period carbon price is chosen to target cumulative emissions specified by the cap. In the modeling exercise, no distinction is made between Phase III (2013–2020) and Phase IV (2021–2028) of the EU ETS. We assume that the aviation sector has to buy some allowances in the general ETS even if this is partly compensated by the use of offsets (CDM and JI credits) as explained in Appendix. Similarly, we simulate an ETS covering the US electricity and energy intensive industries, with an emission reduction constraint of 16% by 2020 below 2005 levels and of 29% by 2030. We also allow banking of emissions permits for the whole time period, so the period-by-period emissions caps are converted to a cumulative emissions cap between 2020 and 2030. For China, we translate the economy wide carbon intensity objectives of Chinese INDC into ETS targets of a 70% increase in emissions by 2020 above the 2005 level and a 109% increase in 2030.

2.4. Scenarios

Nine core scenarios are used to analyze the impact of carbon trading with a limit on the amount of permits that can be exchanged, as summarized in Table 2. In the NO-POLICY scenario, no emission constraints are imposed. In the CHN-ETS scenario, emissions from Chinese electricity and energy intensive sectors are capped from 2020 to 2030 in a way that is consistent with the emissions intensity objectives announced by China in the last years: the emission targets discussed in Section 2.3 are simulated by imposing caps that reduce emissions by 17% in 2020 and 25% in 2030, relative to the NO-POLICY case. In the EU-ETS scenario, emissions from the European power and energy intensive sectors are capped at a level that takes account of the official EU ETS objectives and the use of CDM and JI credits as well as emission targets specified for aviation and other EU ETS sectors, as outlined in the previous section. In the US-ETS scenario, emissions from the power and energy intensive industries are capped at a level consistent with the emission reduction objectives announced by the US in its INDC as explained in Section 2.3. These commitments correspond to cumulative emission reductions of 13 billion tons between 2015 and 2030.

In the EU–CHN-TRADE scenario, carbon trading is allowed between the EU and Chinese ETS from 2020 onwards without any limit on the amount of permits traded. Similarly, for the US–CHN-TRADE scenario, emissions permits are exchanged between the US and China ETSs from 2020 onwards. In the EU–CHN-LIMIT scenario, carbon trading is allowed but the amount of carbon permits that can be imported from China to the EU ETS for each time period is limited to 10% of the total amount of European allowances for this time period ($\alpha = 0.1$). Given the constraint imposed on the EU ETS sectors, this fraction limits trade

of certificates to 151, 130 and 110 million respectively in 2020, 2025 and 2030. In the US–CHN-LIMIT scenario, the amount of permits that can be imported from China to the US ETS is similarly limited to 10% of the US cap for each time period, which corresponds to a limit of 247, 232 and 209 respectively in 2020, 2025 and 2030. Finally, in the EU–US–CHN-TRADE scenario, we simulate a coupling between the three regional carbon markets considered in this study.

In alternative variants of the US–CHN-LIMIT and EU–CHN-LIMIT scenarios, we consider limits of 5%, 10% and 20%. We assign the certificates revenue to the EU or the US in the core simulations. Alternative allocations of the certificate revenue are considered in additional simulations, in particular for the welfare analysis.

3. Results and discussion

3.1. Emissions transfers and carbon prices

Unlimited sectoral trading leads to a carbon price equalization between the two regions involved. Under limited sectoral trading, as long as the limit is binding, carbon prices in the two regions are not equalized and the difference in prices in the two regions depends on α.

Emissions from the ETS covered sectors in each region are presented in Fig. 1, and carbon prices in each region are displayed in Fig. 2.

Under the ETS constraint and in the absence of carbon trading with other countries, the emissions of Chinese power and energy intensive industries are 8.04 billion tons in 2030 (Fig. 1a), i.e. 2.71 billion tons less than NO-POLICY emissions, and the corresponding carbon price $17.5/tCO_2$ (Fig. 2a). If the US ETS is not coupled with the Chinese ETS, the US carbon price is $80/tCO_2$ in 2030 (Fig. 2b) and the emissions covered by the US ETS amount to 2.15 billion tons in 2030, compared to 3.66 in the NO-POLICY scenario (Fig. 1b). If unlimited sectoral trading is allowed between the two regions (US–CHN-TRADE), Chinese carbon permits corresponding to 663 million tons CO_2 are exported to the US and the carbon price is equalized across the two systems at $23.9/tCO_2$ in 2030. Emissions from the sectors covered by the US ETS are 2.85 billion tons while those from the Chinese ETS sectors are 7.37 billion tons in 2030.[11]

In the US–CHN-LIMIT scenario, imports of Chinese permits cannot exceed 10% of the number of permits issued under the US-ETS for each time period. This limit is 158 million in 2030. In this scenario, Chinese emissions are equal to 7.83 billion tons of CO_2, while US emissions are 2.43 billion tons in 2030. Carbon prices ($50.6/tCO_2$ in the US and $19.3/tCO_2$ in China in 2030) are not equalized in the two regions.

In the case of unlimited carbon trading between the EU and China ETS, Chinese carbon permits corresponding to 296 million tons CO_2 are exported to Europe (Fig. 1c). EU and China carbon prices are equalized at $20.1/tCO2$, which corresponds to a 60% drop in the EU carbon

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[10] As the EPPA model is recursive dynamic, rather than including an endogenous interest rate that equates savings and investment, savings enters each representative household's utility function as a proxy for future consumption. In the absence of an interest rate, we assume an exogenous discount rate of 5% in each region. This approach is consistent with other studies built on recursive dynamic models – see for example, Paltsev et al. (2009).

[11] The amount of permits transferred in 2030 is the difference between Chinese ETS sectors emissions in the CHN-ETS and the US–CHN-TRADE scenarios in 2030. It is not equal to the difference between US emissions specified under the US ETS and the US–CHN-TRADE scenario in 2030, as assumed banking of allowances allows US agents to fulfill part of their 2030 emissions reductions obligations in previous periods.
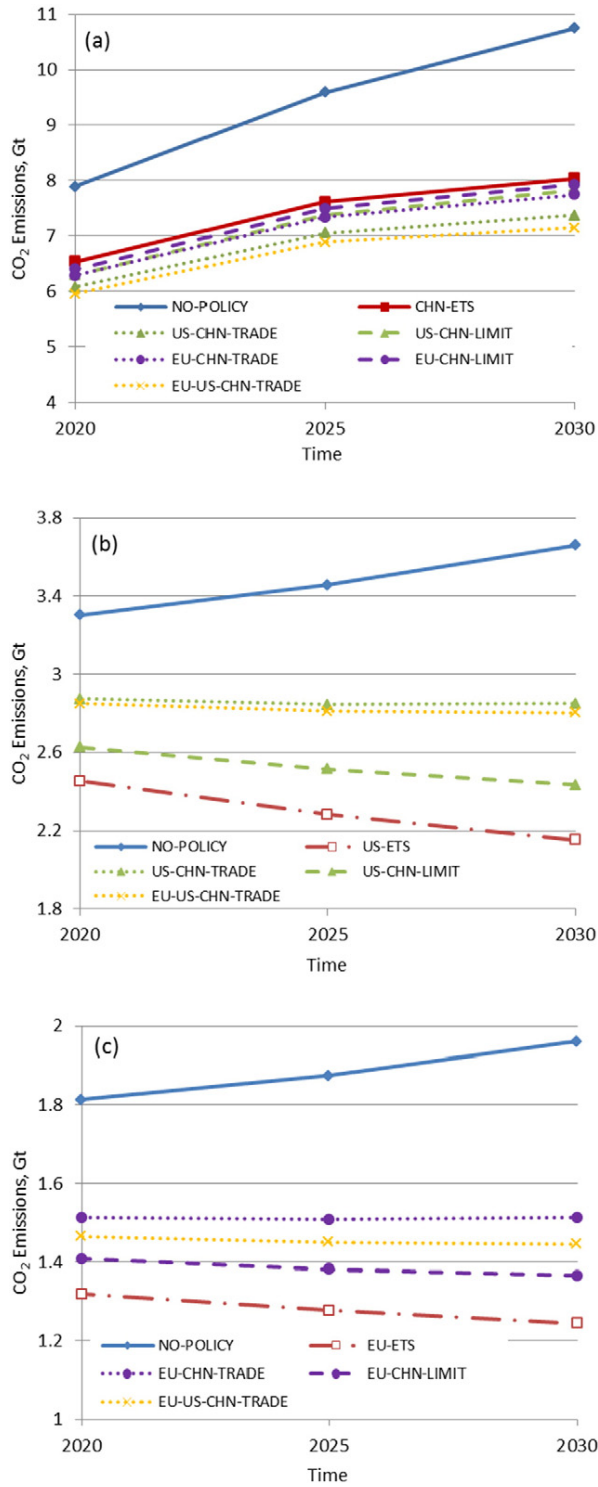
Fig. 1. CO$_2$ emissions from (a) the Chinese, (b) US and (c) EU ETS sectors.

Fig. 2. Carbon prices in (a) China, (b) the US, and (c) the EU.

price (from \$49.3/tCO$_2$ in the EU-ETS scenario), as shown in Fig. 2c. If a limit is set on the emissions permits that can be exported from China to the EU, the EU carbon price reduction is 30%, while the Chinese carbon price is \$18.5/tCO$_2$.

In the case of a trilateral market (EU–US–CHN-TRADE), relative to the bilateral cases, the carbon price is higher (26.5\$/t in 2030) and emission reductions in each regions are deeper. This is understandable as the carbon price in the EU-ETS case is greater than in the US–CHN-TRADE
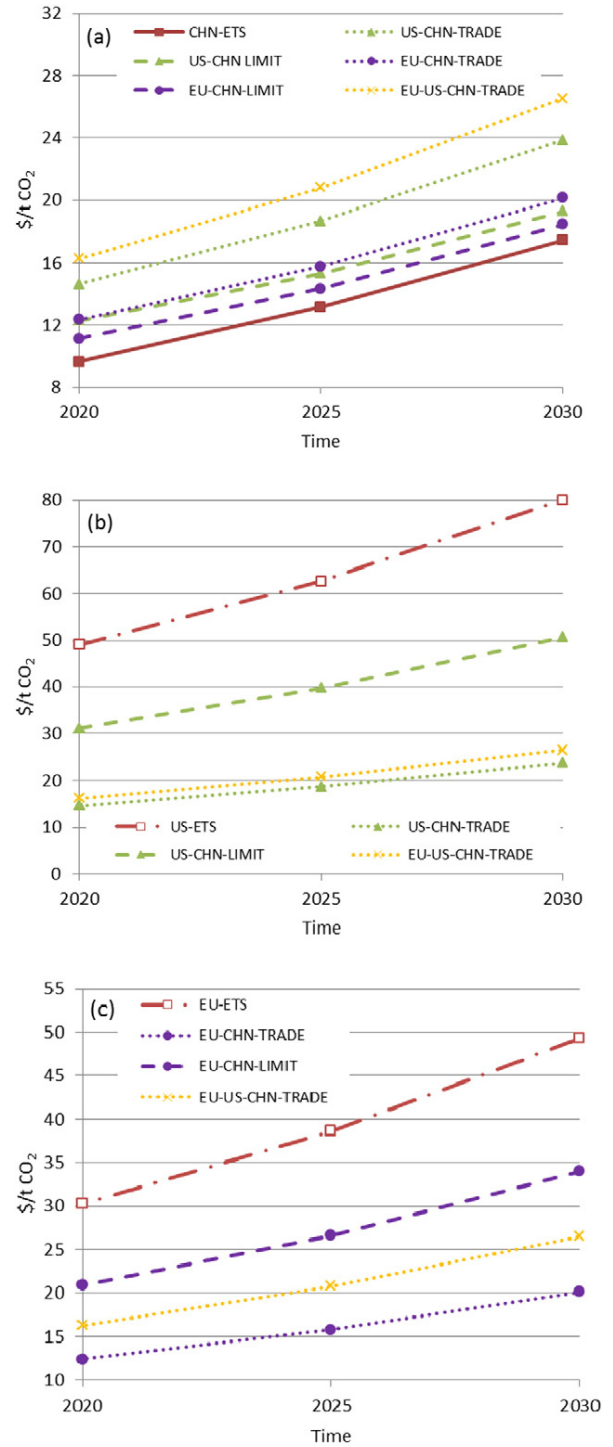
scenario and, symmetrically, the carbon price in the US-ETS scenario is higher than in the EU–CHN-TRADE case.

Carbon prices and the volume of permits transferred vary with α. The stricter the limit, the lower the amount of permits that are transferred from China to the US or the EU, and the larger the price difference between the two regions as reported in Table 3. In the US–China case, when α = 0.05, the volume of permits traded is 104 million tons in 2030, the carbon price is \$18.5/tCO$_2$ in China and \$64.4/tCO$_2$ in the US. In comparison, when α = 0.2, the volume of emission permits transferred is 418 million tons and the 2030 carbon price is \$21/tCO$_2$ in

Table 3
Carbon prices and volume of permits transferred in 2030 in the cases of US–China and EU–China carbon trading.

	Volume of permits transferred (Mt CO$_2$)	Chinese carbon price ($/tCO$_2$)	US or EU carbon price ($/tCO$_2$)
CHN-ETS	–	17.47	–
US-ETS	–	–	80.0
US–CHN-LIMIT, $\alpha = 0.05$	104	18.5	64.4
US–CHN-LIMIT, $\alpha = 0.1$	209	19.3	50.6
US–CHN-LIMIT, $\alpha = 0.15$	313	20.1	39.5
US–CHN-LIMIT, $\alpha = 0.2$	418	21.0	30.4
US–CHN-TRADE	663	23.9	23.9
EU-ETS	–	–	49.3
EU–CHN-LIMIT, $\alpha = 0.05$	55	18.1	41.4
EU–CHN-LIMIT, $\alpha = 0.1$	110	18.5	34.0
EU–CHN-LIMIT, $\alpha = 0.15$	164	18.9	28.1
EU–CHN-LIMIT, $\alpha = 0.2$	219	19.3	22.7
EU–CHN-TRADE	296	20.1	20.1
EU–US–CHN-TRADE	886	26.5	26.5

China and $30.4/tCO$_2$ in the US. Under unlimited sectoral trading, the US carbon price decreases by 70% and under limited trading, this reduction is 36% if $\alpha = 0.1$ and 19% if $\alpha = 0.05$.

Comparable effects are observed in the EU-China case. For a limit $\alpha = 0.05$, 55 million tons of CO$_2$ permits are transferred from Europe to China and the EU carbon price is reduced by 16% compared to the EU-ETS scenario. For a limit $\alpha = 0.2$, the volume of permits transferred from China to the EU corresponds to 219 million tons and the European price decreases by 54%.

3.2. Electricity generation profiles

Carbon emission constraints in China, the US and Europe change electricity generation profiles in these regions. While carbon trading between the two regions only implies a transfer of emissions, the impact on low carbon technologies in China is not the same as in Europe or the US due to differences in abatement cost. Figs. 3, 4 and 5 present electricity generation in China, the US and the EU in all scenarios (for limited emission trading cases, α is equal to 0.1).

In China, unlimited sectoral trading enhances the changes induced by the China ETS on the electricity sector. For example, electricity production from coal decreases by 7.5% in the US–CHN-TRADE scenario relative to the CHN-ETS scenario. Electricity production from low-carbon technologies is also impacted: in the US–CHN-TRADE scenario, relative to the China-Cap scenario, electricity production from nuclear energy increases by 1.2%, hydropower increases by 5.2%, and wind and solar power increase by 3.4%. The price of electricity increases by 16% in the US–CHN-TRADE scenario, which decreases demand and ultimately production by 3.2% compared to the CHN-ETS scenario. When sectoral trading is limited ($\alpha = 0.1$), these effects are smaller: relative to the CHN-ETS scenario, the electricity price increases by 1.8% and the total amount of electricity generated decreases by 0.9%. The total

amount of electricity produced in the US–CHN-TRADE scenario is 32.35 exajoules (EJ), out of which 12.10 EJ from low carbon technologies, compared to a total of 32.64 EJ including 12.04 EJ from low carbon technologies in the CHN-ETS scenario. In the EU–US-CHN-TRADE scenario, the total amount of electricity produced is 31.19 EJ, with 12.57 EJ from (combined) solar, wind, nuclear and hydropower.

In the US, unlimited sectoral trading partially reverses technological changes induced by the US ETS. Setting a limit on the amount of carbon permits that can be imported from China to the US reduces this effect. For example, in comparison to the US-ETS scenario, electricity production from coal increases by 40.4% in the US–CHN-TRADE scenario, by 37.8% in the EU–US–CHN-TRADE case, and by 16.9% in the US–CHN-LIMIT scenario. Additionally there is greater generation from low-carbon technologies in the US–CHN-LIMIT scenario than the US–CHN-TRADE scenario: nuclear power production increases by 1%, hydropower production increases by 8.6%, and solar and wind power production increase by 6.3%.
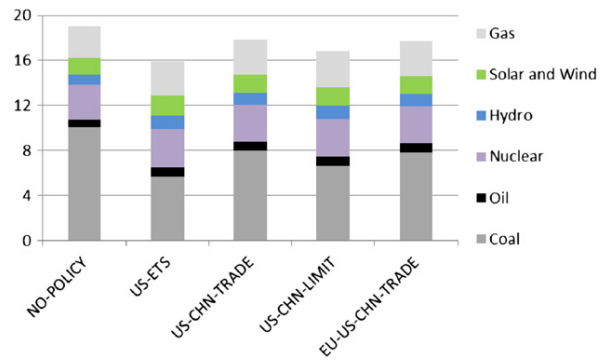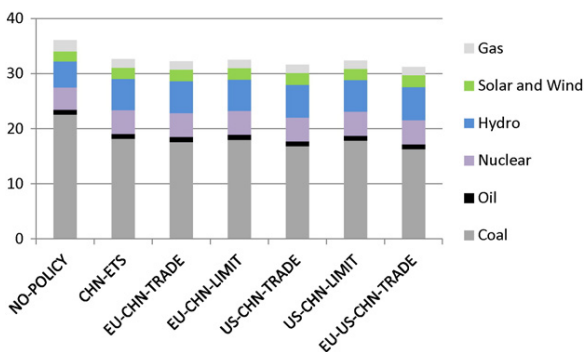

Fig. 4. Electricity generation the US in 2030 (EJ).

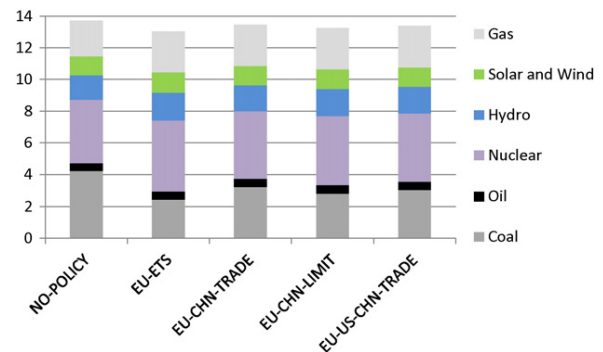**Fig. 3.** Electricity generation in China in 2030 (EJ).

Fig. 5. Electricity generation in the EU in 2030 (EJ).

In the case of carbon trading between the EU and China, we observe comparable results. Unlimited imports of Chinese emission permits to Europe induce an electricity price increase of 7.2% in China. This is associated with a reduction of 1.4% in the total amount of power produced domestically and an increase in generation from low-carbon technologies of 1.4% (0.16 EJ). If carbon trading between the EU and China is limited, these effects are reduced. Relative to when there is unrestricted trade in permits, limited sectoral trading induces an increase of 2.8% in the price of electricity, a 0.47% reduction in total power production in China, and a 0.5% increase in generation from low-carbon technologies (0.06 EJ).

In Europe, unlimited carbon trading with China reduces power generation technologies from low-carbon technologies by 4.7% (0.35 EJ) compared to EU-ETS scenario. In the case of a trilateral market, this reduction is 3.5% (0.26 EJ). In the case of limited trading, this decrease is 2.2%.

In summary, unlimited sectoral trading between the EU or US ETS and the Chinese carbon market would enhance the development of low-carbon electricity technologies in China relative to an isolated China ETS and also decrease the total amount of electricity produced. In Europe, or the US, this would partly reverse deployment of low-carbon power technologies incentivized under policy without international permit trading. Limiting the amount of carbon permits that could be imported from China to the EU or the US would reduce these effects.[12]

3.3. Leakage and aggregate emission reductions

The emission reduction constraint imposed in Europe, the US and China in the analysis induces leakage of emissions to non-covered sectors and regions. As noted by Gavard et al. (2011a), capping electricity emissions can lead to leakage of emissions to other sectors in the country applying the sectoral policy (internal leakage). This occurs because the substitution away from coal in the electricity sectors and the associated price decrease leads to greater coal use in other sectors. These effects can be magnified by international permit trading if the export of permits leads to larger increases in the electricity price.

Here, over the 2020–2030 time period, the cumulative emission reduction constraint imposed in the US–China case is 13 billion tons in the US and 22.1 billion tons in China. In the CHN-ETS case, cumulative internal leakage in China over the 2020–2030 period is 0.89 billion tons of CO_2, which increases to 1.18 billion tons of CO_2 if there is unlimited trade in permits (see Table 4a). Internal leakage is reduced to 1.06 billion tons when there is a limit on the quantity of permits that the US can import from China. This reduction is because Chinese carbon and electricity prices are lower in the US–CHN-LIMIT scenario than in the US–CHN-TRADE case. In the US, leakage to the rest of the economy is negative. This result is because the increased prices for electricity and energy-intensive commodities reduce output elsewhere, which dominated the impact of substitution towards coal in sectors not covered by the emissions cap.

If international leakage (i.e., leakage to countries without emission constraints in our simulations) is also taken into account, aggregate leakage is 3% smaller if carbon trading is not limited than if it is (leakage is 3.74 billion tons of CO_2 in the US–CHN-TRADE scenario compared to 3.84 billion tons of CO_2 for US–CHN-LIMIT). This result is driven by the impact of the US carbon price change on the rest of the world. However this effect is small (the difference in global emission reduction between the unlimited and limited trading scenarios is smaller than 0.3%).

In the case of carbon trading between the EU and China, we observe comparable results (see Table 4b). Carbon leakage to the rest of the economy in China is smaller when there is a limit on the amount of emissions permits that can be exported to the EU (it is 0.98 billion tCO_2 in the EU–CHN-LIMIT scenario compared to 1.04 billion tCO_2 in

the EU–CHN-TRADE scenario). As for the US, there is negative internal leakage in the EU due to the carbon policy increasing costs throughout the economy. International leakage is 8.4% higher under limited carbon trading than under unlimited trading. In aggregate the effect on international emissions dominates the domestic leakage effect and global emission reduction are higher in the unlimited trading scenario, although the difference is again small (0.7%).

In the EU–US–CHN-TRADE case, we estimate total leakage and global emission reductions to be, respectively, 4.91 and 43.22 billion tCO_2. We also estimate that leakage to uncovered sectors in China is 1.28 billion tCO_2, which is larger than in the case of bilateral markets due to the higher carbon price reported in Section 3.1.

3.4. Welfare impacts

The welfare impact of sectoral trading is driven by two effects. On the one hand, trade in carbon permits induces financial transfers from the developed to the developing region (transfer effect). On the other hand, the constraint on the developing country electricity sector makes electricity more expensive, which causes a decrease in aggregate output (general equilibrium effect). Gavard et al. (2011a) show that unlimited sectoral trading improves welfare in developed regions but might decrease it in developing regions. This is driven by the constraint imposed in the developed region being more stringent than the constraint imposed in China. As such, the general equilibrium effect dominates the transfer effect in developing regions when there is sectoral trading. As a consequence, while sharing the carbon constraint improves welfare in the developed country by lowering the cost of its domestic climate policy, this is not necessarily so in the developing country.

As noted in Section 2, modeling limited sectoral trading by introducing a trade certificate system requires making a choice regarding the allocation of the revenue from the certificates, which influences welfare in each region. For the welfare analysis, we consider separate cases where the revenue is allocated to China or to the EU or US.

Table 5 reports welfare changes for the policy scenarios considered relative to the NO-POLICY scenario. Tables 6a and 6b report welfare changes for the US–CHN-LIMIT and EU–CHN-LIMIT scenarios with alternative values of α, and alternative certificate rent allocations.

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[12] Given the fact that Chinese electricity production is nearly three times that in Europe or twice that in the US in 2030, a similar change in absolute values is proportionally more significant in Europe or the US than in China.

Table 4a
Cumulative leakage and emission reductions relative to the NO-POLICY scenario for the time period 2020–2030 (billion tCO_2).

	US-ETS	CHN-ETS	US–CHN-TRADE	US–CHN- LIMIT
Leakage to uncovered sectors in China	0.03	0.89	1.18	1.06
Leakage to uncovered sectors in the US	−0.13	0.00	−0.05	−0.09
Leakage to the rest of the world	1.76	1.35	2.61	2.87
Total Leakage	1.66	2.24	3.74	3.84
Global emission reduction	10.90	19.70	31.27	31.18

Table 4b
Cumulative leakage and emission reductions relative to the NO-POLICY scenario for the time period 2015–2030 (billion tCO_2).

	EU-ETS	CHN-ETS	EU–CHN-TRADE	EU–CHN-LIMIT
Leakage to uncovered sectors in China	0.02	0.89	1.04	0.98
Leakage to uncovered sectors in the EU	−0.15	0.00	−0.10	−0.12
Leakage to the rest of the world	1.59	1.35	2.73	2.96
Total leakage	1.46	2.24	3.67	3.82
Global emission reduction	7.03	19.70	29.94	29.74

Table 5
2030 Welfare changes relative to the NO-POLICY scenario (percent).

Scenarios	In China	In the US	In the EU
CHN-ETS	−0.62	−0.01	0.01
US-ETS	0.00	−0.38	0.03
EU-ETS	0.00	0.00	−0.30
US–CHN-TRADE	−0.70	−0.22	0.03
EU–CHN-TRADE	−0.67	−0.01	−0.20
EU–US–CHN-TRADE	−0.71	−0.26	−0.21

In the CHN-ETS and the US-ETS scenarios, the welfare changes compared to the NO-POLICY scenario (−0.62% in China in the CHN-ETS scenario, −0.38% in the US in the US-ETS case) are driven by the constraints on emissions in each region. Under unlimited sectoral trading (US–CHN-TRADE), the US is better off but China is worse off, as the general equilibrium effect dominates the revenue effect. Unlimited trading of carbon permits is not welfare improving for China as the carbon market only covers parts of the Chinese and US economies and the revenue that China gains from selling emissions permits does not compensate for the welfare loss associated with sharing a tighter emission constraint with the United States. Comparable results are observed for the EU–CHN-TRADE scenario. In the case of a trilateral market, all regions are worse off than in the bilateral markets scenario due to the fact that the common carbon price is higher (as reported in Section 3.1).

Under limited sectoral trading, welfare changes depend on the allocation of certificate revenue. For obvious reasons, welfare is higher in China if it receives the revenue than if certificate revenue is allocated to the US or the EU. For example, for $\alpha = 0.15$, welfare decreases by 0.58% in China if certificate revenue goes to this country, but it decreases by 0.68% if the revenue is allocated to the US. Similarly, the US or the EU is better off if households in these regions are endowed with the certificates. The welfare change as a function of the limit α depends on several factors. On the one hand, the differences in the carbon constraints and the general equilibrium effects associated with sharing them tend to make the developed region better off and China worse off. That is why welfare in the US or the EU is improved in all carbon trading scenarios, compared to when these regions implement isolated ETSs. On the other hand, the financial transfer associated with the certificate rent may compensate this if the rent is allocated to China. That is why we observe that Chinese welfare is improved for any limit α equal to or smaller than 0.15 in the US–China case and 0.1 in the EU–China case. Such limits correspond to *pareto-superior* situations compared to the case in which China does not trade carbon permits internationally.

We note that the relationship between welfare in China and the limit on international permit trade is non-linear function. For example, with permit trading between China and the US, China is better off for $\alpha = 0.1$ than for $\alpha = 0.05$. This is because the financial transfers associated with the certificate rent depend on the certificate price (i.e., the carbon price difference between the two countries) and the volume of transfers. While the certificate price decreases with α, the volume of permits increases with the limit. As a consequence, financial transfers associated with the rent are not necessarily a monotonic function of α (see Table 7).

Table 8 summarizes changes in electricity prices, aggregate output, net exports and the terms of trade in China as a consequence of carbon

Table 6a
2030 welfare changes in the US–CHN-LIMIT scenario relative to the NO-POLICY scenario for alternative values of α (percent).

Scenarios	In China		In the US	
	Rent to China	Rent to the US	Rent to China	Rent to the US
US–CHN-LIMIT, $\alpha = 0.2$	−0.63	−0.70	−0.24	−0.21
US–CHN-LIMIT, $\alpha = 0.15$	−0.58	−0.68	−0.28	−0.23
US–CHN-LIMIT, $\alpha = 0.1$	−0.56	−0.67	−0.32	−0.27
US–CHN-LIMIT, $\alpha = 0.05$	−0.57	−0.65	−0.35	−0.32

Table 6b
2030 welfare changes in the EU–CHN-LIMIT scenarios relative to the NO-POLICY scenario for alternative values of α (percent).

Scenarios	In China		In the EU	
	Rent to China	Rent to the EU	Rent to China	Rent to the EU
EU–CHN-LIMIT, $\alpha = 0.2$	−0.65	−0.66	−0.21	−0.20
EU–CHN-LIMIT, $\alpha = 0.15$	−0.63	−0.65	−0.23	−0.22
EU–CHN-LIMIT, $\alpha = 0.1$	−0.62	−0.64	−0.25	−0.23
EU–CHN-LIMIT, $\alpha = 0.05$	−0.61	−0.63	−0.27	−0.26

trading with the EU or the US. We observe that the electricity price in China in 2030 rises by 16% in the US–CHN-TRADE scenario and by 1.8% in the US–CHN-LIMIT scenario ($\alpha = 0.1$) relative to the CHN-ETS scenario. The aggregate output of Chinese economic sectors decreases by 0.10% in the US–CHN-TRADE scenario and 0.05% in the US–CHN-LIMIT scenario. Exports decrease by 18% in the US–CHN-TRADE scenario and by 4.9% in the US–CHN-LIMIT scenario but the terms of trade increase by 0.10% in the US–CHN-TRADE scenario and by 0.02% in the US–CHN-LIMIT scenario.

In the case of trading with Europe, these figures are more moderate: the electricity price in China increases by 7.2% under unlimited carbon trading, compared to 2.9% under limited trading. While Chinese net exports are reduced in both cases (by 6.7% in the EU–CHN-TRADE scenario and by 2.2% in the EU–CHN-LIMIT scenario) the terms-of-trade is nearly unchanged (it increases by 0.03% in the EU–CHN-TRADE scenario, and by less than 0.005% in the EU–CHN-LIMIT case).

4. Conclusions

In the Paris Agreement adopted at the 21st COP of the UNFCCC, particular attention has been given to international cooperation and support to developing countries to address climate change. As carbon markets are being implemented in many regions of the world, the question of whether linkages between them could contribute to this support is relevant. In earlier sessions of international climate negotiations, new market mechanisms such as sectoral trading were proposed. We analyze such a coupling mechanism between emission trading schemes covering the electricity and energy intensive sectors of a developed and a developing country. As previous studies show that such unlimited carbon trading could lead to a welfare loss in the developing country involved, we limit the volume of permits that can be traded between the two countries or regions by introducing a trade certificate system. Our simulations consider both EU–China and US–China trading cases. We also include the case of a trilateral carbon market.

We find that, while carbon prices in developing and developed regions equalize when trade is unrestricted, the introduction of a limit on the volume traded induces a carbon price difference between the two regions. In the US–China case, carbon prices equalize at $23.9/tCO_2$ under unlimited carbon trading. When the amount of Chinese carbon permits imported by the US cannot exceed 10% of the number of permits issued under a hypothetical US ETS, the carbon price is $50.6/tCO_2$ in the US and $19.3/tCO_2$ in China. The change in the US carbon price represents a 37% decrease compared to 70% when there is no limit. If the amount of Chinese permits that is accepted in the ETS is 5% or 20% of the number of US allowances, the US carbon price is respectively $64.4/tCO_2$ and $30.4/tCO_2$. In the EU–China

Table 7
Price of certificates and corresponding rent in the US–CHN-LIMIT scenario in 2030.

	Certificate price ($)	Rent ($ million)
US–CHN-LIMIT, $\alpha = 0.05$	45.9	8031
US–CHN-LIMIT, $\alpha = 0.1$	31.3	8742
US–CHN-LIMIT, $\alpha = 0.15$	19.4	7456
US–CHN-LIMIT, $\alpha = 0.2$	9.4	4610
US–CHN-TRADE	0	0

Table 8
Change in electricity price, aggregate output, next exports and the terms of trade in China in 2030, relative to the China-ETS scenario (percent).

Scenarios	Change in electricity price	Change in aggregate output	Change in net exports	Change in the terms of trade
EU–CHN–TRADE	+7.20	−0.05	−6.64	+0.03
EU–CHN–LIMIT	+2.88	−0.03	−2.20	+0.00
US–CHN–TRADE	+16.36	−0.10	−17.99	+0.10
US–CHN–LIMIT	+1.80	−0.05	−4.92	+0.02
EU–US–CHN–TRADE	+14.59	−0.11	−26.56	+0.14

case, the European carbon price is reduced by 59% under unlimited carbon trading with China, compared to 31% if the volume of Chinese permits imported by the EU is no more than 10% of the number of European allowances issued under the EU ETS cap.

We observe that, while unlimited sectoral trading enhances adoption of low-carbon technologies induced by the emission reduction constraint in the Chinese electricity sector, this effect is diminished under limited sectoral trading. Low carbon technologies represent 36.9% of a total of 32.6 EJ of electricity produced in China in 2030 under a national ETS. Under unlimited sectoral trading with the US ETS, the amount of electricity from low carbon technologies in China increases by 0.38 EJ but the total amount of electricity produced in this country decreases by 3% (0.06 EJ). If there is a limit on the amount of permits traded, electricity from low carbon technologies represents 12.4 EJ, which is 37.6% of the total amount of electricity generated in China. In the US, while unlimited sectoral trading partially reverses the changes in the electricity sector induced by the US carbon market, a limit on this mechanism moderates this effect. If no emission trading is allowed between the US and China, low carbon electricity in the US is 6.38 EJ in 2030, compared to 6.18 EJ with limited sectoral trading, and 5.92 EJ under unlimited sectoral trading. In the EU-China case, the share of low-carbon technologies in Chinese power generation increases from 12.04 EJ when there is no carbon trading with the EU to 12.10 EJ when the exchange of emissions permits is limited, and 12.20 EJ when it is not. But the total amount of power produced in this country is reduced by 0.16 EJ in the case of unlimited carbon trading and 0.06 EJ if a limit is set on the exports of carbon permits to Europe. In the EU, the share of low-carbon technologies is reduced from 57.4% if the EU ETS does not accept carbon allowances from China to 55.2% if permit imports are limited, and 53% if permit imports are unlimited.

Regarding aggregate emissions, we observe that leakage to the rest of the Chinese economy is lower when a limit is set on the amount of permits that can be traded than without it, due to the fact that the carbon price in China is higher in the absence of limit. On the other hand, international leakage is higher when exports of carbon permit from China to the EU or the US are limited. In aggregate, the international effect more than offsets the domestic impact and global emission reductions are higher under unlimited carbon trading than in the other scenarios. The difference in leakage under the limited and unlimited carbon trading scenarios is, however, less than 1%.

Welfare changes in the regions involved depend on the way the revenue from the certificates is allocated. China is better off if it receives the revenue than if the revenue is allocated to the EU or the US. China suffers a consumption loss in the case of unlimited carbon trading with the EU or the US. On the contrary, if the export of emission permits is limited, it is possible to find a limit that makes both regions better off or at least one region as well off and the other better off relative to when there is no international trade in emissions permits. In the analysis, this *Pareto superior* situation is reached when the volume of Chinese permits imported to Europe cannot exceed 10% of the volume of EU allowances defined by the EU ETS cap. This threshold is 15% in the case of carbon trading between China and the US.

To conclude, sectoral trading would allow some developing countries to participate in the carbon market set by developed countries. If a limit is

set on the amount of permits that can be traded, such a mechanism would not decrease the carbon price in the developed country as much as when there is no limit. As a consequence, it would not reverse the emission reductions initiated in the developed country, and in particular in its power sector, as much as unlimited trading would. In terms of aggregate emission reductions, the difference between the limited and unlimited carbon trading scenarios is minor. Finally, we observe that, if the revenue from the certificates is allocated to the developing country's households, it is possible to find a limit that makes both regions involved better off compared to the case in which no trading is allowed between the two regions.

Appendix A. Aviation emissions, CDM and JI credits in the EU ETS

Initial legislation for extending the EU ETS to aviation aimed to include, from 2012 onwards, emissions from all flights departing or landing at an EU airport (including flights to and from non-EU countries). However, due to political pressure from several non-EU countries, the scheme was amended so that it currently only applies to flights within Europe, including the countries of the European Economic Area (EEA) and European Free Trade Association space (EFTA).[13] The cap set on European aviation is 210 million tons each year from 2013 onwards. Given the high growth rate predicted for the sector and the high cost of abating aviation emissions, the aviation sector will likely purchase permits from the general EU ETS (Malina et al., 2012).

The impact of demand for permits by the aviation industry may be compensated by the use of CDM and JI credits.[14] For the time period 2008–2020, the limit of CDM and JI credits accepted for compliance in the EU ETS is 1.7 billion tCO_2. Some organizations estimated that 1.6 to 1.7 billion tons of offsets could be used in Phases II and III combined (ICAP, 2016). For Phase IV, the 2030 emission reduction objective shall be achieved domestically, ie without the use of international credits.

If we consider that aviation emissions grow at an annual rate of 3%, CDM/JI credits do not fully compensate for the allowances that the aviation sector will have to buy on the general ETS to cover its emissions above the aviation ETS cap. In the analysis, we hence reduce the general EU ETS cap by all aviation emissions above the aviation cap that are not covered by the estimated CDM and JI credits available for compliance in the EU ETS. This simplification does not take account of the marginal abatement cost curve for CDM and JI projects, but it allows the specification of a cap on emissions net of demand for permits by the aviation industry and use of CDM and JI credits. In practice, non-aviation and aviation sectors may purchase CDM and JI credits. As a net cap is used in the modeling framework, the results do not depend on which sectors use the CDM and JI credits.

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[13] The European Economic Area comprises the countries of the EU, plus Iceland, Liechtenstein and Norway. The members of the European Free Trade Association are Liechtenstein, Norway, Iceland and Switzerland.

[14] All projects are accepted except nuclear energy projects, afforestation and reforestation activities, and, from 2013 onwards, projects involving the destruction of industrial gases. Credits from large hydropower projects are subject to conditions.

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