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Claire Gavard[*‡], Niven Winchester[†] and Sergey Paltsev[†]

Abstract

In the negotiations of the United Nations Framework Convention on Climate Change (UNFCCC), new market mechanisms are proposed to involve Non-Annex I countries in the carbon markets developed by Annex I countries, beyond their current involvement through the Clean Development Mechanism (CDM). Sectoral trading is one such mechanism. It would consist of coupling one economic sector of a Non-Annex I country, e.g., the Chinese electricity sector, with the carbon market of some Annex I countries, e.g., the European Union Emission Trading Scheme (EU ETS). Previous research analyzed the potential impacts of such a mechanism and concluded that a limit would likely be set on the amount of carbon permits that could be imported from the non-Annex I country to the Annex I carbon market, should such a mechanism come into effect. This paper analyzes the impact of limited trading in carbon permits between the EU ETS and Chinese electricity sector when the latter is constrained by a 10% emissions reduction target below business as usual by 2030. The limit on the amount of Chinese carbon permits that could be sold into the European carbon market is modeled through the introduction of a trade certificate system. The analysis employs the MIT Emissions Prediction and Policy Analysis (EPPA) model and takes into account the banking–borrowing of allowances and the inclusion of aviation emissions in the EU ETS. We find that if the amount of permits that can be imported from China to Europe is 10% of the total amount of European allowances, the European carbon price decreases by 34%, while it decreases by 74 % when sectoral trading is not limited. As a consequence, limited sectoral trading does not reverse the changes initiated in the European electricity sector as much as unlimited sectoral trading would. We also observe that international leakage and leakage to non-electricity sectors in China are lower under limited sectoral trading, thus achieving more emissions reductions at the aggregate level. Finally, we find that, if China can capture the rents due to the limit on sectoral trading, it is possible to find a limit that makes both regions better off relative to when there is no international trade in carbon permits.

Contents

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1. INTRODUCTION

Carbon markets are developing around the world as policy instruments to reduce greenhouse gases emissions. The European Union Emission Trading Scheme (EU ETS) has existed since 2005. Elsewhere, national or subnational carbon markets are also operating in Australia, Japan, New Zealand and California (Trotignon *et al.*, 2011). Interconnections between them may develop (e.g., a full link between the European and the Australian trading schemes is planned for 2018). Pilot carbon markets are also being trialed in China. To date, Non-Annex I countries[1] 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 CDM Executive Board, a certain amount of credits, called Certified Emission Reductions (CER) are issued.[2] 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 of Annex I countries. Among these carbon markets, the EU ETS is the largest one to accept CERs for compliance. Similarly, under the Joint Implementation mechanism (JI) defined in Article 6 of the Kyoto Protocol, Emissions Reduction Units (ERU) can be emitted for projects occurring in Annex B countries and traded in other Annex B countries.[3] The EU accepts ERUs and CERs for compliance in the European carbon market (EU, 2004). In Phase II of the EU-ETS (2008–2012), the limit set on the amount of ERUs and CERs used in the ETS was 13% of the total amount of European allowances (EUA). This limit was not reached.

For major developing countries, new market mechanisms are being considered to move away from the CDM to a wider approach. These countries could then be involved in a global agreement without making nation-wide commitments. This improvement is supported by the decision of the 2011 United Nations (UN) Climate Conference in Durban to set up such mechanisms under the United Nations Framework Convention on Climate Change (UNFCCC). Sectoral trading is one of the propositions (EU, 2009). It involves including a sector from one nation in the cap-and-trade system of another nation or group of nations (IEA, 2009b). For example, Chinese or Indian electricity sectors could be linked to the emission trading schemes of some Annex I countries. Such approaches have been widely discussed (Baron *et al.*, 2008; Baron *et al.*, 2009; CCAP, 2008; Bradley *et al.*, 2007; ICC, 2008; IEA, 2006a, 2006b; IEA, 2007). Although they are less efficient than a global cap-and-trade system (Tirole, 2009), they may encourage participation in an international climate agreement (Sawa, 2010). As emissions 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; IEA,

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[1] The lists of Annex I and Non-Annex I countries were defined in the Kyoto Protocol (UN, 1998).

[2] 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.

[3] Annex B countries are Annex I countries with an emission reduction or a limitation commitment under the Kyoto Protocol (UN, 1998).

2005b; IEA, 2006a, 2006b; Schneider *et al.*, 2009a, Schneider *et al.*, 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 emissions reductions specified in Annex I sectors are implemented in Non-Annex I sectors. Hence carbon price decreases in Annex I regions resulted in a partial reversal of the technological changes induced by Annex I 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 a sectoral policy leads to carbon leakage to the rest of the emerging country's 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 or Indian electricity sectors. This suggests that policy makers would limit the amount of permits that could be traded, in the same way that caps are imposed on the volume of CERs and ERUs accepted for compliance in the EU ETS, if sectoral mechanisms are adopted.

The purpose of this paper is to quantify the impact of setting a limit on the amount of carbon permits that could be traded under sectoral trading. The analysis considers the case of a coupling between the EU ETS and Chinese electricity sector over the time period 2015–2030.

This paper has 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 the EU-ETS and its extension to the aviation sector, the use of offsets through the CDM, and sectoral trading.

2.1 The EPPA Model

The EPPA model is a recursive–dynamic, multiregion computable general equilibrium model (Paltsev, 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**, 15 individual 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 (CO_2, 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).

Table 1. EPPA model aggregation.

Countries or Regions	***Sectors***	***Factors***
Annex I	***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
Non-Annex I	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)	
	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)	

2.2 Limited Sectoral Trading

Climate policy instruments in EPPA include emissions constraints, carbon taxes, energy taxes and technology regulations such as renewable portfolio standards. When there are emissions 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 sectoral trading requires extending the model to allow trade between international permits and sector-specific permits.

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 the international carbon market of Annex I countries (e.g., the EU ETS). The number of certificates issued is a fraction, α, of the total amount of permits allocated in Annex I countries' carbon markets. Each permit exported from developing countries to Annex I regions requires a trade certificate, which limits the number of permits imported to α multiplied by the number of permits issued in Annex I 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 EU. As a consequence, the impact of the sectoral trading policy on the welfare in the countries involved depends on this allocation choice, as discussed in the results presented in Section 3.

2.3 European and Chinese Energy and Climate Policies

At the UNFCCC Conference of the Parties in Copenhagen in 2009, the EU committed to achieve a 20% emissions reduction below 1990 levels by 2020 (UN, 2009).[4] This reduction is part of the 20-20-20 targets, which are to be met through the application of the Climate and Energy Legislative Package. Two other goals include raising the share of EU energy consumption produced from renewable resources to 20% and improving the EU's energy efficiency by 20% by 2020. The EU ETS is a key instrument for reducing industrial greenhouse gas emissions. Started in 2005, it now covers more than 11,000 power stations and industrial plants in 31 countries.[5] 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. Banking and borrowing is allowed within each phase.

In this analysis, the EU ETS is modeled as a carbon market covering the EU electricity sector and energy-intensive industries. To achieve an economy-wide 20% emissions reduction, the emissions constraint imposed on these sectors is a 42% reduction below 1990 levels 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. The base period carbon price is chosen to target

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[4] The EU offered to increase its emissions reduction to 30% by 2020 if other major economies in the world commit to significant emissions reductions. The options for moving beyond a 20% reduction by 2020 are analyzed in a Communication published by the European Commission (EU, 2010).

[5] In addition to the EU Member States, Croatia, Iceland, Norway and Liechtenstein also participate in the European trading scheme.

cumulative emissions specified by the cap. In the modeling exercise, no distinction is made between Phase III (2013–2020) and Phase IV (2021–2028).

In 2009, before the Copenhagen Conference, China announced a target to reduce its carbon intensity by 40 to 45% by 2020 compared to the 2005 level. Modeling sectoral trading between the Chinese electricity sector and the EU ETS requires setting a trading baseline for Chinese emissions, below which China can sell emissions reductions to the EU. In the current analysis, to reflect emissions reductions due to the Chinese intensity target, we impose a 10% reduction target on Chinese electricity sector emissions by 2030 compared to no policy emissions.

2.4 The Aviation Sector and the EU-ETS

Since the beginning of 2012, emissions from international aviation have been included in the EU ETS (EU, 2008). Currently, the application of the scheme to flights in and out of Europe is under discussion and the legislation applies to all flights within Europe, including the countries of the European Economic Area (EEA) and European Free Trade Association space (EFTA).[6,7] The annual average of 2004, 2005 and 2006 aviation emissions within, from and to covered European countries was 221 million tons. The cap set on European aviation was 97% of this reference in 2012, and 95% 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.[8] From 2008 to 2010, installations under the EU ETS surrendered CERs to cover 277 million tons of CO_2-equivalent emissions and ERUs to cover 23 million tons of CO_2-equivalent. The limit on CER and ERUs in phase II of the EU ETS (13% of the amount of EUAs issued under the European cap) was not reached. By extrapolating these figures to 2011–2030 and comparing them to the limit set on the amount of CERs and ERUs allowed in the EU ETS, we find an approximation of CDM and JI credits that could be used by the aviation sector to cover their emissions.

In the analysis, we consider that aviation emissions grow at an annual rate of 3%. We decrease the general EU ETS cap defined in Section 2.3 by all aviation emissions above the aviation cap that are not covered by 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

[6] A global solution for international aviation emissions is expected from the International Civil Aviation Organization (ICAO) General Assembly that will take place in autumn 2013. If no progress is made, the EU ETS legislation will apply to all flights to and from European countries, regardless of the origin or destination of each flight.

[7] 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.

[8] 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. 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.

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.. The impact of alternative assumptions regarding the availability of CDM and JI credits is considered in Section 3.5.

2.5 Scenarios

Five core scenarios are used to analyze the impact of sectoral trading with a limit on the amount of permits that can be traded. In the No-Policy scenario, no emissions constraints are imposed. This scenario provides the "business as usual emissions" for Chinese electricity sector. In the China-cap scenario, an emissions constraint is imposed on the Chinese electricity sector only, with a target of 10% reduction below business-as-usual emissions by 2030. In the EU-ETS Scenario, cumulative emissions between 2005 and 2030 are reduced by 7.7 billion tons relative to the No-Policy Scenario. This emissions reduction accounts for the use of CDM and JI credits and emissions targets specified for aviation and other EU-ETS sectors. In the Trade Scenario, sectoral trading is allowed between the EU ETS and the Chinese electricity sector without a limit on sectoral trading. In the Limit Scenario, sectoral 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 158, 143, 128 and 113 million respectively in 2015, 2020, 2025 and 2030. In alternative variants of the Limit Scenario, we consider limits of 5, 10 and 20%.

We assign the certificates revenue to the EU in the core simulations. Alternative allocations of the certificate revenue are considered in additional simulations, in particular for the welfare analysis.

3. RESULTS

3.1 Emissions Transfers and Carbon Prices

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

Emissions in the Chinese electricity sector and in the sectors covered by the EU ETS are presented in **Figure 1**, and carbon prices in each region are displayed in **Figure 2**. If China sets a cap on its electricity sector and does not trade carbon permits abroad (China-cap), Chinese electricity emissions are 5.92 billion tons in 2030 (**Figure 1a**), 0.66 billion tons less than No-Policy emissions and the Chinese carbon price for the electricity sector is \$6.2/tCO_2 (**Figure 2a**). If the EU ETS is not coupled with Chinese electricity sector (EU ETS), the European carbon price is \$39.7/tCO_2 in 2030 (**Figure 2b**) and the emissions covered by the EU ETS amount to 1.30 billion tons in 2030, compared to 1.96 in the No-Policy Scenario (**Figure 1b**).

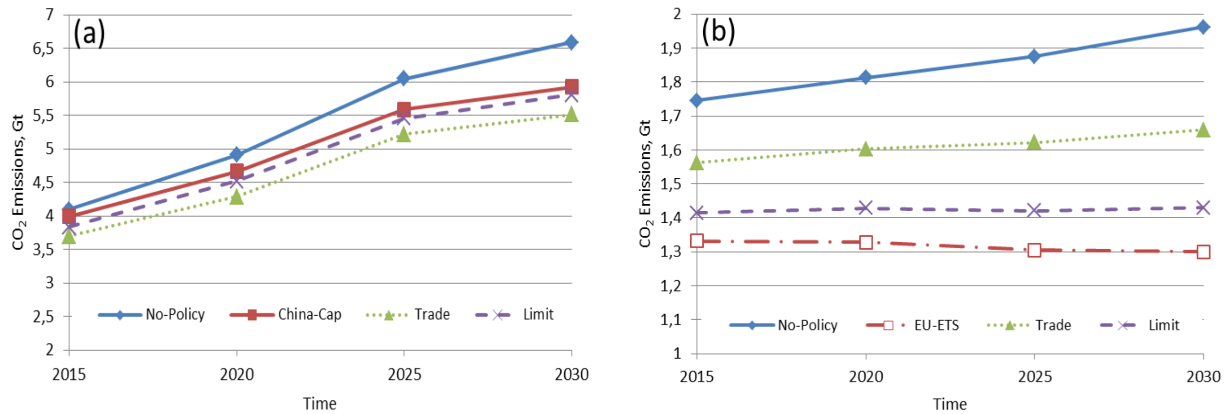

Figure 1. CO_2 emissions, in **(a)** the Chinese electricity sector, and **(b)** EU ETS sectors.

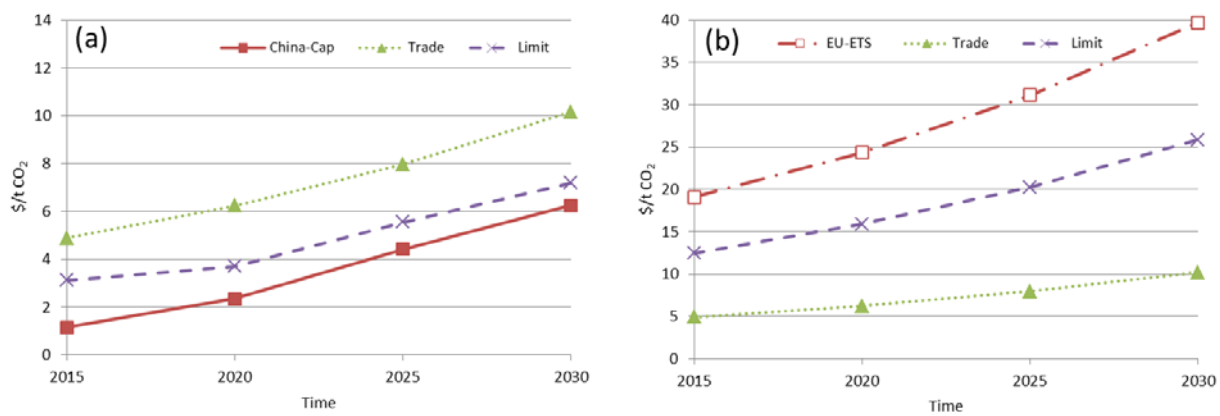

Figure 2. Carbon prices in **(a)** the Chinese electricity sector, and **(b)** the EU ETS.

If unlimited sectoral trading is allowed between the two entities (Trade), Chinese carbon permits corresponding to 410 million tons CO_2 are exported to Europe and the carbon price is equalized across the two systems at \$10.2/tCO_2. Emissions from the sectors covered by the EU ETS are 1.66 billion tons while those from the Chinese electricity sector are 5.51 billion tons in 2030.[9]

[9] The amount of permits transferred in 2030 is the difference between Chinese electricity emissions in the China-Cap and the Trade scenarios in 2030. It is not equal to the difference between European emissions specified under the EU ETS and the Trade scenario in 2030, as banking and borrowing allow European agents to fulfill part of their 2030 emissions reductions obligations in previous periods.

In the Limit Scenario, imports of Chinese permits cannot exceed 10% of the number of permits issued under the EU-ETS for each time period. This limit is 113 million in 2030. In this scenario, Chinese emissions are equal to 5.81 billion tons of CO_2, while EU emissions are 1.43 billion tons in 2030. Carbon prices (\$25.9/tCO_2 in Europe and \$7.20/tCO_2 in China in 2030) are not equalized in the two regions.

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 EU, and the larger the price difference between the two regions (see **Table 2**). When $\alpha = 0.05$, the volume of permits traded is 57 million tons in 2030 and the carbon price is \$6.78/tCO_2 in China and is \$31.4/tCO_2 in Europe. In comparison, when $\alpha = 0.2$, the volume of emissions transferred is 410 million tons and the 2030 carbon price is \$8.05/tCO_2 in China and \$10.2/t CO_2 in the EU ETS.

Table 2. Carbon prices and volume of permits transferred in 2030.

	Volume of Permits Transferred (Mt CO_2)	Chinese Carbon Price (\$/t CO_2)	EU Carbon Price (\$/t CO_2)
China-Cap	-	6.24	-
EU ETS	-	-	39.7
Limit, α=0.05	57	6.78	31.4
Limit, α=0.1	113	7.2	25.9
Limit, α=0.15	170	7.62	20.3
Limit, α=0.2	228	8.05	15.7
Trade	410	10.2	10.2

Table 2 also reports results when there is no limit on sectoral trading. Under unlimited sectoral trading, the European carbon price decreases by 74% and under limited sectoral trading, this reduction is 34% if $\alpha = 0.1$ and 21% if $\alpha = 0.05$.

3.2 Electricity Generation Profiles

Carbon emissions constraints in China and the EU change electricity generation profiles in the two regions. Previous analysis shows that unlimited sectoral trading between Europe and China would reverse most of the changes induced by the EU ETS in the European electricity sector. **Tables 3** and **4** present electricity generation in China and Europe in the No-Policy, China-Cap, EU ETS, Trade and Limit (when $\alpha = 0.1$) scenarios.

Table 3. Electricity generation in China in 2030 (EJ).

	No-Policy	China-Cap	Trade	Limit
Coal	22.6	20.3	19.1	20.1
Oil	0.85	0.85	0.88	0.87
Nuclear	4.09	4.19	4.24	4.20
Hydro	4.67	5.12	5.35	5.17
Solar and Wind	1.86	1.93	1.97	1.94
Traditional Gas	0.24	0.21	0.20	0.21
NGCC*	1.79	2.11	2.08	2.05
Total	36.1	34.7	33.86	34.51

*Note: NGCC refers to natural gas combined cycle.

In China, unlimited sectoral trading enhances the changes induced by the constraint on Chinese electricity sector. For example, electricity production from coal decreases by 6% in the Trade Scenario relative to the China-Cap Scenario. Electricity production from low-carbon technologies is also impacted: in the Trade Scenario, relative to the China-Cap Scenario, electricity production from nuclear energy increases by 1.2%, hydropower increases by 4.5%, and wind and solar power increases by 2.1%. The price of electricity increases by 6.7% in the Trade Scenario, which decreases demand and ultimately production by 2% compared to the China-Cap Scenario. When sectoral trading is limited ($\alpha = 0.1$), these effects are smaller. Relative to the China-Cap Scenario, the electricity price increases by 2.9% and the total amount of electricity generated decreases by 0.5% in the Limit Scenario. Also in this scenario, the total amount of electricity produced is 34.51 exajoules (EJ) out of which 11.31 EJ is from low carbon technologies, compared to a total of 34.7 EJ, including 10.72 EJ from low carbon technologies in the China-Cap Scenario.

Table 4. Electricity generation in Europe in 2030 (EJ).

	No-Policy	EU ETS	Trade	Limit
Coal	4.23	2.64	3.65	3.02
Oil	0.49	0.51	0.49	0.50
Nuclear	4.01	4.39	4.15	4.30
Hydro	1.54	1.73	1.60	1.68
Solar and Wind	1.18	1.26	1.21	1.24
Traditional Gas	2.11	1.94	2.05	1.99
NGCC	0.16	0.69	0.46	0.64
Total	13.72	13.16	13.60	13.37

In Europe, unlimited sectoral trading partially reverses technological changes induced by the EU ETS. Setting a limit on the amount of carbon permits that can be imported from China to Europe reduces this effect. For example, in comparison to the EU-ETS Scenario, electricity production from coal increases by 38% in the Trade Scenario and by 14% in the Limit Scenario. Additionally there is greater generation from low-carbon technologies in the Limit Scenario than the Trade Scenario: nuclear power production increases by 3.6%, hydropower production increases by 5%, and solar and wind power production increases by 2.5%.

In summary, unlimited sectoral trading between the EU ETS and the Chinese electricity sector would enhance the development of low-carbon electricity technologies in China relative to an isolated cap on electricity emissions while decreasing the total amount of electricity produced. In Europe, this would partly reverse changes induced by the EU ETS in European electricity generation. Limiting the amount of carbon permits that could be imported from China to the EU would reduce these effects.[10]

3.3 Leakage and Aggregate Emissions Reductions

From 2005 to 2030, the cumulative emissions reduction constraint imposed in the analysis is 7.06 billion tons in Europe and 4.73 billion tons in China. These caps induce leakage of emissions to non-covered sectors and regions (see **Table 5**).

Table 5. Cumulative leakage and emissions reductions relative to the No-Policy Scenario for the time period 2005–2030 (billion tCO_2).

	EU-ETS	China-Cap	Trade	Limit
Leakage to the Rest of the Chinese Economy	0.36	0.67	1.71	1.25
Leakage to the Rest of the EU Economy	-0.15	0.02	-0.07	-0.12
Leakage to the Rest of the World	1.72	0.29	1.74	1.29
Total Leakage	1.93	0.98	3.39	2.42
Global Emissions Reduction	5.13	3.75	8.40	9.37

Gavard *et al.* (2011a) show how sectoral trading induces leakages in the Non-Annex I countries involved. As the electricity sector is constrained, electricity price rises, which decreases output in other sectors. At the same time, there is a decrease in the price of coal and a substitution toward this input in many sectors. As a consequence, all sectors see their emissions increase due to the substitution effect, except the transport, electricity and oil sectors. In aggregate, there is positive leakage to the rest of the Chinese economy. The amount of cumulative leakage to the rest of the Chinese economy is 1.25 billion tons of CO_2 under limited sectoral trading and 1.71 billion tons when no limit is set on the amount of permits that can be traded. In Europe, leakage to the rest of the economy is negative. As the EU-ETS covers not only the electricity sector but also energy-intensive industries, this result is driven by the output effect dominating the substitution effect between coal and electricity (i.e. there is not a large substitution from electricity to coal in non-electricity sectors as in the China-Cap Scenario). If international leakage is also taken into account, we observe that aggregate leakage is significantly smaller when there is limited sectoral trading (2.42 billion tons of CO_2) than when international trade in permits is not restricted (3.39 billion tons of CO_2). This result is explained

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

by the fact that, when there is limited sectoral trading, a larger proportion of the reduction in emissions takes place within the EU-ETS, which has a broader sectoral coverage. This can be related to the fact that emissions reductions in China target the electricity sector only while they relate to the electricity sector as well as other energy-intensive industries in Europe. Taking into account the constraints imposed in Europe and China, and total leakage, we conclude that aggregate emissions reductions at the world level are higher under limited sectoral trading than in the other scenarios.

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 Annex I country to the Non-Annex I region (transfer effect). On the other hand, the constraint on the Non-Annex I 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 Annex I regions but decreases it in Non-Annex I regions. This is driven by the constraint imposed in the Annex I region being more stringent than the constraint imposed on Chinese electricity sector. As such, the general equilibrium effect dominates the transfer effect in non-Annex I regions when there is sectoral trading. As a consequence, while sharing the carbon constraint improves welfare in the Annex I country, this is not necessarily so in the Non-Annex I 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. We consider separate cases where the revenue is allocated to China or the EU. **Table 6** reports welfare changes for the China-Cap, EU-ETS and Trade Scenarios relative to the No-Policy Scenario. **Table 7** reports welfare changes for the Limit scenario with alternative values of α, and with allocation of the certificate revenue to Chinese or European households.

Table 6. 2030 Welfare changes relative to the No-Policy Scenario (percent).

Scenarios	In China	In the EU
China-Cap	-0.14	0.00
EU ETS	0.00	-0.27
Trade	-0.23	-0.17

In the China-Cap and the EU ETS scenarios, the welfare changes compared to the No-Policy Scenario (-0.14% in China in the China-Cap scenario, -0.27% in Europe in the EU ETS case) are driven by the constraints on emissions in each region. Under unlimited sectoral trading (Trade), the EU is better off but China is worse off, as the general equilibrium effect dominates the revenue effect.

Table 7. 2030 welfare changes in the Limit Scenario 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
Limit, α=0.2	-0.18	-0.21	-0.19	-0.17
Limit, α=0.15	-0.16	-0.20	-0.21	-0.19
Limit, α=0.1	-0.14	-0.18	-0.23	-0.21
Limit, α=0.05	-0.14	-0.16	-0.24	-0.23

Under limited sectoral trading, welfare changes depend on the allocation of certificate revenue. For obvious reasons, welfare is higher in China if Chinese households receive the revenue than if certificate revenue is allocated to the EU. For example, for α = 0.15, welfare decreases by 0.16% in China if certificate revenue goes to China, but it decreases by 0.20% if the revenue is allocated to the EU. Similarly, Europe is better off if European households are endowed with the certificates. In addition, the welfare in China decreases as the limit α increases, while welfare in Europe increases with α. This is related to the general equilibrium effect and the dissymmetry in the carbon constraints as mentioned above; while sharing the constraints improves welfare for Europe, it is not necessarily so for China. **Table 8** summarizes changes in electricity prices, aggregate output, net exports and the terms of trade as a consequence of the policy. We observe that the electricity price in China in 2030 rises by 6.7% in the Trade Scenario and by 2.9% in the Limit Scenario (α=0.1) relative to the China-Cap scenario. The aggregate output of Chinese economic sectors decreases by 0.11% in the Trade Scenario and 0.02% in the Limit Scenario. Exports decrease by 4.9% in the Trade Scenario and by 3.3% in the Limit Scenario but the terms of trade increase by 0.04% in the Trade Scenario and by 0.005% in the Limit Scenario.

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

Scenarios	Change in Electricity Price	Change in Aggregate Output	Change in Net Exports	Change in the Terms of Trade
Limit	+2.89	-0.02	-3.32	+0.01
Trade	+6.72	-0.11	-4.90	+0.04

Compared to the Trade Scenario, for which China is always worse off relative to the China-Cap scenario, it is interesting to note that, under limited sectoral trading, there exists a limit for which China is at least as well off as in the China-Cap Scenario, providing the certificate revenue is allocated to China. The EU is also better off in this scenario. As one entity is better off without the other being worse off, this situation (Limit scenario with α = 0.05 or 0.1) is *pareto superior* to the situation in which each region has its own constraint and no trading is allowed between them. Of the cases considered here, welfare is greater when α =0.1.

3.5 Sensitivity Analysis

In Section 2.4, we explained how European aviation emissions are included in the analysis, taking into account an approximation of the use of CDM and JI credit by this sector. In this subsection, we present the change in results when European aviation emissions are included in the analysis without compensation through CDM and JI projects. The results are summarized in **Table 9**. Under this adjustment, the carbon price in the EU ETS scenario in 2030 is \$43.4/tCO_2 and emissions from the sectors covered by the scheme are 1.28 billion tons. In the Limit Scenario, the European carbon price decreases by 36% with $\alpha = 0.1$, and by 17% if $\alpha = 0.05$. Carbon prices in European and Chinese electricity sectors equalize at \$10.4/tCO_2 in 2030 in the Trade Scenario. Under unlimited sectoral trading, 435 million tons of Chinese carbon permits are sold to Europe in 2030, compared to 114 million tons in the Limit Scenario. Emissions from the sectors covered by the EU ETS reach 1.65 billion tons in the Trade Scenario in 2030 and 1.41 in the Limit Scenario. The carbon price in China is \$7.19/tCO_2 in the Limit Scenario and \$10.4/tCO_2 in the Trade scenario. The welfare analysis presented in the previous section is robust to this sensitivity test.

Table 9. Carbon prices, permits traded, and emissions without CDM and JI credits.

Scenarios	Volume of Permits Transferred (Mt CO_2)	Chinese Carbon Price (\$/tCO_2)	EU Carbon Price (\$/tCO_2)	Chinese Electricity Sector Emissions (billion tCO_2)	EU ETS Sectors Emissions (billion tCO_2)
China-Cap	-	6.24	-	5.9	1.95
EU ETS	-	-	43.4	6.6	1.28
Limit	114	7.19	27.7	5.8	1.41
Trade	435	10.4	10.4	5.5	1.65

4. CONCLUSIONS

In the UNFCCC negotiations, new market mechanisms are proposed to extend Non-Annex I countries participation in carbon markets beyond the current project-based CDM. Sectoral trading is one such proposition. To prevent a large proportion of the reduction in emissions shifting from Annex I to Non-Annex I regions, limits on sectoral trading have been suggested. This paper quantified the impact of limited sectoral trading between the EU ETS and Chinese electricity sector. We find that, while carbon prices in the European and Chinese electricity sectors equalize at \$10.2/tCO_2 under unlimited sectoral trading, the carbon price is \$25.9/tCO_2 in Europe and \$7.2/tCO_2 in the Chinese electricity sector when the amount of Chinese carbon permits imported in the EU cannot exceed 10% of the number of permits issued under the EU-ETS. The change in the EU carbon price represents a 34% decrease compared to when there is no sectoral trading. If the amount of Chinese permits that is accepted in the ETS is 5 or 20% of the number of EUA allowances, the EU carbon price is respectively \$31.4/tCO_2 and \$15.7/tCO_2. We observe that, while unlimited sectoral trading enhances adoption of low-carbon technologies induced by the emissions reduction constraint in the Chinese electricity sector, this effect is diminished under limited sectoral trading. Low carbon technologies represent 31% of a total of 36.1 EJ of electricity produced in China if there is a 10% emissions reduction constraint on this sector. Under unlimited sectoral trading with the EU-ETS, the absolute amount of electricity from low carbon technologies increases by 0.84 EJ but the total amount of electricity produced in China decreases by 2%. If there is a limit on the amount of permits traded, electricity from low carbon technologies represents 11.31 EJ, which is 33% of the total amount of electricity generated in China. In Europe, while unlimited sectoral trading partially reverses the changes in the electricity sector induced by the EU-ETS, a limit on this mechanism moderates this effect. If no trading is allowed between the EU-ETS and Chinese electricity sector, low carbon electricity in Europe produces 7.38 EJ in 2030. With limited sectoral trading, low-carbon electricity production is 7.22 EJ in 2030, compared to 6.96 EJ if no limit is set on the volume of permits that can be traded with China.

Regarding aggregate emissions, we observe that international leakage and leakage to the rest of the Chinese economy are lower when a limit is set on the amount of permits that can be traded than without it. As a consequence, global world emissions reductions are higher under limited sectoral trading than in the other scenarios. Welfare changes in both 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. We find that there exists 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 EUA allowances defined by the European cap.

To conclude, a sectoral trading mechanism would allow some Non-Annex I countries to participate in the carbon market developed by Annex I 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 Annex I country as much as when there is no limit. As a consequence, it would not reverse the changes initiated in the electricity sector of the Annex I country as much as unlimited sectoral trading would. In terms of leakage and aggregate emissions reductions, limited sectoral trading also yields better results than unlimited sectoral trading. Finally, we observe that, if the revenue from the certificates is allocated to Chinese 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.

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