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What to Expect from Sectoral Trading: A U.S.–China Example

Claire Gavard, Niven Winchester, Henry Jacoby, and Sergey Paltsev

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What to Expect from Sectoral Trading: A U.S.–China Example

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Abstract

In recent United Nations Framework Convention on Climate Change (UNFCCC) negotiations, sectoral mechanisms were proposed as a way to encourage early action and spur investment in low carbon technologies in developing countries, particularly in the electricity sector. Sectoral trading, which is one such proposition, involves including a sector from one or more nations in an international cap-and-trade system. In order to assess potential impacts from such a mechanism, we analyze trade in carbon permits between the Chinese electricity sector and a U.S. economy-wide cap-and-trade program using the MIT Emissions Prediction and Policy Analysis (EPPA) model. We find that this sectoral policy induces significant financial transfers between the two countries. In 2030, the U.S. purchases permits valued at $42 billion from China, which represents more than 46% of its capped emissions. Despite these transfers, there is only a small change in Chinese welfare. In the U.S., the availability of relatively cheap emissions permits significantly reduces the cost of climate policy. In China, sectoral trading increases the price of electricity and reduces the amount of electricity generated, particularly from coal, while opposite effects are observed in the U.S. Despite increases in the price of electricity in China, only small increases in electricity generation from nuclear and renewables are projected in the timeframe of our analysis (2010-2030). Because the price of coal decree ses, we also find that sectoral trading leads to emissions increases in non-electricity sectors in China, a form of internal carbon leakage.

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1. INTRODUCTION

While climate bills are being discussed in the U.S., and the European Union has an Emissions Trading Scheme, international negotiations aim to foster wider agreements, particularly with developing countries. Including developing countries in an international agreement is vital to the success of mitigation strategies, as developing countries account for a significant and growing share of global greenhouse gas (GHG) emissions. For example, in a reference scenario defined by the International Energy Agency, global carbon dioxide (CO_2) emissions increase by nearly 50% between 2007 and 2030, by which time non-OECD countries account for 70% of global emissions (IEA, 2009a). In these countries, electricity generation represents more than 50% of

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[1] Appendix available online at: http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt193_AppendixA.pdf

total emissions. As electricity demand in developing countries is growing rapidly, there is a risk of long-lived investment in carbon-intensive electricity technologies. To avoid "carbon lock-in", electricity sectoral agreements have been proposed. Under sectoral mechanisms, developing countries could be involved in a global agreement without making nation-wide commitments. Sectoral trading is one of these propositions (EC, 2009). This measure involves including a sector from a nation without a national emissions constraint in the cap-and-trade program of another nation or group of nations (IEA, 2009b). For example, electricity sectors in China and India could be included in a global cap-and-trade system, or in a system including only the electricity sector of other countries.

Sectoral approaches have been widely proposed and discussed (Baron *et al.*, 2008; Baron *et al.*, 2009; CCAP, 2008; Bradley *et al.*, 2007; ICC, 2008; IEA, 2006, 2007). Although sectoral approaches are less efficient than a global cap-and-trade system (Tirole, 2009), such mechanisms may encourage participation in a global climate agreement (Sawa, 2010). Sectoral trading is also seen as a replacement for the Clean Development Mechanism (CDM). Under the CDM, host countries have generally achieved only modest environmental targets (Schneider, 2007). There is a hope that sectoral crediting and sectoral trading will achieve greater environmental benefits by moving away from a project-based mechanism to a wider approach (IEA, 2005a; IEA, 2005b; IEA, 2006; Schneider *et al.*, 2009a, Schneider *et al.*, 2009b; Sterk, 2008).

Sectoral trading has been analyzed in several studies. For example, CCAP (2010) considers abatement options that might be implemented in emerging economies under sectoral mechanisms, and Hamdi-Cherif *et al.* (2010) examine sectoral trading between all developed and developing countries using a general equilibrium model. Our analysis explores in more detail the case of two countries, so that we can carefully analyze the potential impacts of sectoral trading on the economies involved. For example, we examine electricity generation choices, internal leakage and financial transfers associated with sectoral trading. We examine sectoral trading in CO_2 between the U.S. and China, the two largest CO_2 emitters. In the appendix, we examine sectoral trading between the EU-ETS and four developing countries. Our analysis employs Version 5 of the MIT Emissions Prediction and Policy Analysis (EPPA) model.

This paper has three further sections. Section 2 describes the EPPA model, how we extend the model to allow for sectoral trading, and the scenarios we consider. Our results are presented in Section 3. Section 4 concludes.

2. MODELING FRAMEWORK

The EPPA model is a recursive dynamic, multi-region 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**, 16 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 expenditure 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 are also 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. Periods in which advanced technologies become available reflect 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 oxide, 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 C. 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	
	Advanced Gas	
	Advanced Gas with CCS	
	Advanced Coal with CCS	
	Advanced Nuclear	
	Wind with Biomass Backup	
	Wind with Gas Backup	
	Fuels	
	Coal	
	Crude oil, Refined Oil	
	Natural Gas	
	Shale Oil	
	Gas from Coal	
	Liquids from Biomass	
	Hydrogen	

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.

In our analysis, we impose a national constraint on U.S. emissions and a sector-specific cap on Chinese electricity emissions. To model sectoral trading, we extend the model to allow Chinese electricity permits to be traded for national U.S. permits, which equalizes permit prices across the two regimes. Although EPPA can be run to 2100, we run our analysis only to 2030, as sectoral trading has been proposed as an intermediary step before wider agreements are achieved. Additionally, to focus on the impact of electricity sectoral trading, we only consider a constraint on CO_2 (rather than all GHGs).

As modeling of sectoral trading requires setting a cap on U.S. emissions and a cap on Chinese electricity emissions, the results of our analysis are influenced by these constraints. As a consequence, we implement three core scenarios, which are later supplemented with simulations examining the sensitivity of results to the constraint on Chinese electricity emissions. In the first scenario (NO-POLICY), there are no emissions constraints in any region.[2] In a second scenario (US-CAP), U.S. emissions are capped at 85% of 2005 emissions in 2015, and the cap is gradually reduced to 70% of 2005 emissions by 2030. U.S. permits are tradable across sectors and there is no limit on Chinese emissions in the US-CAP scenario.

To model trade in carbon permits, it is necessary to set a trading baseline for each entity involved. In the Chinese electricity sector, the emissions level observed in the NO-POLICY scenario (which we call the business as usual, BAU, level of emissions) is taken as a baseline for trading in our third scenario (TRADE). Also in the trade scenario, U.S. emissions are capped at the same level as in the US-CAP scenario and trade in U.S. and Chinese emissions permits is allowed, creating an international market for emissions permits.

We infer the impact of sectoral trading by comparing results from the TRADE and US-CAP scenarios. Alternatively, the impact of sectoral trading could also be evaluated by comparing results from the TRADE scenario with results from a scenario where U.S. emissions are capped at the same level as in the US-CAP scenario and there is a BAU cap on Chinese emissions (to eliminate international leakage of emissions to China) without trading of permits. We prefer to compare results from the TRADE and US-CAP scenarios as adoption of emissions constraints by developing countries may be contingent on sectoral trading provisions.

In our sensitivity tests, we vary the constraint on Chinese electricity emissions in the TRADE scenario. In one sensitivity analysis, emissions are capped at the BAU level in 2010 and the constraint is reduced in a linear fashion so that Chinese electricity emissions are 10% below BAU emissions in 2030. More aggressive constraints, which are also reduced in a linear fashion, are considered in other sensitivity analyses. We consider Chinese electricity emissions reductions of 20%, 30%, 40% and 50% relative to the BAU level by 2030.

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[2] Following the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen, China announced a target of 40% to 45% reduction in carbon intensity by 2020 compared to 2005 levels, and a plan to build 70 gigawatts (GW) of nuclear capacity by 2020. In the U.S., the Environmental Protection Agency (EPA) may implement regulations on electricity generation from coal to address climate concerns. In our analysis, we account for China's nuclear capacity target, but we do not consider China's carbon-intensity target or additional EPA regulations.

3. RESULTS

3.1 Emissions, CO_2 Prices and Welfare

Sectoral trading results in emissions transfers between the countries involved, through a common carbon price, which impacts welfare in both countries. CO_2 emissions in our three core scenarios for the U.S. and Chinese electricity are displayed in **Figure 1**. In the NO-POLICY scenario in 2030, U.S. emissions are 7.2 Gt CO_2 and Chinese electricity emissions are 6.6 Gt. Chinese electricity CO_2 emissions represent more than 45% of total Chinese CO_2 emissions.

In the US-CAP scenario, U.S. emissions, limited by the cap in each period, fall to 4.15 Gt by 2030. The 30% reduction in U.S. emissions is equal to 7% of global emissions in 2030. Emissions from Chinese electricity increase slightly and are 6.8 Gt in 2030. International leakage of emissions is driven by increased energy consumption and an expansion of energy-intensive production outside the U.S.

In the TRADE scenario, there is a cap on U.S. emissions and a cap (at the BAU level) on Chinese electricity emissions. The U.S. buys emissions permits from China, so U.S. emissions increase above capped levels and Chinese electricity emissions decrease below their cap. In 2030, the U.S. purchases permits for 1.94 Gt of emissions from China, an amount equivalent to 64% of the reduction in U.S. emissions in the US-CAP scenario in this year.

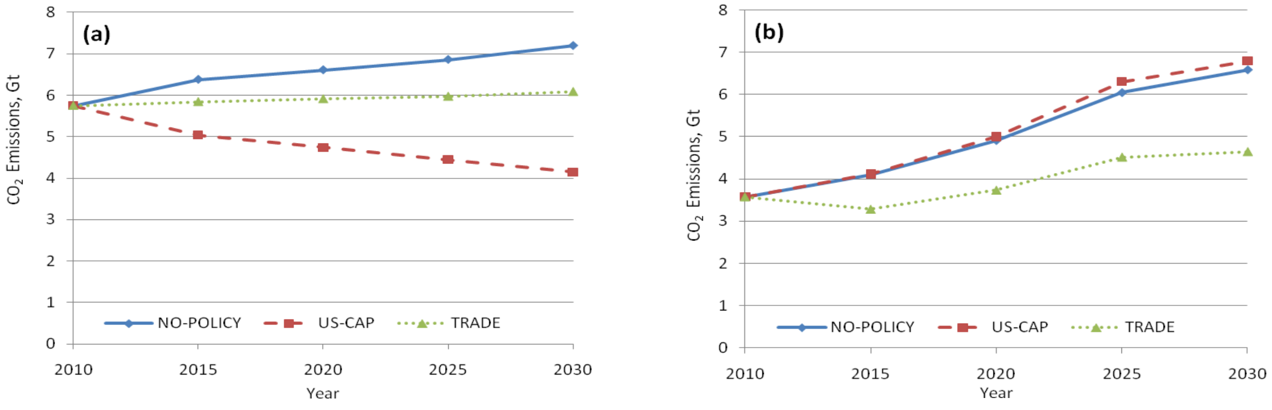

Figure 1. CO_2 emissions, **(a)** in the U.S., and **(b)** in the Chinese Electricity sector.

CO_2 prices and welfare changes are reported in **Figures 2** and **3**. In the US-CAP scenario, the U.S. permit price (in 2005 dollars) is \$43 per ton of CO_2 (t/CO_2) in 2015 and rises to \$105 by 2030. The CO_2 price in China is zero as there is no constraint on Chinese emissions. In the TRADE scenario, the common CO_2 price in the two countries in 2030 is \$21/tCO_2. That is, sectoral trading decreases the U.S. CO_2 price by \$84 (80%) in 2030. The CO_2 price reduction is achieved by replacing high-cost emissions abatement options in the U.S. with low-cost options in the Chinese electricity sector. Scope for such replacements is enhanced by the large volume of Chinese electricity CO_2 emissions relative to total U.S. emissions. Financial transfers resulting from international permit trading are significant: in 2030 the U.S. purchases allowances valued at $42 billion from China.

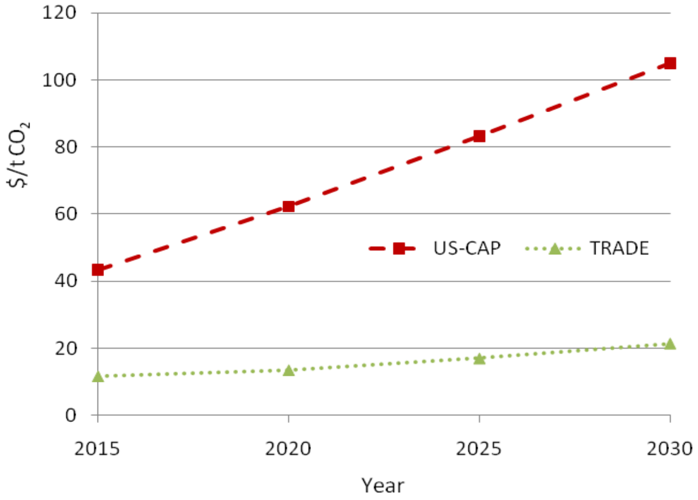

Figure 2. Carbon price in the US-CAP and TRADE scenarios.

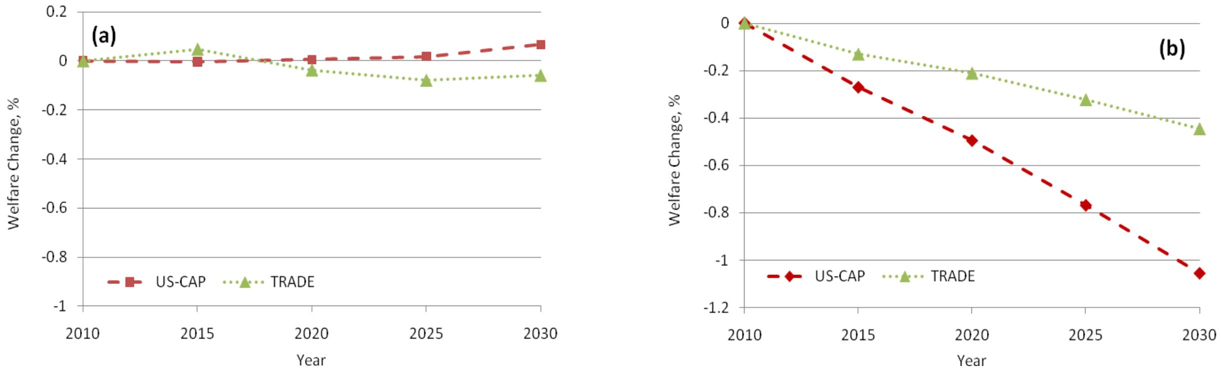

Figure 3. Welfare changes relative to the NO-POLICY scenario **(a)** in China and **(b)** in the U.S.

To put the value of transfers in perspective, the total value of exports from the U.S. to China in 2009 was $69 billion and the trade deficit between China and the U.S. in 2009 was $227 billion. If we assume the amount of U.S. exports to China grows proportionally to GDP, exports would reach $103 billion in 2030. These figures indicate that U.S. exports to China would need to increase by 41% in 2030 to offset financial transfers under sectoral trading and maintain the current trade balance.[3]

Welfare effects are expressed as equivalent variation changes in annual income relative to the NO-POLICY scenario and do not include benefits from reduced emissions. Sectoral trading reduces the cost of climate policy in the U.S. by more than half in 2030, from 1.05% to 0.44%.

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[3] Jacoby *et al.* (2010) also analyze financial transfers resulting from international climate change agreements.

China experiences a small welfare increase in the US-CAP scenario as the U.S. emissions cap advantages Chinese producers relative to U.S. producers in international markets. Relative to the NO-POLICY case, changes in Chinese welfare in the TRADE scenario are very small. The change in Chinese welfare is driven by two opposing effects: (i) financial transfers from the U.S. benefit China, and (ii) the constraint on electricity emissions decreases Chinese welfare. In dollar terms, sectoral trading increases U.S. welfare by $88 billion and decreases Chinese welfare by $6 billion in 2030. Welfare in China decreases because the rise in the electricity price increases production costs and hurts China's international competitiveness, which outweighs benefits from the sale of permits to the U.S. In our example, the decrease in welfare in China indicates that the U.S. may need to transfer an amount greater than the value of permits purchased to entice China to participate in a sectoral trading agreement.

3.2 Electricity Generation in China and the U.S.

Electricity sectoral trading has been proposed to encourage early investment in low-carbon electricity technologies in developing countries. Sectoral trading influences electricity generation by increasing the price of electricity and changing the relative cost of generation from different sources. We find that sectoral trading decreases the amount of electricity generated, particularly from coal, but does not have significant impacts on electricity generation from nuclear and renewables.

Relative to the US-CAP scenario, the Chinese electricity price rises by 21% in the TRADE scenario in 2015 and 29% in 2030. Chinese electricity generation profiles for the US-CAP and TRADE scenarios in 2030 are presented in **Figure 4**. In the US-CAP scenario, Chinese electricity production is 36.2 exajoules (EJ) in 2030, with 23.2 EJ from coal. Sectoral trading reduces Chinese electricity generation by 4.4 EJ (12%) in 2030. To put these numbers in perspective, U.S. electricity production in 2009 was 14.9 EJ (EIA, 2010).

Examining generation sources in China, electricity from coal, which is the most CO_2-intensive generation source, decreases by 6.9 EJ in 2030 (30%) when sectoral trading is introduced. This change is brought about by reduced investment in coal generation and retirement of less efficient coal-fired electricity capital. Generation changes from other sources are small relative to total electricity production, although electricity from some sources increases by large proportions. For example, sectoral trading increases hydro electricity by 1.2 EJ (27%) and nuclear by 0.3EJ (6%). Notably, solar and wind generation are the only advanced technologies in operation in the US-CAP scenario and sectoral trading does not induce entry of additional advanced technologies. These results suggest that sectoral trading is effective in preventing "carbon lock-in" by reducing coal-fired electricity, but not lead to widespread adoption of low-carbon electricity generation in China.

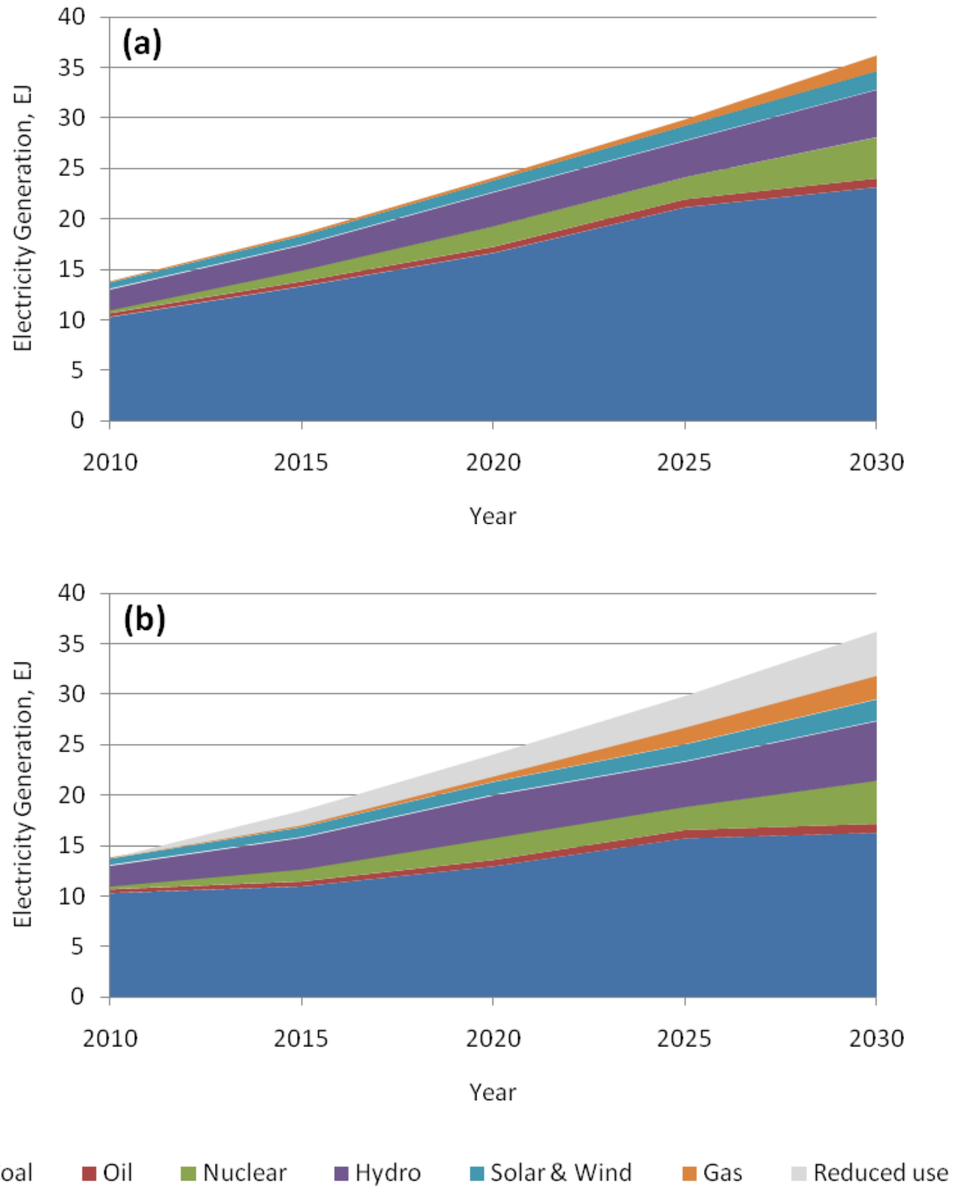

Figure 4. Chinese Electricity generation for the **(a)** US-CAP and **(b)** TRADE scenarios.

In our modeling exercise, we examine sectoral trading between two countries. In this specific case, sectoral trading also has an impact on the electricity sector of the country that faces an economy-wide emissions constraint. In the U.S. in 2030, electricity generation amounts to 19.1 EJ in the NO-POLICY case, including 10.1 EJ from coal and 2.8 EJ from gas. In the US-CAP scenario, U.S. electricity generation decreases to 15.1 EJ, including 4.4 EJ from coal and 3.4 EJ from gas. In the TRADE scenario, total U.S. electricity generation increases to 17.9 EJ, including 8.0 EJ from coal and 3.2 EJ from gas. These changes are driven by sectoral trading facilitating more emissions from domestic sources than in the US-CAP scenario. In general, the impact of sectoral trading will depend on the size of the countries involved and the size and generation composition of each nation's electricity sector.

3.3 Emissions from Other Sectors: "Internal Leakage"

The Chinese electricity sector accounts for three-quarters of domestic demand for coal. Consequently, reduced use of coal for electricity generation decreases the price of coal, which influences energy use in other sectors. The decrease in the coal price induces carbon leakage towards the rest of the Chinese economy. In our simulations, sectoral trading decreases the price of coal in China by 8% in 2015 and 15% in 2030. Conversely, sectoral trading increases the 2030 price of crude oil by 3%, which is driven by increased U.S. energy demand and its effect on the international oil market. Price changes for other energy commodities in 2030 are less than 2%.[4] Ceteris paribus, these price changes will induce Chinese firms to substitute towards coal and away from other commodities, which will increase emissions. Opposing this change, higher electricity prices increase production costs and ultimately reduce sectoral outputs and emissions.

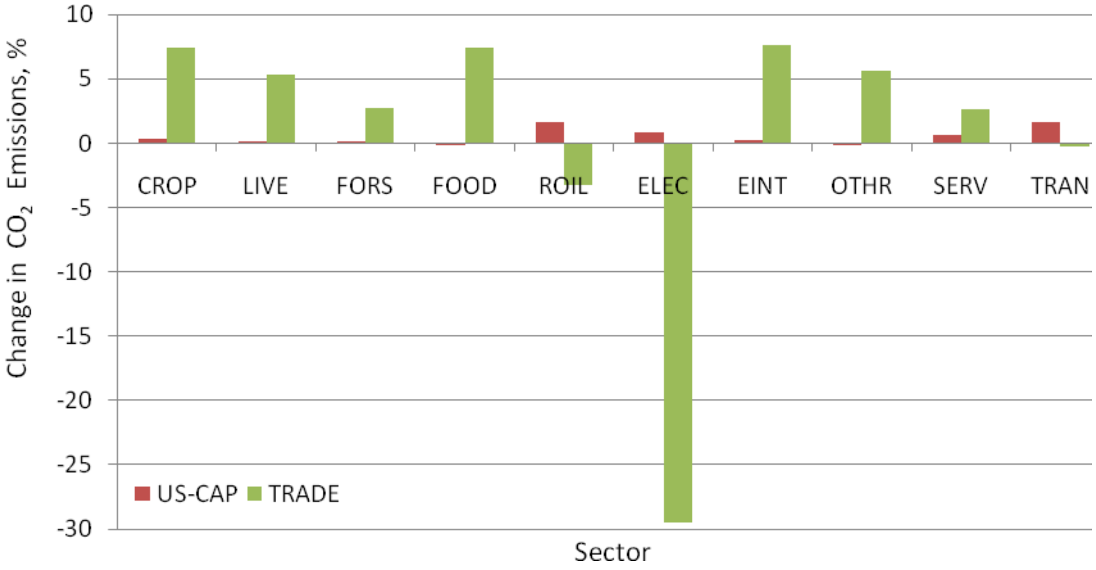

Figure 5. Percent change in sectoral CO_2 emissions in China in 2030 relative to the No Policy case.

Figure 5 presents proportional changes in Chinese CO_2 emissions by sector in 2030 for the US-CAP and TRADE scenarios. In China under the US-CAP scenario, emissions increase in all sectors relative to the NO-POLICY case. This is due to the U.S. cap reducing world energy prices, especially the refined oil price. These price reductions ultimately increase energy use and emissions in China.

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[4] Changes in energy prices can also impact welfare via terms-of-trade effects, as discussed in Paltsev *et al.* (2004).

In the TRADE scenario, however, emissions from most non-electricity sectors increase, as producers substitute away from other energy commodities and towards relatively cheaper coal. The two exceptions are refined oil and transport.[5] Changes in sectoral emissions are driven by changes in electricity and coal prices. The increase in the electricity price decreases production in all sectors. While most sectors substitute towards coal, which increases sectoral emissions, transport and refined oil have limited scope to substitute towards coal, so emissions decrease for these sectors. To summarize, the sectoral emissions changes are the result of two opposing effects: a decrease in production due to a higher electricity price and a substitution towards coal when it is possible.

In aggregate, electricity emissions reductions due to sectoral trading result in emissions increases elsewhere in the economy, or “internal leakage”. As a consequence, global emissions reductions are smaller than the reductions imposed by the cap on the U.S. and the cap on Chinese electricity emissions. Internal leakage in 2030 for our TRADE scenario is 0.38 Gt of CO_2, which represents 19% of the reduction in Chinese emissions from electricity, or 12% of the reduction imposed on the U.S. in the US-CAP scenario. It is also interesting to compare internal and international leakage across scenarios. In the US-CAP scenario, international leakage is 0.56 Gt of CO_2, which represents 18% of the reduction that is imposed on U.S. emissions. In the TRADE scenario, international leakage is 0.30 Gt of CO_2.

To summarize results presented so far, sectoral trading allows the U.S. to buy carbon permits in China and creates a common carbon price in the two countries. This allows the U.S. to emit above its cap while China must reduce its electricity emissions below its cap. The resulting carbon price is lower than the one the U.S. would face under a U.S. cap and trade system without sectoral trading. As a consequence, this mechanism lowers the cost of climate policy in the U.S. and increases welfare in the U.S. In China, sectoral trading decreases the amount of electricity generated and increases the price of electricity. Despite large financial transfers associated with international permit trading, there is not a large change in Chinese welfare, as increased electricity prices reduce China’s international competitiveness.

Through general equilibrium effects, the sectoral policy impacts the rest of the Chinese economy. The higher electricity price induces a decrease in the activity level in all sectors of the Chinese economy. Also, as electricity generation from coal decreases (by 30% in 2030), the coal price decreases (by 15% in 2030), which induces substitution towards coal in all sectors where it is possible (all the sectors except refined oil and transport). As a result, in addition to decreasing electricity emissions, sectoral trading increases emissions in most other sectors. In the scenario we consider, sectoral trading has little impact on electricity generation from nuclear or renewables because of an increase in efficiency of coal-based generation and a price-induced reduction in energy intensity.

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[5] Coal-to-liquids conversion technology is not considered in this analysis as it is unlikely to be economic at the resulting oil prices.

3.4 Alternative Sectoral Emissions Constraints in China

Sectoral trading requires a cap on emissions from electricity in the country implementing the sectoral policy. The cap may be set equal to projections from a scenario where energy policies are assumed to remain unchanged, such as the IEA reference scenario (IEA, 2009a). In results presented so far, we followed such an approach by using the level of Chinese electricity emissions in the NO-POLICY scenario as the sectoral cap. Alternatively, a tighter cap may be chosen. If sectoral trading is implemented, the sectoral cap is likely to be a key issue in policy negotiations. In this section, we explore the impact of alternative constraints on Chinese electricity emissions. As noted in Section 2, we consider simulations where emissions are reduced below the BAU level by linearly decreasing the cap each period so as to reach a target percentage reduction by 2030. In separate simulations, we consider targets of 10%, 20%, 30%, 40% and 50% below the BAU level by 2030. These alternative constraints allow us to examine the sensitivity of our results to the cap set on Chinese electricity emissions.

Global emissions and CO_2 prices in 2030 for alternatives caps on Chinese electricity emissions under sectoral trading are displayed in **Figure 6**. As the sectoral constraint is tightened, allowances become scarcer and the CO_2 price rises. Under a 50% constraint, the emissions price is \$71/tCO_2, more than three times larger than the emissions price under a BAU constraint (\$21). Tightening the constraint also induces a large decrease in global emissions, from 41 Gt under a BAU constraint to 39 Gt under a 50% constraint. The significant impact of the sectoral constraint on the CO_2 price and global emissions reflects the large size of the Chinese electricity sector.

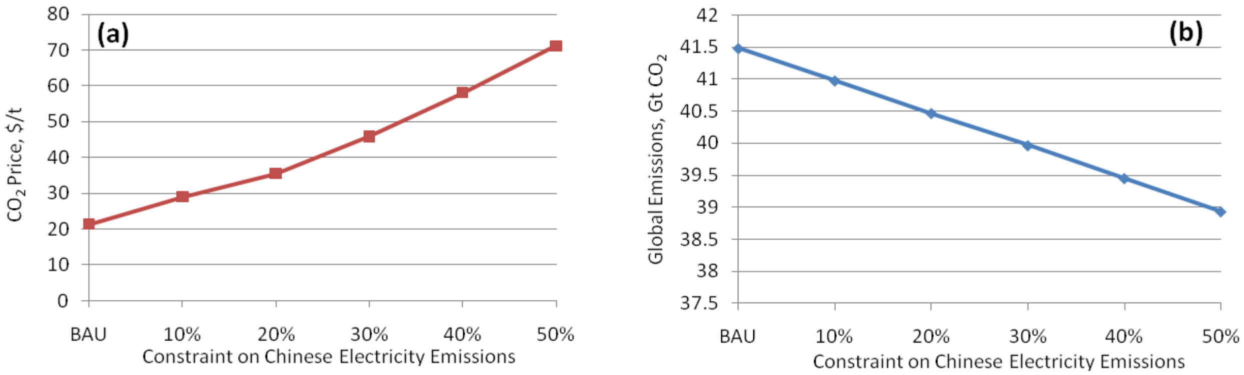

Figure 6. (a) The 2030 international carbon price and **(b)** 2030 global emissions for alternative constraints on Chinese Electricity sector.

The value of permits traded internationally and proportional welfare changes relative to the US-CAP scenario are displayed in **Figure 7**. The value of permits initially rises and then falls as the sectoral constraint is tightened, reflecting a combination of price and quantity effects. As the sectoral constraint increases, CO_2 price increases but the volume of permits traded between the two countries decreases. Welfare in both China and the U.S. falls as the sectoral cap is tightened, as stricter sectoral caps reduce the overall constraint on the two economies. However, while welfare in the U.S. in these cases remains higher than the welfare in the US-CAP scenario, welfare in China is lower than in the US-CAP scenario. In other words, the U.S. is always better off with sectoral trading as defined here, but China is always worse off and Chinese welfare falls swiftly as the cap is tightened. If sectoral trading is to be used as an incentive to encourage China to participate in a global agreement, these observations indicate that a moderate constraint on Chinese emissions and transfers that exceed the value of allowances sold may be required.

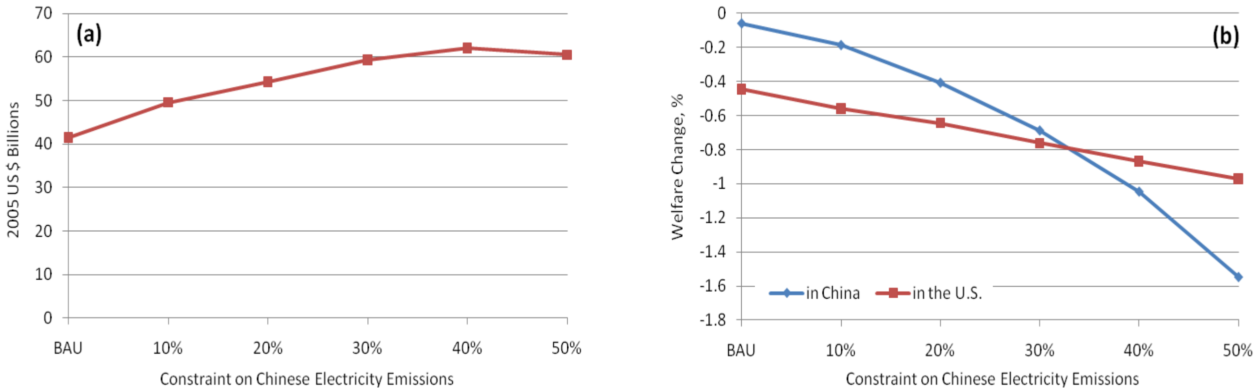

Figure 7. (a) Financial transfers between the U.S. and China and **(b)** welfare changes in the U.S. and in China, 2030.

Regarding electricity generation in China, higher CO_2 prices under tighter constraints increase the effects observed in the TRADE scenario (where Chinese electricity emissions face a BAU constraint). Specifically, under stricter constraints, total electricity generation decreases, generation from coal decreases, and there is a small increase in generation from less carbon-intensive technologies. The Chinese electricity price increases with the constraint imposed on electricity emissions. For a 30% constraint, the electricity price in 2030 increases by 61% relative to the price in the US-CAP scenario, compared with a 29% under a BAU constraint.

The price of coal also falls by a larger amount as the constraint is tightened (e.g, relative to the NO-POLICY case, the 2030 coal price falls by 24% when there is a 30% constraint, compared to 15% under a BAU constraint). Larger coal price reductions are associated with larger amounts of internal leakage, although leakage rates are similar across scenarios (where the leakage rate is defined as the amount of internal leakage divided by the reduction in electricity emissions specified by the sectoral cap). For example, under a 30% constraint, internal leakage is 0.61 Gt, which represents a leakage rate of 18%. Under a 50% constraint, internal leakage is 0.74 Gt and the leakage rate is 18%. In comparison, under a BAU constraint internal leakage is 0.38 Gt and the leakage rate is 19%.

4. CONCLUSIONS

Sectoral trading measures have been proposed to encourage early action and investment in low carbon technologies in developing countries. To analyze the potential impacts of such a mechanism, we considered sectoral trading between the Chinese electricity sector and a national U.S. cap-and-trade program. Our central analysis sets a BAU cap on CO_2 emissions from Chinese electricity and an economy-wide reduction on U.S. CO_2 emissions of 30% of 2005 emissions by 2030. Under sectoral trading, in 2030, the Chinese electricity sector sells 1.94 Gt of CO_2 allowances to the U.S. and the price U.S. firms pay for permits is \$21 per tCO_2 (in 2005 dollars), compared to \$105 in the U.S. when there is a U.S. cap without sectoral trading. The sale of permits to the U.S. decreases Chinese electricity emissions and increases Chinese electricity prices.

Emission decreases in China are driven by reductions in electricity generation from coal, but there is only a small increase in low-carbon electricity generation. Thus, our results suggest that sectoral trading will be effective at reducing coal-fired generation but, in the absence of other regulatory policies, does not spur wide-spread adoption of advanced technologies. In the U.S., as sectoral trading decreases the carbon price, U.S. electricity emissions are greater than under sectoral trading. Notably, electricity generation from coal is higher under sectoral trading than without this mechanism.

In China, decreased coal-fired electricity generation also reduces the price of coal. While the electricity price increase tends to reduce output in all sectors in China, the coal price decrease induces an increase in coal consumption. As a consequence, the cap on Chinese electricity emissions increases emissions in most other sectors. The two exceptions are refined oil and transport sectors that see their emissions decrease. In aggregate, internal leakage is 0.38 Gt, around 6% of Chinese BAU electricity emissions. This results in a global emissions reduction that is less than the sum of the reductions imposed on the U.S. and on Chinese electricity sectors.

We also analyzed sectoral trading when Chinese electricity emissions are capped below BAU levels. Tighter constraints on Chinese electricity emissions decrease global emissions and increase the CO_2 price. Tighter caps on electricity emissions also amplify changes in Chinese electricity generation observed in our core sectoral trading scenario. In turn, larger changes in generation profiles result in larger reductions in the coal price and ultimately larger absolute internal leakage, but internal leakage rates (the unanticipated absolute emission increase divided by the emission reduction constraint) did not change significantly.

Our results also indicate that, under a BAU constraint on Chinese electricity emissions, sectoral trading increases welfare in the U.S., but not in China, relative to a scenario where China does not participate in an agreement with the U.S. As the constraint on electricity emissions is tightened, Chinese welfare declines sharply.

Our sectoral trading analysis considered the specific case of trading between the U.S. and the Chinese electricity sector. Considering a different set of countries would likely yield different results. For example, if a country implementing the sectoral policy was a small economy, the sectoral constraint would have a smaller influence on the CO_2 price and financial transfers induced by sectoral trading would decrease. In the appendix, we quantify the impact of sectoral trading between the EU-ETS and four developing countries and compare the results with those presented for the U.S.-China case.

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Appendix A: Sectoral Trading between the EU-ETS and Emerging Countries[1]

Claire Gavard, Niven Winchester, Henry Jacoby, and Sergey Paltsev

Abstract

In international negotiations on climate change, sectoral trading has been proposed as a way to encourage investment in low carbon technologies in developing countries. In the main report (MIT Joint Program Report 193), we analyzed the impacts of sectoral trading between the U.S. and China. As the U.S. is unlikely to implement a cap-and-trade regime in the near future and a carbon market has existed in Europe since 2005, sectoral trading could be used to extend the European Emission Trading Scheme (EU-ETS) to electricity sectors in some developing countries. Our analysis seeks to quantify the effects of sectoral trading between the EU-ETS and four emerging countries: China, India, Brazil and Mexico. Applying the same EPPA version as in the main report, we analyze sectoral trading between the EU-ETS and each country individually and all four nations simultaneously. We find that the impacts change significantly with the size and number of countries involved. Under sectoral trading with China, the European Union (EU) buys $1.5 billion of carbon permits and the EU carbon price decreases by 88% in 2030. Sectoral trading has a small impact on Chinese electricity generation but reverses changes in EU electricity generation driven by the EU-ETS. Under sectoral trading with Mexico, the EU buys $0.6 billion of permits and the carbon price decreases by 8% in 2030. Moderate impacts on Mexican electricity generation are observed while changes in EU electricity generation induced by the EU-ETS persist. Sectoral trading between the EU and the four countries simultaneously reduces the carbon price by more than 90% and the EU buys $1.2 billion dollars of permits, mostly from India and China.

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A1. MOTIVATION

Sectoral trading has been proposed in international climate change negotiations. This mechanism provides an avenue for extending existing carbon markets to sectors in developing countries, which may spur deployment of low-carbon technologies. In the main report, we analyzed the impacts of sectoral trading in carbon permits between a hypothetical U.S. cap-and-trade regime and the Chinese electricity sector. We considered a U.S.-China example, as the two nations are the largest emitters of carbon dioxide (CO_2), and focusing on only two countries allowed us to analyze sectoral trading in a simplified setting. However, as the EU may use this mechanism to extend its carbon market externally, this appendix considers sectoral trading involving the European Emissions Trading Scheme (EU-ETS), which has been in operation since

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[1] This is an appendix to Gavard *et al.* (2011): What to Expect from Sectoral Trading: A U.S.–China Example, MIT Joint Program on the Science and Policy of Global Change *Report 193* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt193.pdf)

2005. Specifically, we analyze sectoral trading between the EU-ETS and electricity sectors in China, India, Mexico and Brazil, both for each nation individually and all nations simultaneously.

This appendix has four further sections. Section A2 details how we model the EU-ETS and the scenarios we consider. Results are presented in section A3. Section A4 concludes and compares results from our supplementary analysis with those from the main report.

A2. MODELING FRAMEWORK AND THE EU-ETS

As in the main report, our analysis employs version 5 of the MIT Emissions Prediction and Policy Analysis (EPPA) model, adjusted to account for China's target to build 70 gigawatts (GW) of nuclear capacity by 2020. Also similar to our U.S.-China example, we only consider constraints on CO_2 emissions and trade in CO_2 permits for the period 2010-2030.

The European Union (EU) has set a series of climate and energy goals to be met by 2020 (EC, 2010). These goals, known as the "20-20-20" targets, include (a) a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels, (b) 20% of energy consumption from renewable sources, and (c) a 20% reduction in primary energy use compared with projected levels, achieved by energy efficiency improvements. Given the uncertainty in the way these targets may be fulfilled, we do not include the 20-20-20 goals in our analysis. Instead, we calibrate the electricity generation profile for the EU in EPPA using an International Energy Agency policy scenario projection (IEA, 2010).

To approximate the EU-ETS in the EPPA model, we set a progressive constraint on Electricity and Energy intensive industries in the EU and allow trade in CO_2 permits among member states. The constraint stipulates emissions reductions in both sectors of 28% in 2020 and 42% in 2030, relative to 1990 emissions. Important features of the EU-ETS not included in our approximation include the availability of offsets through the Clean Development Mechanism, the possible inclusion of aviation from 2012, and provisions for banking of allowances.

We consider seven scenarios. The NO-POLICY scenario assumes that climate policies are not implemented by any region. Our EU-ETS scenario implements the EU-ETS emissions constraint described above, and is applied in the remaining five scenarios. In the CHN scenario, emissions from the Chinese electricity sector are capped at the level observed in the NO-POLICY scenario, and trade in CO_2 permits between the EU and the Chinese electricity sector is allowed. Similarly, our MEX, IND and BRA scenarios set NO-POLICY caps on electricity emissions in, respectively, Mexico, India and Brazil, and allow trade in CO_2 permits between each nation and the EU-ETS. Our final scenario, ALL4, implements NO-POLICY caps on electricity emissions in China, India, Brazil and Mexico and allows the EU to trade CO_2 permits with all four nations.

To foreshadow results from the above scenarios relative to findings from the main report, EU emissions from Electricity and Energy-intensive industry in the NO-POLICY case are 1.68 Gigatons (Gt) and U.S. emissions in the same scenario are 7.19 Gt, both in 2030. Therefore, EU-China sectoral trading will have a smaller impact on Chinese electricity generation than U.S.-

China sectoral trading. Also, sectoral trading will have a larger impact on the EU than on the U.S.

A3. RESULTS

A3.1 Emissions and Carbon Prices

As in the U.S.–China example analyzed in the main paper, sectoral trading allows the developed region to buy cheap emissions permits in developing countries. The quantity of permits transferred as well as the reduction in the CO_2 price due to sectoral trading depends on the number and the size of the developing countries involved, and the electricity generation profile of partner countries.

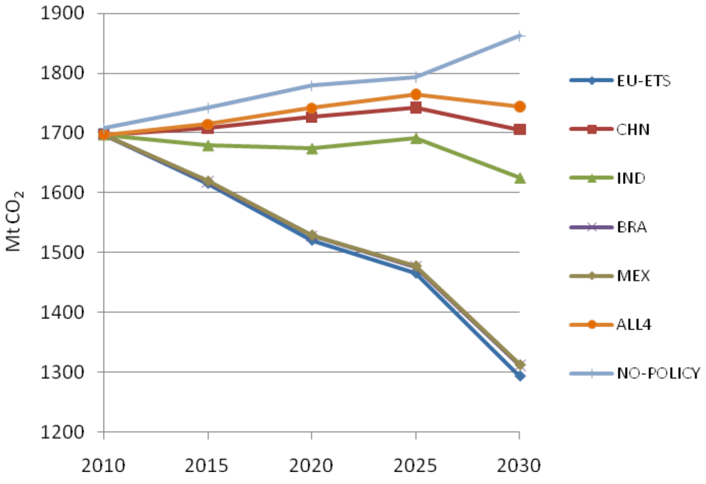

Figure 1. Aggregate Emissions from EU-ETS sectors.

For our seven scenarios, we present EU Electricity and Energy-intensive industry emissions under the EU-ETS in **Figure 1**. Sectoral trading with Mexico or Brazil has little impact on EU-ETS emissions. In contrast, sectoral trading between the EU and China, India or all four nations facilitates a significant increase in EU emissoins. In the NO-POLICY scenario, EU-ETS emissions are 1.78 Gt in 2020 and 1.86 Gt in 2030. In the EU-ETS scenario, EU-ETS emissions decrease to 1.52 Gt in 2020 and 1.29 Gt in 2030. In the MEX and BRA scenarios, compared to the EU-ETS scenario, EU-ETS emissions increase by 3% of the reduction imposed by the EU-ETS cap. In contrast, EU-ETS emissions increase by 72% of the reduction imposed by the cap in the CHN scenario. In the ALL4 scenario, EU-ETS emissions are 1.74 Gt in 2030, which represents an emissions increase equal to 79% of the reduction imposed by the cap.

To analyze the impact of sectoral trading on countries with sectoral constraints, we present Chinese and Mexican electricity emissions for selected scenarios in **Figure 2**. While Chinese emissions decrease by roughly the same in the CHN and ALL4 scenarios, the change in Mexican emissions heavily depends on the involvement of other countries. Chinese and Mexican electricity emissions in the NO-POLICY scenario are, respectively, 6.59 Gt and 0.12 Gt in 2030. Chinese 2030 electricity emissions decrease by 6% in the CHN scenario and 5% in the ALL4 scenarios. Mexican electricity emissions decrease by 17% in the MEX scenario, but only 2% in the ALL4 scenario. Electricity emissions in India and China are not displayed in Figure 2, but we describe key changes below. Indian 2030 electricity emissions are 2.63Gt in the NO-POLICY case and decrease by 13% in the IND scenario and 6% in the ALL4 scenarios. Brazilian 2030 electricity emissions are 0.069 Gt in 2030 and decrease by 26% in the BRA scenario and 2% in the ALL4 scenario.

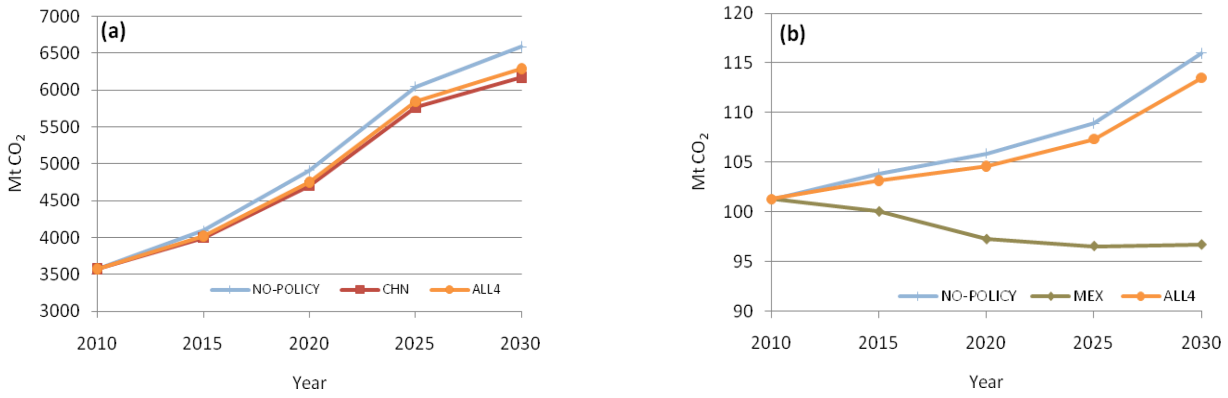

Figure 2. Electricity Emissions in **(a)** China and **(b)** Mexico.

Changes in electricity emissions influence the number of permits sold to the EU. In the CHN scenario, permits for 0.41 Gt of CO_2 are transferred to the EU from China in 2030, and the EU sources 0.33 Gt of CO_2 permits from India in the IND scenario. Under sectoral trading with Mexico and Brazil, transfers of CO_2 permits to the EU are much smaller – around 0.02 Gt in both scenarios.

EU CO_2 prices are presented in **Figure 3**. The EU carbon price is strongly affected by sectoral trading with China or India but is only reduced by a small percentage when trading with Mexico or Brazil. In the EU-ETS scenario, the permit price is \$32 per metric ton of CO_2 (tCO_2) in 2030.[2] The 2030 permit price decreases by 88% (to \$4/tCO_2) in the CHN scenario and by 80% (to 6/tCO_2) in the IND scenario. The CO_2 price in both the BRA and MEX scenarios is around \$30/tCO_2, an 8% decrease. In the ALL4 scenario, the CO_2 price decreases by 92% (to \$3/tCO_2).

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[2] The EU CO_2 price is lower than some other estimates of future CO_2 prices as we do not consider banking of emissions allowances.

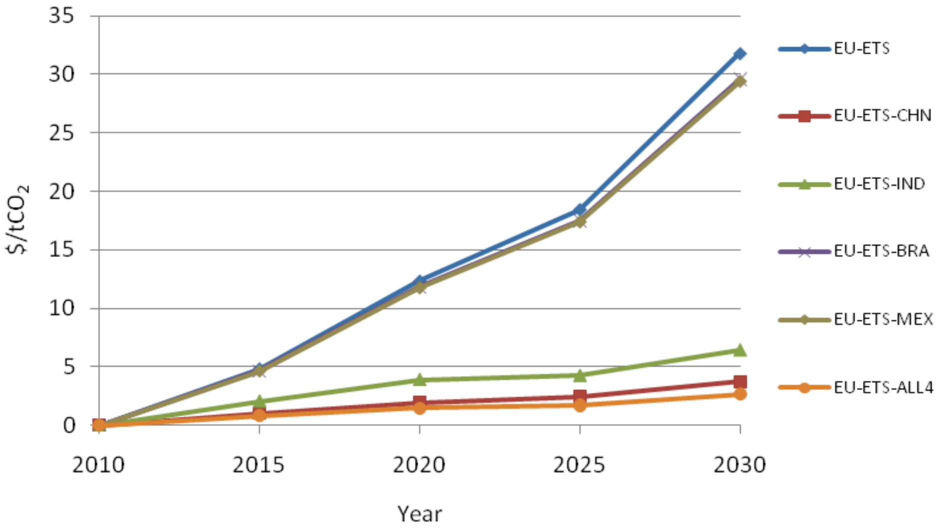

Figure 3. The EU-ETS Carbon Price.

Compared to the impact of sectoral trading between the U.S. and China in the main text, sectoral trading between the EU and China or India has a much larger impact on the CO_2 price. This result is driven by the small volume of emissions covered by the EU-ETS compared to the quantity of U.S. emissions. Due to the large changes in EU-ETS emissions and the CO_2 price in these scenarios, international negotiations may call for a limit on sectoral mechanisms involving some country pairs. In contrast, the impact of sectoral trading between the EU-ETS and Mexico or Brazil on EU emissions and CO_2 prices is much smaller.

A3.2 Financial Transfers

Permit sales are associated with financial transfers at a common carbon price. The quantity of financial transfers is influenced by the size and the number of countries involved in the sectoral agreement. We summarize financial transfers in the CHN and IND scenarios in **Table 1**, and financial transfers in the ALL4 scenario are reported in **Table 2**.

In the CHN scenario in 2020, the CO_2 price is \$2/tCO_2 and 206 Mt of permits are traded, resulting in a financial transfer from the EU to China of \$401 million. In 2030, the CO_2 price is \$4/tCO_2, 413 Mt of permits are traded and the financial transfer is \$1,535 million. The quantity of permits traded in the MEX scenario is less, but CO_2 prices (\$12/tCO_2 in 2020 and \$29/tCO_2 in 2030) are higher than in the CHN scenario. As a result, financial transfers in the MEX scenario (\$101 million in 2020 and \$566 million in 2030) are about one-quarter of those in the CHN scenario. To put these numbers in perspective, the EU trade deficit with China was €133 billion (\$184 billion) and the EU trade surplus with Mexico was €6 billion (\$8 billion), both in 2009.

Table 1. Carbon Prices and Financial Transfers in the CHN and MEX Scenarios.

CHN scenario	**2020**	**2030**
CO_2 Price, \$/t	1.9	3.7
Permits Transfers, Mt CO_2	206	413
Financial Transfers, \$ million	401	1,535
MEX scenario		
CO_2 Price, \$/t	11.7	29.4
Permits Transfers, Mt CO_2	9	19
Financial Transfers, \$ million	101	566

In the ALL4 scenario, the CO_2 price is \$1.5/tCO_2 in 2020 and \$2.7/tCO_2 in 2030. China sells more permits to the EU (156 Mt CO_2 in 2020 and 299 Mt CO_2 in 2030) than any other nation. The financial transfer from the EU to China is \$229 million in 2020 and \$798 million in 2030. India is the second largest seller of permits to the EU and sells 63 Mt of permits in 2020 and 148 Mt in 2030. Compared to the number of permits offered by China and India, a small number of permits are sold by Brazil and Mexico. In 2030, the EU purchases 451 Mt of CO_2 permits, 66% from China, 33% from India and 1% from Brazil and Mexico. Also in 2030, the EU purchases \$1.2 billion worth of foreign permits. In comparison, the EU's aggregate trade deficit with the four countries was €129 billion (\$179 billion) in 2009.

Table 2. Carbon Prices and Transfers in the ALL4 Scenario.

	2020	**2030**
CO_2 Price, \$/t	1.5	2.7
Permits Transfers, Mt CO_2		
EUR	221	451
CHN	-156	-299
IND	-63	-148
BRA	-0.9	-1.7
MEX	-1.3	-2.5
Financial Transfers, \$ million		
EUR	-324	-1,205
CHN	229	798
IND	92	395
BRA	1	5
MEX	2	7

In our U.S.-China example in the main report, around \$40 billion of permits were traded internationally. Financial transfers for sectoral trading scenarios involving the EU are smaller than in the U.S.-China case, as U.S. economy-wide emissions are larger than emissions covered by the EU-ETS.

A3.2 Electricity Generation

Sectoral trading drives changes in electricity generation profiles, both in the EU and in countries selling permits. As for changes in the CO_2 price, the effect of sectoral trading on electricity generation choices in the EU from trading with China and India is significantly different from trading with Mexico and Brazil. Also, the impact of sectoral trading on electricity generation profiles in developing countries depends on the size of the partner country. For example, in the U.S.-China example in the main report, sectoral trading induced a 12% decrease in electricity generation in China in 2030, but the corresponding decrease is 2.3% in the CHN scenario, and 1.7% in the ALL4 scenario.

Under the CHN scenario in China in 2030, compared to the NO-POLICY scenario, electricity generation from coal decreases by 1.3 exajoules (EJ) (6%), generation from hydro increases by 0.28 EJ (6%), and there are small proportional changes in generation from other sources. In the ALL4 scenario, changes in Chinese electricity generation are smaller: generation from coal decreases by 4% and generation from hydro increases by 4%.

In the MEX scenario, proportional changes in Mexican electricity generation sources are larger than the corresponding changes in China under the CHN scenario. Compared to the NO-POLICY case in 2030, electricity generation in Mexico decreases by 0.06 EJ (6%). This change is associated with a 0.06 EJ (43%) decrease in generation from coal, a 0.01 EJ (16%) increase in generation from hydro, and 0.02 EJ (5%) increase in generation from gas. In the ALL4 scenario, changes in Mexican electricity generation are smaller due to competition from other countries. The total amount of electricity generated in Mexico decreases by less than 1% compared to the NO-POLICY scenario, and generation from coal decreases by 6%.

There are only small electricity generation changes in the EU in the MEX and BRA scenarios. For example, compared to the NO-POLICY case, generation from coal decreases by 56% in the EU-ETS scenario and the corresponding decrease in the MEX scenario is 54%. In contrast, there are large changes in EU electricity generation when there is sectoral trading between the EU and China or India, or between the EU and all four countries. For example, generation from coal in the EU decreases by 15% and 11% in, respectively, the CHN and ALL4 scenarios (compared to 56% in the NO-POLICY scenario).

The observation that sectoral trading with large emitters may reverse most of the changes induced by the EU-ETS, further supports our assertions that limits may be placed on sectoral mechanisms in international negotiations.

A4. CONCLUSIONS

Sectoral trading can be used to extend CO_2 markets in developed nations to developing countries. In this appendix, we examined the impact of sectoral trading between sectors included in the EU-ETS and electricity sectors in China, India, Mexico and Brazil, both individually and simultaneously. Our analysis focused on the EU CO_2 price, financial transfers and electricity generation profiles in the countries involved.

In our analysis, under sectoral trading between the EU and China or India, without a limit on the quantity of permits traded, the EU carbon price decreased by more than 75% and the EU purchased permits equal to more than 50% of the reduction in 2030 emissions set out by the EU-ETS. In contrast, under sectoral trading between the EU and Mexico or Brazil, the amount of permits purchased was less than 4% of the 2030 emissions reduction dictated by the EU-ETS, and the CO_2 price decreased by less than 8%. In 2030, sectoral trading between the EU and electricity sectors in all four countries reduced the EU CO_2 to \$3/tCO_2 and the EU purchased permits equal to 79% of the emissions reduction called for by the EU-ETS. Most of these permits were sourced from China and India.

Changes in electricity generation due to sectoral trading depend on relative sizes of countries participating in the agreement. Sectoral trading between the EU-ETS and China had a small impact on Chinese electricity generation, but a significant impact on EU electricity generation. In China, a small decrease in generation from coal and a small increase in generation from hydro were observed. In the EU, sectoral trading with China reverses a large amount of electricity generation changes induced by the EU-ETS. Conversely, sectoral trading between the EU-ETS and Mexico resulted in large changes in electricity generation in Mexico, but only small changes in the EU. In Mexico, sectoral trading resulted in a large decrease in generation from coal, a significant increase in generation from hydro and a small increase in generation from gas.

We close by comparing our results for EU-ETS sectoral trading with results for U.S.-China sectoral trading presented in the main report. In 2030, EU-China sectoral trading reduced the EU CO_2 price from \$32/tCO_2 to \$4/tCO_2, and U.S.-China sectoral trading reduces the U.S. CO_2 price from \$105/tCO_2 to \$21/tCO_2. The quantity of permits traded and financial transfers under sectoral trading between the EU-ETS and the four countries considered are much smaller than in the U.S.-China example. Under U.S.-China sectoral trading, permits valued at \$42 billion were traded, but only \$1.5 billion worth of permits were traded under EU-China sectoral trading. These differences are due to differences in the quantity of emissions from EU-ETS sectors and U.S. economy-wide activity. In our simulations without climate policy, emissions from EU-ETS sectors were 1.86 Gt and U.S. economy-wide emissions were 7.19 Gt, both in 2030. As a result, EU-China sectoral trading had a smaller impact on electricity generation in China than U.S.-China sectoral trading. Conversely, EU-China sectoral trading had a larger influence on EU electricity generation than the impact of U.S.-China sectoral trading on U.S. electricity generation.

EU-China sectoral trading reversed a large part of the changes brought about by the EU-ETS. As a result, maximum limits may be placed on sectoral mechanisms, so that each nation involved in an international agreement undertakes meaningful domestic action. However, the ability of sectoral mechanisms to reverse changes induced by domestic policies in the developed countries is a decreasing function of the size of the entity wishing to purchase emissions permits. Sectoral trading would have smaller impacts if all Annex 1 nations used this mechanism simultaneously with national cap-and-trade policies, than in the examples considered in our analysis.

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