What to Expect from Sectoral Trading: A US-China Example[1]

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Abstract

In recent United Nations Framework Convention on Climate Change (UNFCCC) negotiations, sectoral trading was proposed to encourage early action and spur investment in low carbon technologies in developing countries. This mechanism involves including a sector from one or more nations in an international cap-and-trade system. We analyze trade in carbon permits between the Chinese electricity sector and a US economy-wide cap-and-trade program using the MIT Emissions Prediction and Policy Analysis (EPPA) model. In 2030, the US purchases permits valued at $42 billion from China, which represents 46% of its capped emissions. In China, sectoral trading increases the price of electricity and reduces aggregate electricity generation, especially from coal. However, sectoral trading induces only moderate increases in generation from nuclear and renewables. We also observe increases in emission from other sectors. In the US, the availability of cheap emissions permits reduces the cost of climate policy and increases electricity generation.

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1. INTRODUCTION

While climate bills are being discussed in the US, 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 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 US and China, the two largest CO_2 emitters. 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 *et al.*, 2005). The model is designed to assess the impact of energy and environmental policies on emissions and economic activity. Version 5 of the model is calibrated to 2004 economic data and is solved through time by specifying exogenous population and labor productivity increases, for 2005 and for five-year increments thereafter. As indicated in **Table 1**, 16 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.

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	

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.

Costs for advanced technologies relative to existing technologies are described by multiplicative mark-up factors provided in **Table 2.** For electricity, mark-ups are determined by dividing the levelized cost for each technology by the cost from conventional sources.[2] For fuels, the mark-up for each technology represents the cost of fuel from that technology relative to the cost of fuel from the existing technology that it competes against (e.g., production costs for oil from shale are 2.5 more expensive that oil from conventional sources). Assumptions for mark-up calculations are provided in Paltsev *et al.* (2005, 2010).

Table 2. Mark-Up Factors for Advanced Technologies.

Technology	Mark-Up
Advanced Gas	1.03
Advanced Gas with CCS	1.57
Advanced Coal with CCS	1.71
Advanced Nuclear	1.64
Wind	1.43
Biomass	1.58
Solar	3.60
Wind with Biomass Backup	3.67
Wind with Gas Backup	1.85
Shale Oil	2.50
Hydrogen	3.00
Gas from Coal	3.50
Liquids from Biomass	2.10

The model projects emissions of GHGs (CO_2, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulfur hexafluoride) and urban gases that also impact climate (sulfur

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[2] Levelized electricity cost measures the price of electricity at which a specific electricity generation technology breaks even. For each technology, generation costs are based on lifetime costs, including upfront investment, operation and maintenance expenditure, and fuel costs.

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).

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 US 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 US 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 US 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.[3] In a second scenario (US-CAP), US emissions are capped at 85% of 2005 emissions in 2015, and the cap is gradually

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[3] 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.

reduced to 70% of 2005 emissions by 2030. US 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, US emissions are capped at the same level as in the US-CAP scenario and trade in US 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 be evaluated by comparing results from the TRADE scenario with results from a scenario where US 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.

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 US and Chinese electricity are displayed in **Figure 1**. In the NO-POLICY scenario in 2030, US 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.

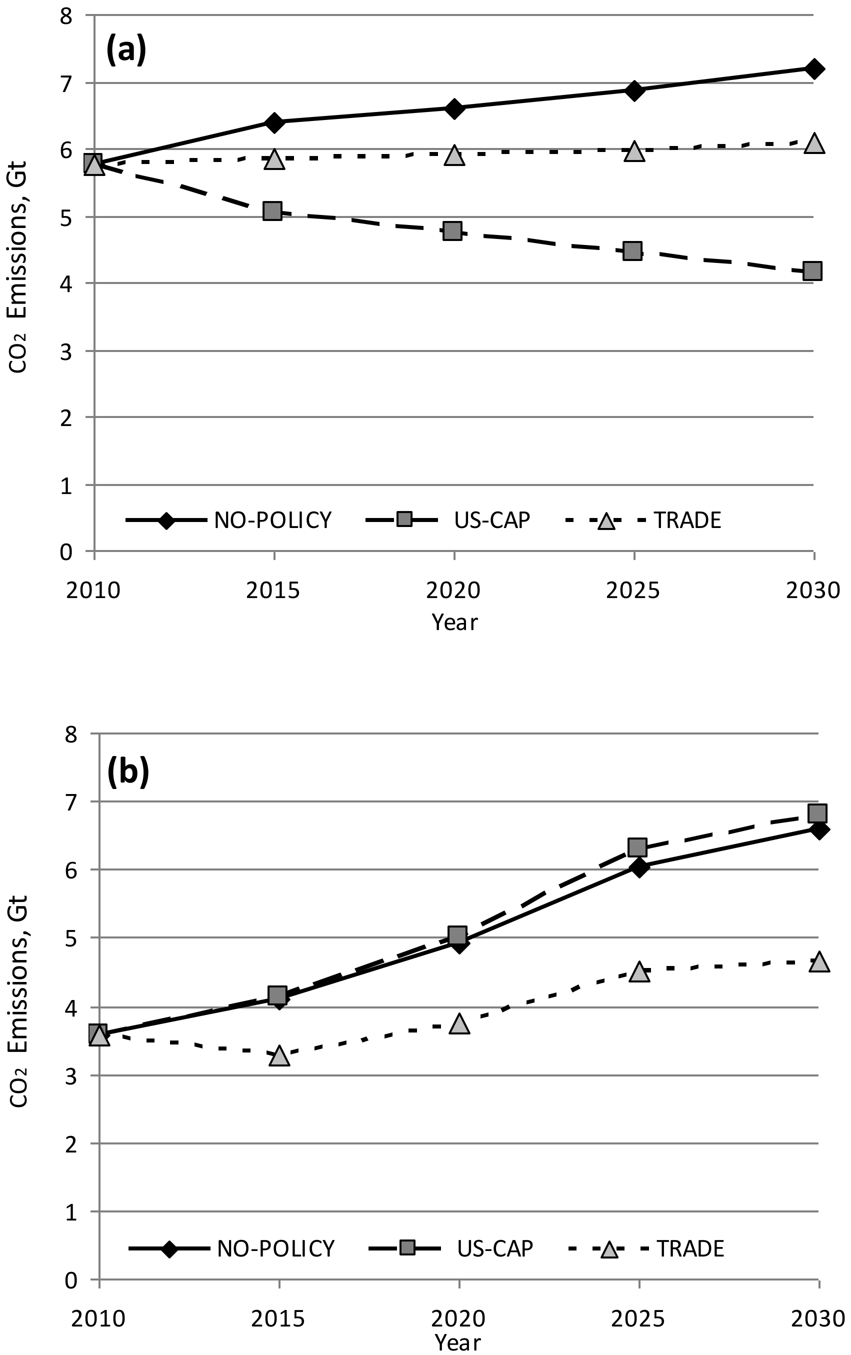

Figure 1. CO_2 Emissions, **(a)** in the US, and **(b)** in the Chinese Electricity Sector.

In the US-CAP scenario, US emissions, limited by the cap in each period, fall to 4.15 Gt by 2030. The 30% reduction in US 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 US.

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

CO_2 prices and welfare changes are reported in **Figures 2** and **3**. In the US-CAP scenario, the US 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 US CO_2 price by \$84 (80%) in 2030. The CO_2 price reduction is achieved by replacing high-cost emissions abatement options in the US 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 US emissions. Financial transfers resulting from international permit trading are significant: in 2030 the US purchases allowances valued at \$42 billion from China.

To put the value of transfers in perspective, the total value of exports from the US to China in 2009 was \$69 billion and the trade deficit between China and the US in 2009 was \$227 billion. If we assume the amount of US exports to China grows proportionally to GDP, exports would reach \$103 billion in 2030. These figures indicate that US exports to China would need to increase by 41% in 2030 to offset financial transfers under sectoral trading and maintain the current trade balance.[4]

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 US by more than half in 2030 – relative to the NO-POLICY case, US welfare decreases by 1.05% in the US-CAP scenario and by only 0.44% in the TRADE scenario (**Figure 3**). China experiences a small welfare increase in the US-CAP

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

scenario, because an emissions constraint on the U.S. tends to lower the cost of imports to China, particularly of oil. The changes in Chinese welfare in the TRADE scenario also are small, but negative. In dollar terms, sectoral trading increases US welfare by $88 billion and decreases Chinese welfare by $6 billion in 2030. The U.S. benefits from relief from a constraint driving the economy to a steep portion on its marginal cost of control. China benefits from the permit revenue, but this benefit is counteracted by the fact that the economy must adjust to higher electricity prices. These results suggest that profit maximizing behavior by Chinese electricity producers reduces national welfare via external effects on other sectors. This difference in relative advantage suggests that the US might need to transfer an amount greater than the value of permits purchased to entice China to participate in a sectoral trading agreement.

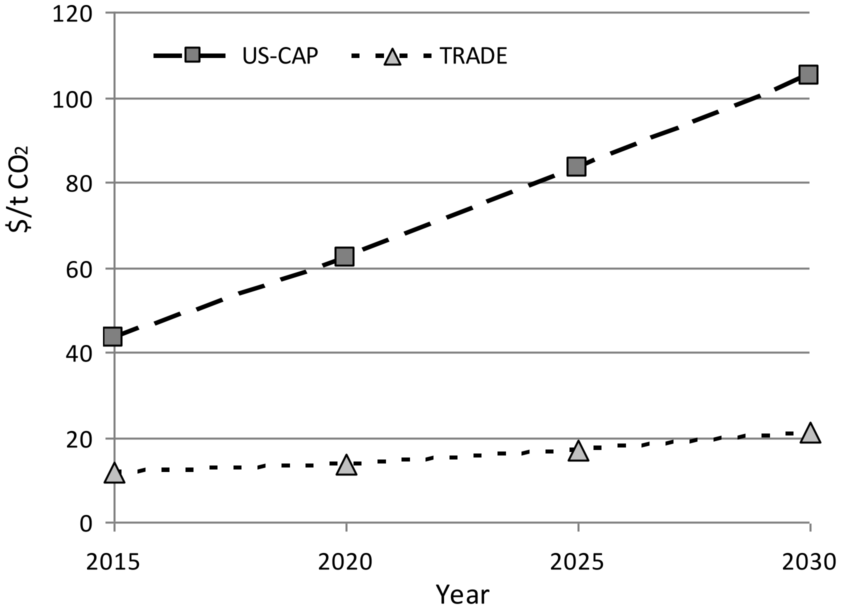

Figure 2. Carbon Price in the US-CAP and TRADE Scenarios.

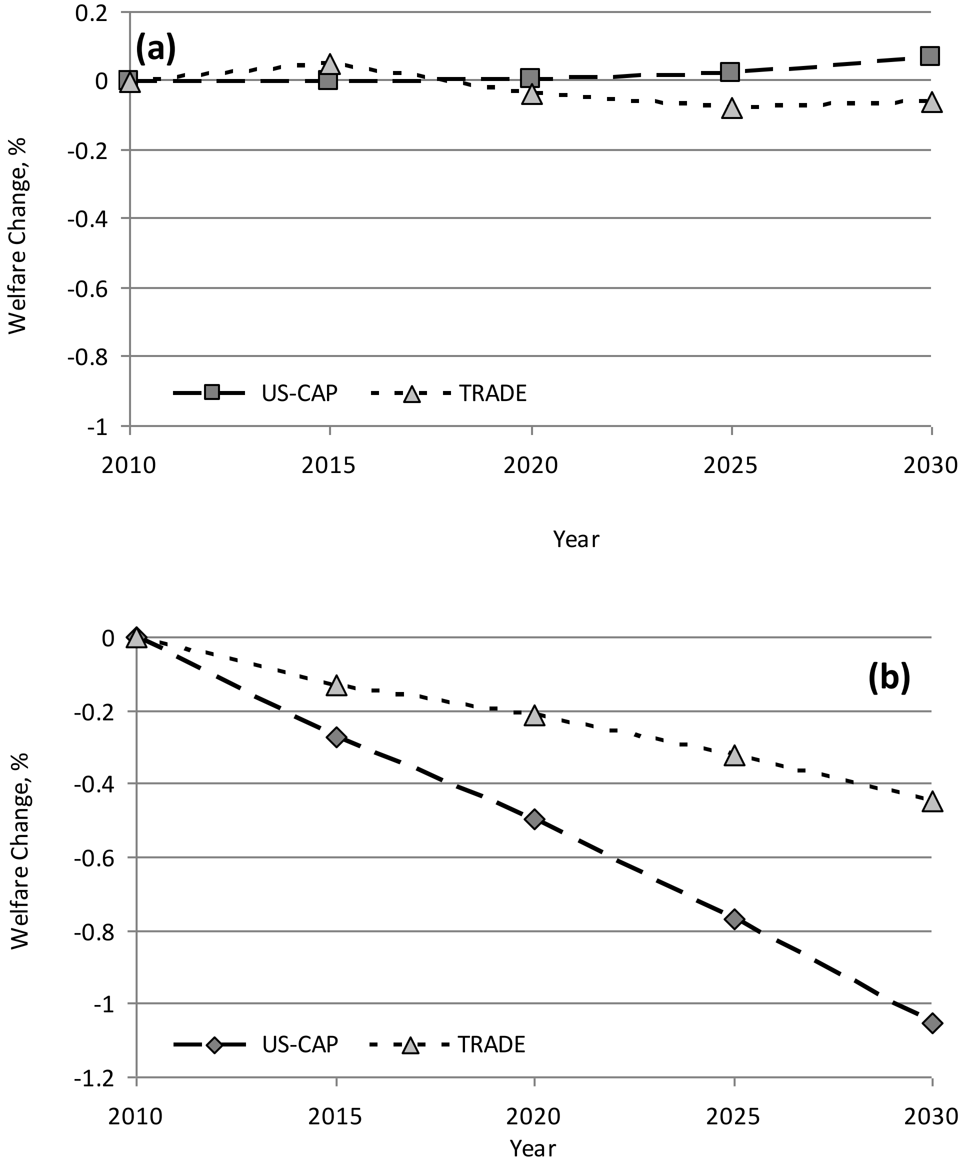

Figure 3. Welfare Changes relative to the NO-POLICY Scenario **(a)** in China and **(b)** in the US.

3.2 Electricity Generation in China and the US

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**.

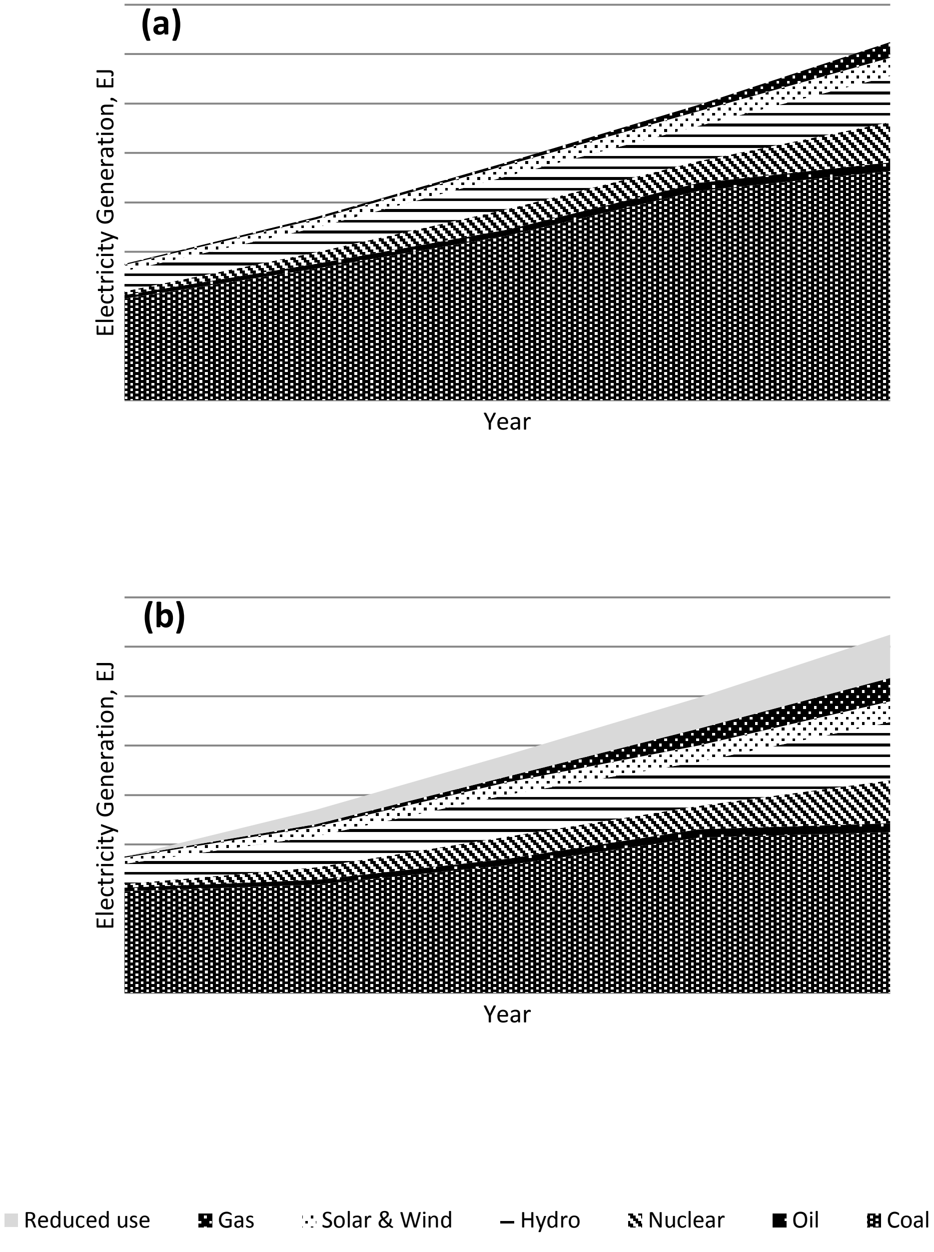

Figure 4. Chinese Electricity Generation for the **(a)** US-CAP and **(b)** TRADE Scenarios.

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, US 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 does not lead to widespread adoption of low-carbon electricity generation in China.

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 US 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, US electricity generation decreases to 15.1 EJ, including 4.4 EJ from coal and 3.4 EJ from gas. In the TRADE scenario, total US 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 US energy demand and its effect on the international oil market. Price changes for other energy commodities in 2030 are less than 2%.[5] 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 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 US cap reducing world energy prices, especially the refined oil price. These price reductions ultimately increase energy use and emissions in China.

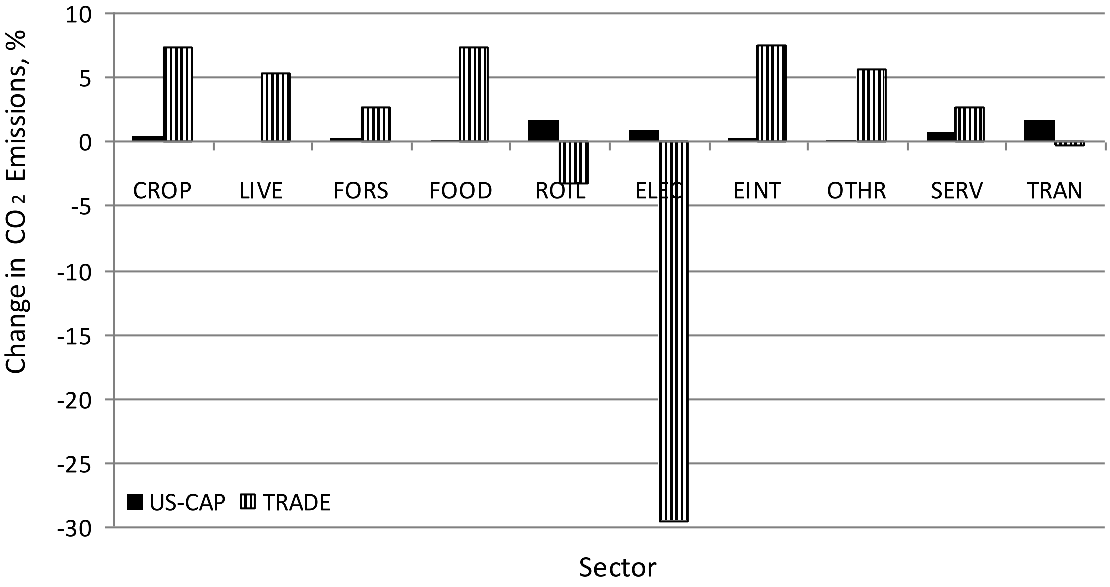

Figure 5. Percent Change in Sectoral CO_2 Emissions in China in 2030 relative to the No Policy Case.

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.

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

The two exceptions are refined oil and transport.[6] 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 US 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 US 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 US emissions. In the TRADE scenario, international leakage is 0.30 Gt of CO_2.

To summarize results presented so far, sectoral trading allows the US to buy carbon permits in China and creates a common carbon price in the two countries. This allows the US 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 US would face under a US cap and trade system without sectoral trading. As a consequence, this mechanism lowers the cost of climate policy in the US and increases welfare in the US. 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

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

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.

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.

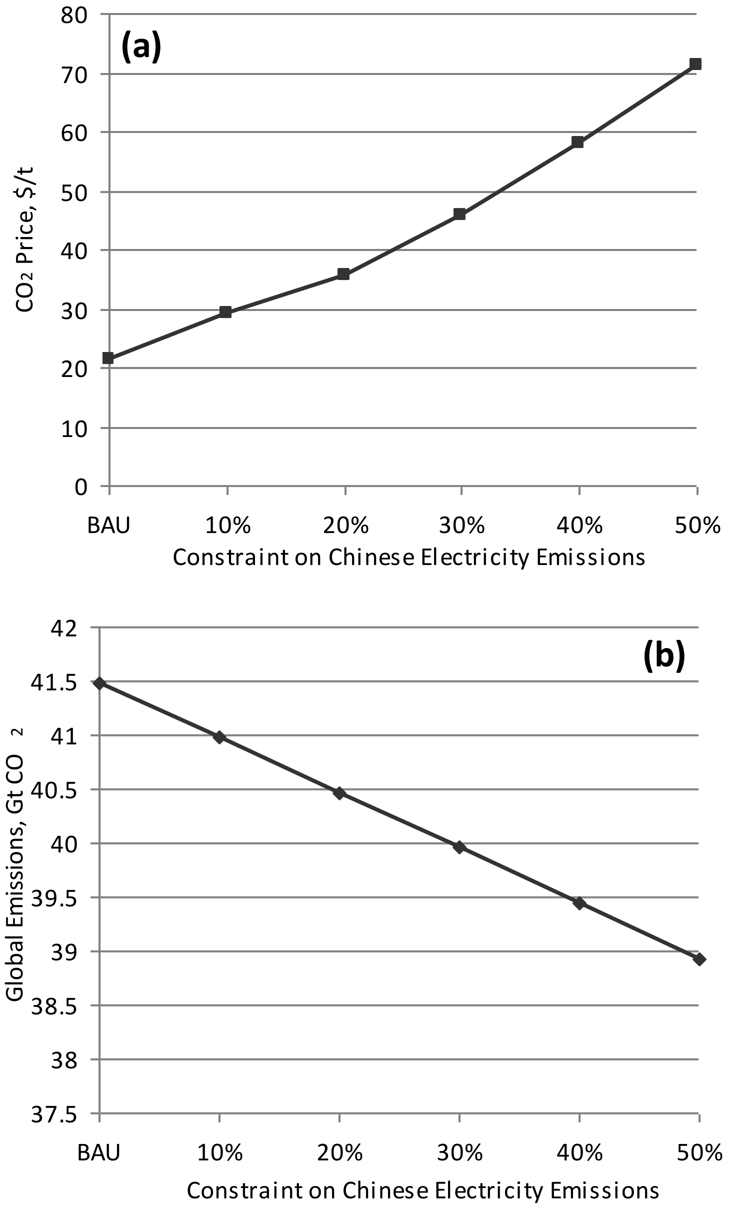

Figure 6. (a) The 2030 International Carbon Price and **(b)** 2030 Global Emissions for Alternative Constraints on Chinese Electricity Sector.

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.

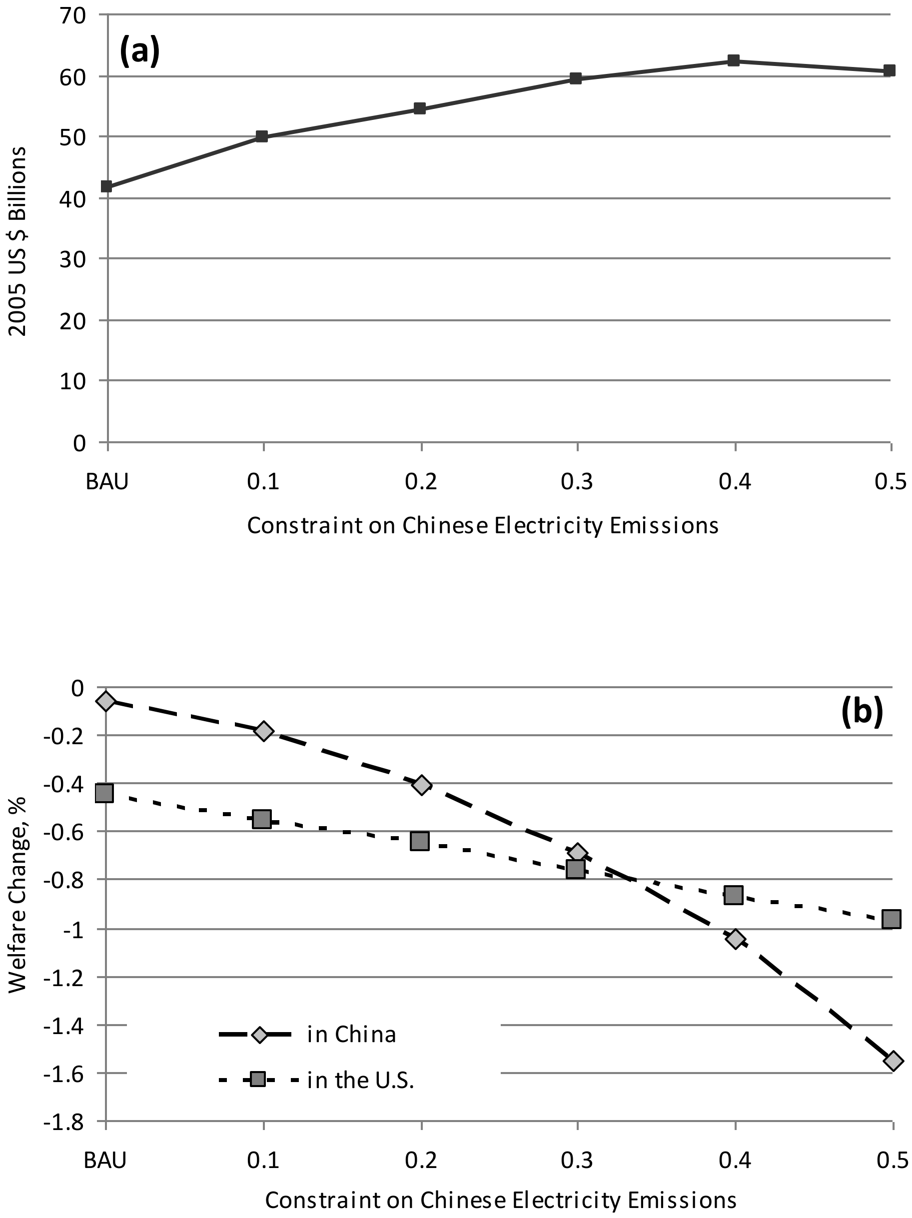

Figure 7. (a) Financial Transfers between the US and China and **(b)** Welfare Changes in the US and in China, 2030.

Welfare in both China and the US falls as the sectoral cap is tightened, as stricter sectoral caps reduce the overall constraint on the two economies. However, while welfare in the US in these cases remains higher than welfare in the US-CAP scenario, welfare in China is lower than in the US-CAP scenario. In other words, the US 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.

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 on Chinese electricity emissions, the electricity price in 2030 increases by 61% relative to the price in the US-CAP scenario, compared to a 29% increase under a BAU constraint on these emissions.

The price of coal also falls by a larger amount as the constraint is tightened. For example, relative to the NO-POLICY case, the 2030 coal price falls by 24% when there is a 30% constraint on Chinese electricity emissions, compared to 15% under a BAU constraint. Larger coal price reductions are associated with larger absolute amounts of internal leakage. Leakage *rates*, on the other hand, 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 on Chinese electricity emissions, internal leakage is 0.61 Gt, which represents a leakage rate of 18%. Under a 50% constraint on these emissions, internal leakage is 0.74 Gt but the leakage rate remains at 18%. In comparison, under a BAU constraint on Chinese electricity emissions, internal leakage is only 0.38 Gt, but 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 US cap-and-trade program. Our central analysis sets a BAU cap on CO_2 emissions from Chinese electricity and an economy-wide reduction on US 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 US and the price US firms pay for permits is \$21 per tCO_2 (in 2005 dollars), compared to \$105 in the US when there is a US cap without sectoral trading. The sale of permits to the US 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 US, as sectoral trading decreases the carbon price, US 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 US 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 US, but not in China, relative to a scenario where China does not participate in an agreement with the US. As the constraint on electricity emissions is tightened, Chinese welfare declines sharply.

Our sectoral trading analysis considered the specific case of trading between the US 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 permits transfers induced by sectoral trading would decrease.

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