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The Economic and Energy Effects of Carbon Dioxide Emissions Trading in the International Market: New Challenge Conventional Measurement

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Abstract Starting from the planned linkage of the European Union's Emissions Trading System with a new system in Australia in 2015, this paper simulates the impacts of expanding this international emissions market to include China and the USA, which are respectively the largest and second largest carbon dioxide emitters in the world. The findings suggest that including China and the USA significantly impacts the price and the quantity of permits traded worldwide. When China joins the EU-Australia-New Zealand (EU-ANZ)-linked market, we find that the prevailing global carbon market price falls significantly, from \$35/tCO_2 to \$11.4/tCO_2. In contrast, adding the USA to the EU-ANZ market increases the price to \$48/tCO_2. If both China and the USA join the linked market, the market price of an emissions permit is \$18.1/tCO_2 and 610 million metric tons are traded, compared to 95 million metric tons in the EU-ANZ scenario. When permit trading between all countries is considered, relative to when all carbon markets operate in isolation, renewable energy in China expands by more than 22 % and shrinks by 50 and 95 % in the USA and ANZ, respectively. In all scenarios, global emissions are reduced by around 5 % relative to a case without

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climate policies. Such results may attract the attention of the policy makers as well as the stakeholders for future investment in energy and environmental technology.

Keywords European Union emissions trading scheme · CGE model · EU climate policy

Introduction

Emission trading systems are recognized as a cost-effective way to facilitate emissions abatement and are expected to play an important role in international cooperation for global climate mitigation. However, it is widely accepted in the global market for the greenhouse gas emissions as the most cost-effective way to mitigate climate change. More countries are implementing national and regional emission trading schemes, and interest in the implications of linking these systems at the global level has grown.

Actually, a small number of markets for greenhouse gas emissions exist at the national level (e.g., the New Zealand Emissions Trading System), at the local level (e.g., California's cap-and-trade program), or at the level of a single economic group (e.g., the EU Emissions Trading System, EU-ETS). Australia currently has a carbon tax, but is planning to create an ETS that will link to the European Union as early as 2020 (DCCEE 2011).

Currently, China is experimenting with ETS designs at the provincial level with the emphasis on creating a trading market at the national level (Guoyi et al. 2012). Although the latest attempt to establish a national emission trading system in the USA dropped in 2010, many regional carbon markets have been implemented (Lavelle 2010; California Environmental Protection Agency Air Resources Board 2012; RGGI 2013), which can speed up the steps to a national market in the USA. Although a multi-region agreement is yet to materialize, the potential benefits of linking emission markets across countries and regions are well recognized (Marschinski et al. 2012). In addition, the prospects for linking carbon markets in the developing and developed countries have been widely discussed and seen as a way of encouraging participation by the developing countries in a global climate agreement (ICAP 2007; European Union Commission 2009).

Australia's ETS represents the first effort to create an international emission market since the EU-ETS was established in 2005 (Australia Greenhouse Gas Reduction Scheme Administrator 2012; Nelson et al. 2012). In addition, China indicated that it would consider participating in an international carbon market if plans to expand pilot programs to the nation level are successful (Guoyi et al. 2012; Environment News Service 2013). The impact from linking carbon markets depends in some measure on the relative amount of emissions in both regions. For example, a link between the EU-ETS and a hypothetical ETS in the USA has a larger impact on the EU carbon price as is the link between the EU-ETS and a hypothetical ETS in Mexico (Gavard et al. 2011). Within the framework that we consider, relevant markets have very different emission levels. However, the total CO_2 emissions caused by the use of fossil fuels in Australia were around 385 million metric tons (mmt) in 2010, compared to 3861 mmt in the EU, 7259 mmt in China, and 5763 mmt in the USA (International Energy Agency 2011). Therefore, linking the EU-ETS with a cap-trade program in China and the US should have a more important impact on the EU permit price than linking this system with an ETS in Australia.

This paper examines the impacts including changes in carbon prices, emissions, and welfare of carbon markets in the Europe Union (EU), the USA, Australia-New Zealand (ANZ), and China (CHN).

Some benefits from establishing an international ETS are obvious. Particularly, a global market provides more elasticity for parties to achieve emission reductions at the lowest marginal cost across all the covered sectors and jurisdictions (Flachsland et al. 2009b). However, the impact of global trading cannot always be positive for all parties. For example, market distortions or trade effects can affect the relative advantages to each country of participation (Babiker et al. 2004; Flachsland, et al. 2009a). Other researchers suggest that emissions trading regimes may alter the way economic shocks are transmitted through international markets (McKibbin et al. 2008).

In this paper, we utilize a multiregional computable general equilibrium (CGE) model. Such model is well suited to the task at hand, as it captures linkages between energy and economic systems and interactions among regions (Marschinski et al. 2012).

The paper is organized as follows. "Methods" discusses the model and data used for the analysis. "Results and discussions" describes the scenarios implemented in the model and "Conclusions and policy implications" discusses the results and concludes.

Methods

Model Description

To evaluate the energy and CO_2 emissions impacts of linking carbon markets in China, the EU, the USA, and Australia-New Zealand (ANZ), we use the CGE model (see Appendix B). However, The CGE is a dynamic general equilibrium model of the world economy developed by the International Institute for Clean Energy and Climate Change (Appendix A). In the model, we employ 18 production sectors, which are summarized in Table 1. These sectors are classified into six types of production processes: extraction of primary fuels (crude oil, coal and gas), production of electricity, refined oil production, energy-intensive industries, agriculture, and other production activities including other manufacturing industries, transportation, and services.

Each of the production processes is captured by a nested constant elasticity of substitution (CES) function. A typical detailed nesting structure for the six production activities is portrayed in Fig. 1, where σ is used to denote the elasticity of substitution between inputs. An important feature of the nesting structure is the ability of firms to substitute among fossil fuels and between aggregate energy and value added based on their cost competitiveness, which is influenced by energy and climate policies.

Basically, the CGE model represents 11 types of advanced technologies, which are summarized in Table 2. Three technologies produce perfect substitutes for conventional fossil fuels (crude oil from shale oil, refined oil from biomass, and natural gas from coal gasification). The remaining eight technologies are electricity generation technologies. Wind, solar, and biomass electricity technologies are treated as imperfect substitutes for other sources of electricity due to their intermittency. The final five technologies (NGCC, NGCC with CCS, IGCC, IGCC with CCS, and advanced nuclear) are all perfect substitutes for electricity output (Table 3).

Table 1 Energy sectors in the CGE model

Energy sectors	Industry included in sector
Crops	Crops
Forestry	Forestry, logging, and related services
Livestock	Livestock
Coal	Mining and agglomeration of hard coal, lignite, and peat
Oil	Extraction of crude oil
Gas	Extraction and distribution of natural gas
Petroleum and coke	Refined oil and petro-chemical products, coke production
Electricity	Electricity production, collection and distribution
Non-metallic minerals	Cement, plaster, lime, gravel and concrete
Iron and steel	Manufacture and casting of basic iron and steel
Non-ferrous metals	Production and casting of copper, aluminum, zinc, lead, gold, and silver
Chemical, rubber, and plastics	Basic chemicals, other chemical products, rubber, and plastics products
Fabricated metals	Sheet metal products (except machinery and equipment)
Mining	Mining of metal ores, uranium, gems, other mining, and quarrying
Food and tobacco	Manufacture of foods and tobacco
Equipment	Electronic equipment, other machinery, and equipment
Other industries	Industries not included elsewhere
Transportation Services	Water, air and land transport, and pipeline transport
Other Services	Communication, finance, public service, dwellings, and other services

Wind, solar, and Biomass electricity have similar production structures as shown in Fig. 2. As they produce imperfect substitutes for electricity, a fixed factor is introduced on the top level of the CES nest to control the penetration of each technology (McFarland et al. 2004). Other inputs, including labor, capital, and equipment as intermediate inputs, are parameterized on the basis of engineering information for each technology (Qi et al. 2012).

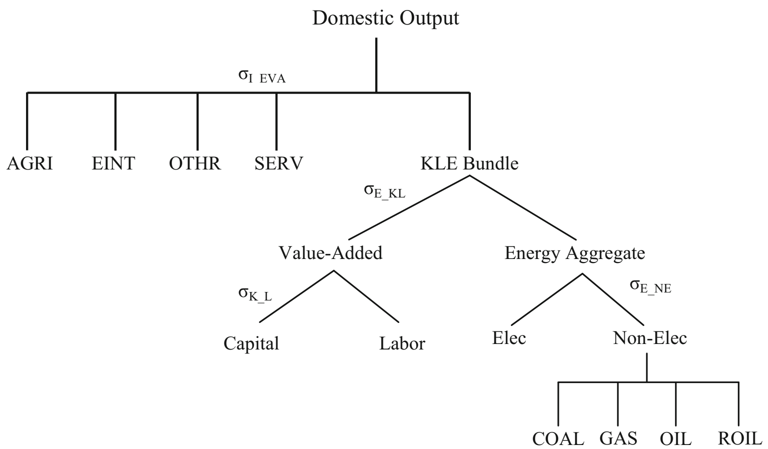

Fig. 1 A typical nesting structure for the CES production function in CGE model

Table 2 Advanced technologies in the CGE model

Technology	Description
Wind	Converts intermittent wind energy into electricity
Solar	Converts intermittent solar energy into electricity
Biomass electricity	Converts biomass into electricity
IGCC	Integrated gasification combined cycle (coal) to produce electricity
IGCC-CCS	Integrated gasification combined cycle (coal) with carbon capture and storage to produce electricity
NGCC	Natural gas combined cycle to produce electricity
NGCC-CCS	Natural gas combined cycle with carbon capture and storage to produce electricity
Advanced nuclear	Nuclear power beyond existing installed plants
Biofuels	Converts biomass into refined oil
Shale oil	Extracts and produces crude oil from oil shale
Coal gasification	Converts coal into a perfect substitute for natural gas

Table 3 Regions in the CGE model

Region	Countries included in region
Australia-New Zealand	Australia, New Zealand and rest of the world (Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories)
Brazil	Brazil
Canada	Canada
China	Mainland China
Asia	Hong Kong, Taiwan, and Singapore
Southeast Asia	Cambodia, Indonesia, Malaysia, Philippines, Thailand, Vietnam, Laos, and the rest of Southeast Asia
Rest of Asia	Rest of Asia countries
Europe Union	EU-27 and countries of the European Free Trade Area (Switzerland, Norway, Iceland)
Rest of Europe	Albania, Croatia, Belarus, Ukraine, Armenia, Azerbaijan, Georgia, Turkey, Kazakhstan, Kyrgyzstan, and the rest of Europe
India	India
Japan	Japan
Latin America	Rest of Latin America countries
Mexico	Mexico
Middle East	Middle East Iran, United Arab Emirates, Bahrain, Israel, Kuwait, Oman, Qatar, and Saudi Arabia
Russia	Russia
South Africa	South Africa
Rest of Africa	Rest of Africa countries
South Korea	South Korea
USA	USA

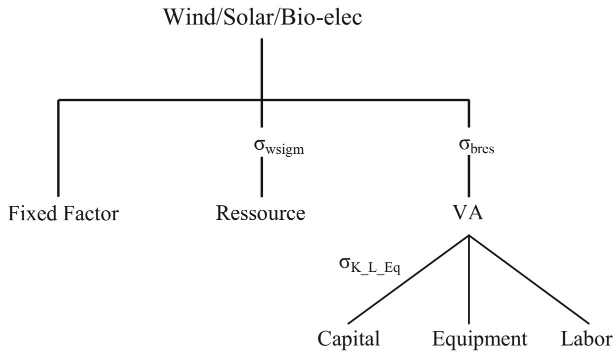

Fig. 2 CES production structure for wind, solar, and biomass power

Bilateral trade is specified using the Armington assumption that domestic and imported goods are imperfect substitutes and are distinguished by region (Armington 1969). That is, each commodity purchased in a region is a CES composite of a domestic variety and an imported variety, where the latter is a further CES composite of inputs from different regions. The CGE model is calibrated based on the Global Trade Analysis Project Version 8 (GTAP8) global database (Badri et al. 2012) and China's official statistical publications, using 2008 as the base year. The GTAP8 data set includes consistent national accounts for production and consumption activities (input-output tables) integrated together with bilateral trade flows for 57 sectors and 129 regions for the year 2008 (Narayanan 2012; Narayanan et al. 2012).

The CGE model replaces GTAP8 observations for China with data from China's official data sources, including national input-output tabs and energy balance tables for 2008. To keep consistency between these two datasets, the revised global database is rebalanced using least-squares techniques (Rutherford and Paltsev 2000). The CGE model aggregates the GTAP database to 19 sectors (see Table 1) and 19 regions, as shown in Table 2.

The CGE model is solved recursively in 5-year intervals, starting with the year 2010. The model is written in the General Algebraic Modeling System (GAMS) software system and solved using Mathematical Programing System for General Equilibrium analysis (MPSGE) modeling language (Rutherford 2005). In CGE model, CO_2 emissions are calculated by applying constant emission factors to the fossil fuel energy flows of coal, refined oil, and natural gas based on the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The emission factors are assumed to remain constant across regions and over time. CO_2 emissions together with fuel consumption are introduced as a Leontief input. This implies that the reduction of emissions in production sectors can only be achieved by reducing the use of carbon-intensive fuels. In the current version of CGE model, only fossil-fuel-related CO_2 emissions are projected.

Modeling Scenarios

We develop five scenarios to examine the impact of international permit trading among the EU, the USA, China, and ANZ, which are listed in Table 4. Based on the idea that

Table 4 Description of scenarios

Scenario	Regions with a separate ETS	Regions with linked ETSs
No ETS	None	None
Separate	ANZ, CHN, EUR, USA	None
AE	CHN, USA	ANZ, EUR
ACE	USA	ANZ, CHN, EUR
AEU	CHN	ANZ, EUR, USA
ACEU	None	ANZ, CHN, EUR, USA

New Zealand will link its market with Australia in 2015, we have represented a fully integrated ANZ emission trading market.

In order to examine the impacts of expanding the emission market size, we first simulate the model with no controls on CO_2 emissions (no ETS) to observe "business-as-usual" emissions in each region. We then consider four policy scenarios: (1) a separate market scenario (separate) that simulates the four regional emissions markets independently, (2) an EU-ANZ scenario (AE) that links the EU-ETS to the ANZ ETS, (3) a scenario that links carbon markets in the EU, ANZ, and CHN (ACE), (4) a scenario that links carbon markets in the ANZ, EU, and USA (AEU), and (5) a scenario that links markets in the ANZ, EU, USA, and CHN (ACEU).

Policy Assumptions

To assess the impacts of linking the three participant trading systems, it is important to consider existing complementary policies that promote energy savings and renewable energy deployment through direct regulatory measures or other channels. For instance, Australia and the EU have a legislation to ensure that 20 % of energy consumption will originate from renewable sources by 2020, while China plans to accelerate the deployment of nuclear, hydro, and renewable energy by 2020. Since the cost of deploying renewable energy is different in each region, emissions abatement costs and ultimately the distribution of emissions reductions in a linked system will be influenced by renewable directives in each region. These "current policies" are included in all scenarios and are summarized in Table 5.

Table 5 Policies included in all scenarios

Regions	Policy description
ANZ	By 2020, at least 20 % of energy consumption is from renewable sources (Australian Government 2012)
CHN	Targets for nuclear, hydro, and renewable energy in 2020 set out in China's Twelfth Five-Year Plan and Medium-Term Plan for Renewable Energy (National Energy Administration 2012)
EU	By 2020, at least 20 % of energy consumption originates from renewable sources and there is a 20 % improvement in energy efficiency (European Union 2012c)
USA	A 5 % efficiency improvement is achieved by 2020 (ACEEE 2013)

Previously, The EU and New Zealand have had existing emission trading systems, whereas Australia, CHN, and the USA have not yet finalized the structure of their domestic carbon market. In this paper, we make assumptions about the coverage of the emissions trading systems in Australia, CHN, and the USA based on available information and focus on the effects of linking carbon markets in different regions. The EU-ETS covers the power generation and energy intensive sectors (European Union 2003; European Union 2012a). For ANZ, CHN, and the USA: we assume that all sectors, except agriculture, are included in the emission trading.

CO_2 emission allowances allocated to regional markets are based on their national reduction targets in 2020, as presented in Table 6. For the EU, the 2020 target is a 21 % reduction in GHG emissions from 2010 levels (European Union 2012a, b). In this analysis, we only consider CO_2 emissions. For the USA, we use the 17 % emission reduction target from 2005 levels by 2020 stated in the American Clean Energy and Security Act of 2009 (Waxman and Markey 2009).

For Australia, we utilize their 2020 unconditional 5 % reduction target below 2000 emission level in all the sectors. Although New Zealand holds an intensity target rather than an explicit reduction target, we apply a 5 % reduction to the composite ANZ region. For CHN, the national target for 2020 is a 45 % reduction of emission intensity based on 2005 levels (which equates to a 27 % reduction in CO_2 emissions intensity relative to 2010 levels). The combined emission caps in the four regions reduce global emissions by around 5.3 %.

Results and Discussions

Emission Abatement in the Separate Emissions Markets Scenario

Let us first try to examine the impact of separate emission trading systems in each region. Table 7 presents the carbon prices changes and the global emission abatement results in a separate scenario. However, results show that carbon price is significantly different in each of the markets. This is due in mainly to the differences in the emissions caps applied. ANZ has the highest carbon price, $134/t$CO_2$, followed by the USA ($40/tCO_2), the EU ($13/t$CO_2$), and CHN ($8/tCO_2). Hence, the lower carbon price in China, compared to other capped regions, reflects the relative abundance of low-cost abatement options in this country and the small proportional reduction in emissions.

These differences are driven by (1) production technologies in CHN, as it is, on average, older than those in the EU, the USA, and ANZ, and (2) a large share of coal

Table 6 Emissions allowance totals for ANZ, CHN, the EU and the US

Emissions allowance totals	ANZ	CHN	EU	USA
No Policy 2020 emissions (mmt)	495	11094	1996	5705
2020 emissions caps (mmt)	354	10331	1863	4794
Proportional abatement in emissions[a] (%)	29.6	7.5	7.5	16.7

[a] Proportional reductions are relative to 2020 emissions in the no policy scenario

Table 7 Carbon prices and global emissions abatement results in the separate scenario

Emissions allowance totals	ANZ	CHN	EU	USA
Emissions abatement (mmt)	143	762	135	912
Carbon price ($/t)	134	008	013	040
Welfare change (%)	−0.60	−0.02	−0.01	−0.05

in the total energy production in China relative to other regions. These attributes drive differences in CO_2 intensity (CO_2 emissions per unit of GDP) across regions. Particularly, in 2010, the emission intensity of output in China was 1.61 kg CO_2/US$, which is six times as longer as that of the EU (0.24 kg CO_2/US$) and three times as that of ANZ (0.41 kg CO_2/US$). Older used less-efficient technologies in CHN mean that a greater reduction in emissions is achieved by adopting advanced technologies, and a large use of coal in this region provides greater scope for reducing emissions by substituting away from this input towards cleaner fossil fuels or improving energy efficiency.

Figures 3 and 4 present changes in electricity generation from advanced technologies and primary energy use. On account of the carbon caps, less energy is consumed to support similar scale of economic activity in ANZ (31 % less), CHN (5 % less), the EU (2 % less), and the USA (13 % less). In ANZ and the USA, significant proportional reductions in coal consumption are achieved with 37 and 29 %, respectively, as compared to more moderate reductions in CHN (8 %) and the EU (9 %). In absolute terms, the largest reduction in coal consumption occurs in CHN (213 million tons of oil equivalent) which is about 69.8 % of EU's total coal consumption in 2010. In addition, carbon price increase the cost competitiveness of renewable electricity. For instance, in the USA, electricity generation from wind increases from 6.4 million tons of oil equivalent to 16.2 million tons of oil equivalent, and solar power doubles. In the EU, renewable energy production increases by more than 20.3 % (from 20.7 to 24.3 million tons of oil equivalent) and in CHN generation from these technologies increases by more than 26.1 % (from 44.1 to 54.5 million tons of oil equivalent).

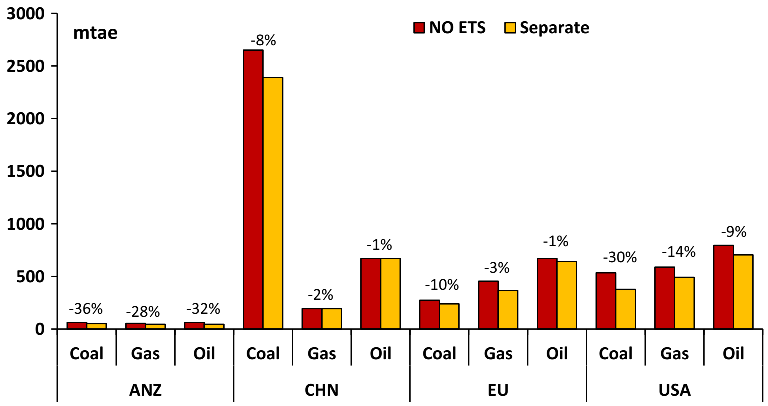

Fig. 3 Fossil fuel consumption in the separate and no ETS scenarios in 2020

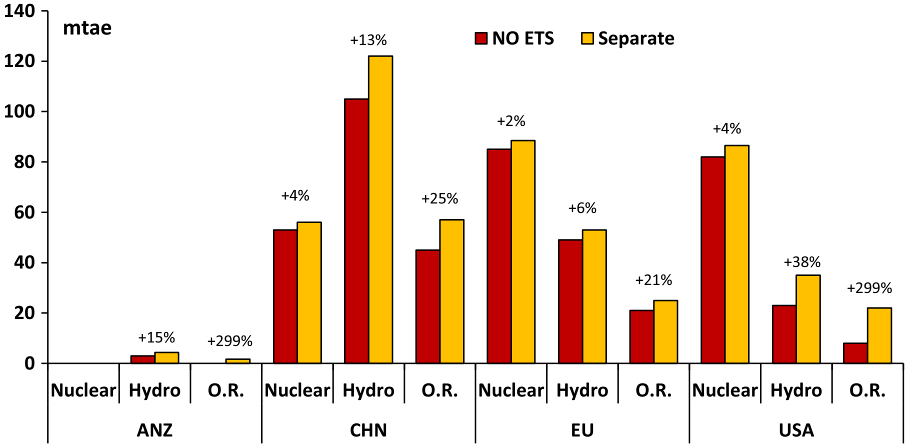

Fig. 4 Renewable energy production in the separate and no ETS scenarios in 2020

Impact of Linking Emissions Markets

Table 8 presents the results for the AE, ACE, AEU, and ACEU scenarios, when emissions markets are related to each other. However, linking carbon markets in

Table 8 Carbon prices and emissions abatement in AE, ACE, AEU, and ACEU scenarios

Scenario	Region	2020 emissions reduction[a]		Change in abatement[b]	Carbon price	International Transfer	Welfare change
		mmt	%	mmt	USD/t	Billion USD	%
AE	EU	230	11.4	95	34	3.10	−0.03
	USA	914	16.0	–	38.5	–	0.00
	ANZ	50	10.2	−95	34	−3.10	0.39
	CHN	765	7.5	–	7.3	–	0.00
ACE	EU	90	4.2	−46	11.5	−0.55	0.02
	USA	914	16.0	–	38.5	–	0.00
	ANZ	25	5.3	−118	11.5	−1.34	0.57
	CHN	929	8.1	165	11.5	1.82	0.03
AEU	EU	293	15.2	158	46.2	7.28	−0.03
	USA	836	15.0	−77	46.2	−3.52	−0.01
	ANZ	61	12.3	−82	46.2	−3.75	0.30
	CHN	765	7.5	–	7.3	–	0.00
ACEU	EU	143	7.2	8	17.4	0.11	−0.02
	USA	417	7.2	−501	17.4	−8.75	−0.02
	ANZ	32	6.3	−112	17.4	−1.95	0.49
	CHN	1365	12.0	598	17.4	10.5	0.15

[a] Emissions reductions are expressed relative to the no policy scenario

[b] Changes in emissions abatement and welfare are relative to the separate scenario

ANZ and CHN (AC) results in a carbon price of \$10.7/tCO_2, which is an important reduction compared to the ANZ price (\$134/tCO_2) in the separate scenario. As the linked emission price is still lower than that of the carbon in the EU market (\$13/tCO_2), both the EU and ANZ purchase permits from CHN in the ACE scenario, resulting in an international emission price of \$11.2/tCO_2. In this scenario, CHN sells permits for 164 mmt of CO_2 emissions, 119 mmt to ANZ, and 45 mmt to the EU. If CHN is not involved in the international carbon market, as the case in the AEU scenario, the global carbon price is \$46.1/tCO_2 and permits for 157 mmt of emissions are traded. In this scenario, permits are sold by the EU to ANZ and the USA.

In the ACEU scenario, linking all considered carbon markets result in a permit price of \$17.4/tCO_2 and 606 mmt of permits traded (compared to 164 mmt in the ACE scenario). The USA buys 501 mmt of the emission permits, accounting for 55 % of its reduction target and ANZ purchases permits for 110 of emissions, accounting for 78 % of its reduction target. Most of the permits are supplied by China and a small amount (1 % of total supply) by the EU. Turning to financial transfers, the US pays \$8.75 billion to permit suppliers and ANZ pays \$1.95 billion, and the EU and CHN receive, respectively, \$0.11 billion and \$10.5 billion. The transfer to CHN is equivalent to 0.23 % of China's 2010 GDP. The observation that the EU is a net exporter of permits is perhaps surprising, but it is worth noting that existing renewable and other mandates essentially offer reductions towards EU's goal that are pursued regardless of the carbon price, making the EU an attractive source of emission reductions. Concerning the welfare changes for each scenario, ANZ generally experiences the largest welfare gain (in proportional terms) due to international permit trading, reflecting relatively high abatement costs in this region. Global welfare increases by 0.02 % in the ACEU scenario. Interestingly, not all participating regions benefit from permit trading. This is due to the interaction between existing distortions (for example, fuel taxes as well as existing sectoral policies within regions) and permit trading, as discussed in Babiker et al. (2004).

Impact on Energy Production

International permit trading minimizes the overall abatement cost within the covered regions. Therefore, emission reductions may occur in different locations compared with the case in which cap-and-trade programs operate separately. Permit exporters will face a tighter emission constraint which, in return, will require them to consume more low-carbon energy. On the other hand, permit importers will be able to use more fossil fuels and the development of clean energy will be postponed. Figures 5 and 6 present changes in the fossil fuel consumption and electricity generation in the separate and ACEU scenarios.

Coal consumption in CHN decreases in the ACEU scenario (by 7 %) relative to the separate scenario. In addition, there is a small reduction in gas and oil consumption in CHN in these scenarios. Reductions in fossil fuel use are driven by a combination of lower demand due to higher prices, improved energy efficiency, and expansion of low-carbon energy sources. In the ACEU scenario, renewable energy in China expands by over 20 %. On the other hand, the USA,

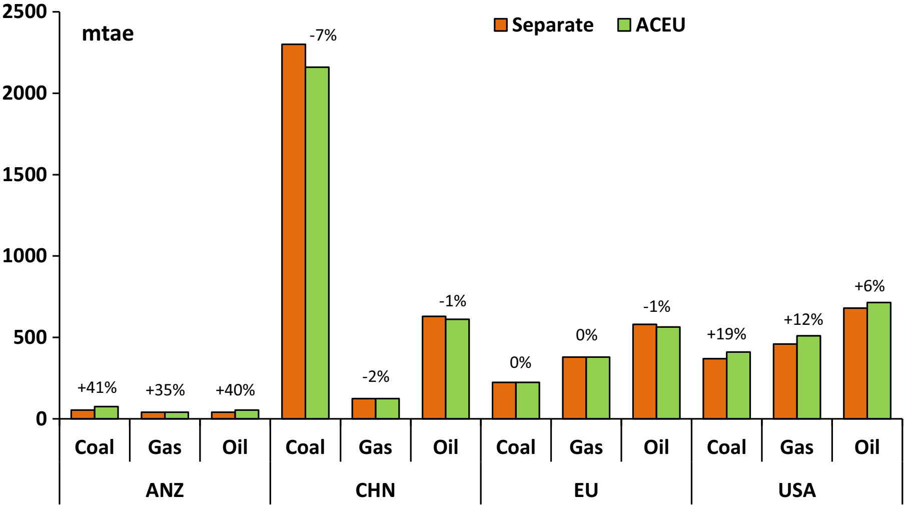

Fig. 5 Fossil fuel consumption in the separate and ACEU scenarios

a permit importer, consumes more coal 19 %, more gas 11 %, and more oil 6 % than in the ACEU scenario relative to the separate scenario.

Moreover, in this scenario in the USA, electricity from hydro and other energy falls by 14 and 48 %, respectively. It seems that changes in energy production due to permit trading are the largest in the ANZ region. This region consumes more coal 41 %, more gas 35 %, more oil 40 %, and less renewable energy 90 % in the ACEU scenario compared to the separate scenario. As a result, international permit trading redistributes the production of renewable energy from permit importers to permit exporters.

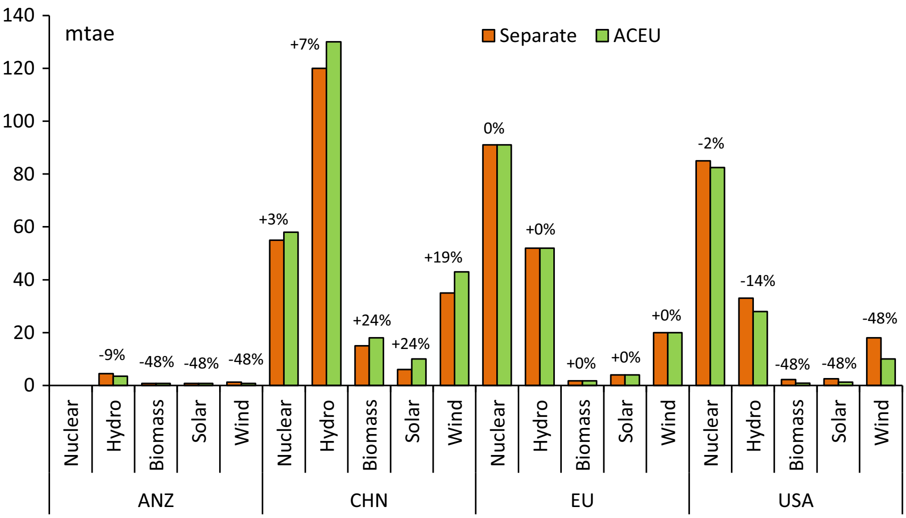

Fig. 6 Renewable energy production in the separate and ACEU scenarios

Conclusions and Policy Implications

This study examines the hypothetical expansion of an international emission markets including changes in carbon emissions, financial transfers, carbon prices, regional welfare, and trade flows of the proposed linkage of carbon markets in the EU and ANZ and the impact of the USA and China joining this market. We start from the planned linkage of the EU-ETS with a new system in Australia in 2014–2015 and consider a full range of likely trading system combinations. This paper provides several interesting insights for policy makers concerning the effects of the link trading systems based on currently announced emission reduction targets through 2020. The results show that introducing the EU and the USA into an ETS has a significant impact on the results in a linked system. Basically, we explain these outcomes as a function of the stringency of the cap, the marginal cost of potential reduction in each market, and the interaction between existing sectoral policies and an expanded carbon market.

First, we find that some regions are still importers of emission permits across all scenarios, while the status of others depends on the coverage of the linked market. The targets of abatement in each region result in different amounts of CO_2 reduction, if markets are not bound, achieving these goals within the territorial limits is very expensive for some regions. For example, ANZ must reduce a significant amount compared to territorial emissions (33 %) but low compared to the total emissions in a related market framework, particularly, when CHN or the USA are both included. This territorial reduction burden translates into high marginal costs and still makes ANZ an importer of emissions permits when included in a related market. On the other hand, the EU, as an importer or exporter of permits, depends on the include countries. However, if ANZ, CHN, and the EU are linked, CHN absorbs a large part of the burden of ANZ and the EU. In addition, integrating the USA in a linked system, ANZ and the USA pay CHN and the EU to undertake some reductions on their behalf. Under the assumptions made here, the EU gains to join a trading system that includes CHN but not the USA. It is crucial that gains or losses in participating in a linked system are relatively modest for all the regions, except for ANZ. This region faces the highest marginal abatement costs but represents only a small proportion of the total require reductions; therefore, it always outsources a large share of its reduction burden given the opportunity.

Second, our findings suggest that interaction between existing region-specific sectoral or control policies and the internationally linked emissions market is important. Such policies that target reductions in CO_2 emissions act independently of carbon price, which means that they are prosecuted regardless of the availability of more than profitable opportunities, raising the average cost of the reductions and the welfare cost of climate policies (Morris et al. 2010). From the perspective of a linked international ETS, sectoral policies restrict the amount of extra-territorial emissions that can be used to meet the cap. The EU has adopted multiple sectoral policies that result in the EU undertaking some emission reductions (e.g., by deploying renewable energy and efficiency) despite the international CO_2 price. The fact that these reductions are predetermined is probably one of the reasons that made the EU an exporter for reductions in 2020 when the four regions are linked.

Third, we assume that all the sectors are covered in markets including an ETS linked, but there are many potential designs that involve partial sectoral coverage or staggered arrangements that may increase the acceptability of policy makers to connect markets.

The results may attract the attention of policy makers as well as stakeholders for future investment in energy and environmental technologies. The CGE models are powerful tools for policy analyses, but their results require a careful validation of underlying technical assumptions. These assumptions adopted in such models are of critical importance for results of policy simulations. In the sensitivity analysis, we identified a list of parameters (like import or Armington elasticities) which affect not only the magnitude but also the sign of carbon prices, regional welfare, and trade flows.

Appendix A

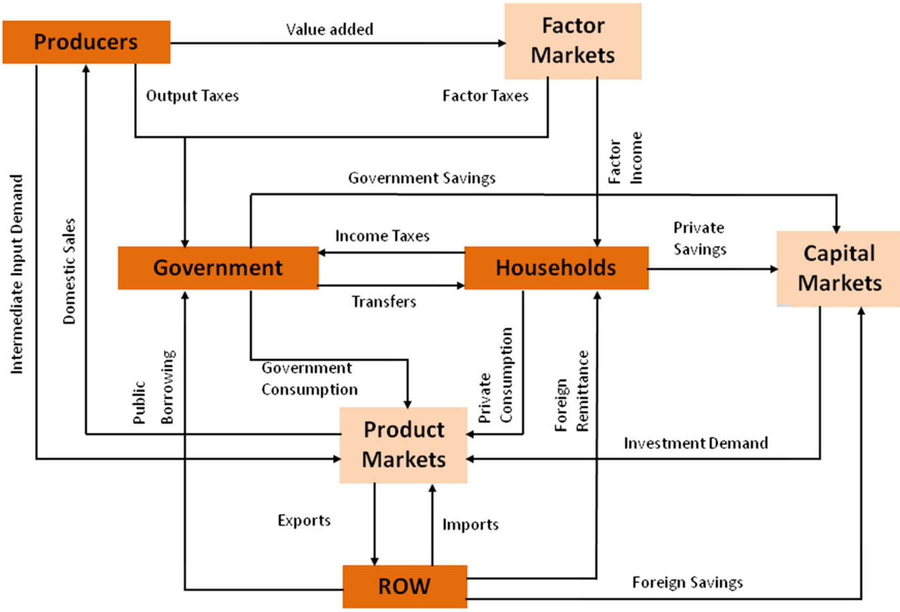

Fig. 7 Simplified structure of a CGE model

Appendix B. Equations

Import Price

$$PM_c = pwm_c(1 + tm_c)EXR + \sum_{c' \in CT} PQ_{c'} icm_{c'\ c} \quad (1)$$

where

$c \in C$	a set of commodities (also referred to as *c*. and *C*.)
$c \in CM(\subset C)$	a set of imported commodities
$c \in CT(\subset C)$	a set of domestic trade inputs (distribution commodities)
PM_c	import price in LCU (local-currency units) including transaction costs
pwm_c	c.i.f. import price in FCU (foreign-currency units)
tm_c	import tariff rate

EXR	exchange rate (LCU per FCU)
PW_c	composite commodity price (including sales tax and transaction costs)
$icm_{c' c}$	quantity of commodity c. as trade input per imported unit of c.

Exporte Price

$$PE_c = pwe_c(1-te_c)EXR-\sum_{c' \in CT} PQ_{c'} ice_{c' c} \qquad (2)$$

where

$c \in CM(\subset C)$	a set of exported commodities (with domestic production)
PE_c	export price (LCU)
pwe_c	f.o.b. export price (FCU)
te_c	export tax rate
$ice_{c' c}$	quantity of commodity c. as trade input per exported unit of c.

Demand Price of Domestic Non trated Goods

$$PDD_c = PDS_c + \sum_{c' \in CT} PQ_{c'} icd_{c' c} \qquad (3)$$

where

$c \in CM(\subset C)$	a set of commodities with domestic sales of domestic output
PDD_c	demand price for commodity produced and sold domestically
PDS_c	supply price for commodity produced and sold domestically
$icd_{c' c}$	quantity of commodity c. as trade input per unit of c produced and sold domestically

Absorption

$$PQ_c = (1-tq_c)\, PQ_c = PDD_c\, QD_c + PM_c\, QM_c \qquad (4)$$

where

QQ_c	quantity of goods supplied to domestic market (composite supply)
QD_c	quantity sold domestically of domestic output
QM_c	quantity of imports of commodity
tq_c	rate of sales tax (as share of composite price inclusive of sales tax)

Marketed Output Value

$$PX_c\, QX_c = PDS_c\, QD_c + PE_c\, QE_c \qquad (5)$$

where

PX_c	aggregate producer price for commodity
QX_c	aggregate marketed quantity of domestic output of commodity
QE_c	quantity of exports
$c \in CX(\subset C)$	a set of commodities with domestic output

Activity Price

$$PA_a = \sum_{c \in C} PXAC_{a\, c} \theta_{a\, c} \qquad (6)$$

where

$a \in A$	a set of activities
PA_a	activity price (gross revenue per activity unit)

$PXAC_{a\ c}$ producer price of commodity c for activity a
$\theta_{a\ c}$ yield of output c per unit of activity a

Aggregate Intermediate Input Price

$$PINTA_a = \sum\nolimits_{c\in C} PQ_{\ c} ica_{c\ a} \tag{7}$$

where

$PINTA_\alpha$ aggregate intermediate input price for activity a
$ica_{c\ a}$ quantity of c per unit of aggregate intermediate input a

Activity Revenue and Costs

$$PA_a = (1-ta_a)\ QA_a = PVA_a\ QVA_a + PINTA_a\ QINTA_a \tag{8}$$

where

ta_a tax rate for activity
QA_a quantity (level) of activity
QVA_a quantity of (aggregate) value-added
$QINTA_a$ quantity of aggregate intermediate input
PVA_a price of (aggregate) value-added

Consumer Price Index

$$\overline{CPI} = \sum\nolimits_{c\in C} PQ_{\ c} cwts_c \tag{9}$$

where

$cwts_c$ weight of commodity c in the consumer price index
$\overline{CPI}$ consumer price index (exogenous variable)

Producer Price Index for Nontrated Market Output

$$DPI = \sum_{c\in C} PDS_{\ c} dwts_c \tag{10}$$

where

$dwts_c$ weight of commodity c in the producer price index
DPI producer price index for domestically marketed output

CES Technology: Activity Production Function

$$QA_a = \alpha_a^a \left(\delta_a^a\ QVA_a^{-\rho_a^a} + \left(1-\ \delta_a^a\right)\ QINTA_a^{-\rho_a^a}\right)^{\frac{1}{\rho_a^a}} \tag{11}$$

CES Technology: Value-Added-Intermediate-Input Ratio

$$\frac{QVA_a}{QINTA_a} = \left(\frac{QINTA_a}{QVA_a}\ \frac{\delta_a^a}{1-\delta_a^a}\right)^{\frac{1}{1+\rho_a^a}} \tag{12}$$

where

$a\in ACES(\subset A)$ a set of activities with a CES function at the top of the technology nest
α_a^a efficiency parameter in the CES activity function

δ_a^a CES activity function share parameter
ρ_a^a CES activity function exponent

Value-Added and Factor Demands

$$QVA_a = \alpha_a^{va}\left(\sum_{f\in F}\delta_{f\ a}^{v\ a}\, QF_{f\ a}^{-\rho_a^{v\ a}}\right)^{\frac{1}{\rho_a^{v\ a}}} \quad (13)$$

Factor demand

$$\begin{aligned} &WF_f\ \overline{WFDIST}_{f\ a} = \\ &PVA_a\ (1-tva_a)\ = QVA_a\left(\sum_{f\in F}\delta_{f\ a}^{v\ a}\, QF_{f\ a}^{-\rho_a^{v\ a}}\right)^{-1}\ \delta_{f\ a}^{v\ a}\, QF_{f\ a}^{-\rho_a^{v\ a-1}} \end{aligned} \quad (14)$$

where

$f\in F(=F')$ a set of factors
tva_α rate of value-added tax for activity a
α_a^a efficiency parameter in the CES value-added function
$\delta_{f\ a}^{v\ a}$ CES value-added function share parameter for factor f in activity a
QF_{fa} quantity demanded of factor f from activity a
$\rho_a^{v\ a}$ CES value-added function exponent
WF_f average price of factor
$\overline{WFDIST}_{f a}$ wage distortion factor for factor f in activity a (exogenous variable)

Disaggregated Intermediate Input Demand

$$QINT_{c\ a} = ica_{c\ a}\ QINTA_a \quad (15)$$

where

$QINT_{c\ a}$ quantity of commodity c as intermediate input to activity a

Commodity Production and Allocation

$$QXAC_{a\ c} + \sum_{h\in H} QHA_{a\ c\ h} = \theta_{a\ c}\ QA_a \quad (16)$$

where

$QXAC_{a\ c}$ marketed output quantity of commodity c from activity a
$QHA_{a\ c\ h}$ quantity of household home consumption of commodity c from activity a for household h

Output Aggregation Function

$$QX_c = \alpha_c^{ac}\left(\sum_{a\in A}\delta_{ac}^{ac}\ QXAC_{ac}^{-\rho_c^{ac}}\right)^{-\frac{1}{\rho_c^{ca}-1}} \quad (17)$$

where

α_c^{ac} shift parameter for domestic commodity aggregation function
δ_{ac}^{ac} share parameter for domestic commodity aggregation function
ρ_c^{ca} domestic commodity aggregation function exponent

First-Order Condition for Output Aggregation Function

$$PXAC_{a\ c} = PX_{\ c}\ QX_{\ c}\left(\sum\nolimits_{a\in A'}\delta^{ac}_{a\ c}\ QXAC^{-\rho^{ac}_{c}}_{a\ c}\right)^{-1}\ \delta^{ac}_{a\ c}\ QXAC^{-\rho^{ac}_{c}-1}_{a\ c} \tag{18}$$

Output Transformation (CET) Function

$$QX_c = \alpha^t_c\left(\sum\nolimits_{a\in A}\delta^t_{\ c}\ QE^{\rho^t_c}_c +\ \left(1-\delta^t_{\ c}\right)\ QE^{\rho^t_c}_c\right)^{\frac{1}{\rho^t_c}} \tag{19}$$

where

α^t_c a CET function shift parameter
δ^t_c a CET function share parameter
ρ^t_c a CET function exponent

Export-Domestic Supply Ratio

$$\frac{QE_c}{QD_c} = \left(\frac{PE_c}{PDS_c}\ \frac{1-\delta^t_c}{\delta^t_c}\right)^{\frac{1}{\rho^t_{c-1}}} \tag{20}$$

Import-Domestic Demand Ratio

$$\frac{QM_c}{QD_c} = \left(\frac{PDD_c}{PM_c}\ \frac{\delta^q_c}{1-\delta^q_c}\right)^{\frac{1}{1+\rho^q_c}} \tag{21}$$

Demand for Transactions Services

$$QT_c = \sum\nolimits_{c'\in C'}\sum\left(icm_{c\ c'}\ QM_{c'}\ + ice_{c\ c'}\ QE_{c\ c'}\ + icd_{c\ c'}\ QD_{c'}\right. \tag{22}$$

where

QT_c quantity of commodity demanded as transactions service input

Household Consumption Spending on Marketed Commodities

$$PQ_c\ QH_{c\ h} = PQ_c\ \gamma^m_{c\ h} + \beta^m_{c\ h}\left(EH_h - \sum_{c'\in C} PQ_c \gamma^m_{c'\ h} \sum_{a\in A}\sum_{c'\in C} PXAC_{a\ c'}\gamma^h_{a\ c'\ h}\right. \tag{23}$$

where

$QH_{c\ h}$ quantity of consumption of marketed commodity c for household h
$\gamma^m_{c\ h}$ subsistence consumption of marketed commodity c for household h
$\gamma^h_{a\ c'\ h}$ subsistence consumption of home commodity c from activity a for household h
$\beta^m_{c\ h}$ marginal share of consumption spending on marketed commodity c for household h

Factor Markets

$$\sum\nolimits_{a\in A} QF_{f\ a} = \overline{QFS}_f \tag{24}$$

where

$\overline{QFS}_f$ quantity supplied of factor (exogenous variable)

Composite Commodity Markets

$$QQ_c = \sum_{a \in A} QINT_{c\,a} + \sum_{a \in A} QH_{c\,h} + QG_c + QINV_c + qdst_c + QT_c \quad (25)$$

where

$qdst_c$ quantity of stock change

Direct institutional Tax Rates

$$TINS_i = \overline{tins}_i \left(1 + \overline{TINSADJ}\ tins01_i\right) + \overline{DTINS}_i\ tins_i \quad (26)$$

where

$TINS_i$	rate of direct tax on domestic institutions i
$\overline{tins}_i$	exogenous direct tax rate for domestic institution i
$\overline{TINSADJ}$	direct tax scaling factor (=0 for base; exogenous variable)
$tins01_i$	0.1 parameter with 1 for institutions with potentially flexed direct tax rates
$\overline{DTINS}_i$	change in domestic institution tax share (=0 for base, exogenous variable)

Institutional Savings Rates

$$MPS_i = \overline{mps}_i \left(1 + \overline{MPSADJ}\ mps01_i\right) + DMPS\ mps01_i \quad (27)$$

where

$\overline{mps}_i$	base savings rate for domestic institution i
$\overline{MPSADJ}$	savings rate scaling factor (=0 for base)
$mps01_i$	0–1 parameter with 1 for institutions with potentially flexed direct tax rates
$DMPS$	change in domestic institution savings rates (=0 for base, exogenous variable)

Total Absorption

$$TABS = \sum_{h \in H} \sum_{c \in C} PQ_c\ QH_c + \sum_{a \in A} \sum_{c \in C} \sum_{h \in H} PXAC_{a\,c}\ QHA_{a\,c\,h} \quad (28)$$
$$+ \sum_{c \in C} PQ_c\ QG_c + \sum_{c \in C} PQ_c\ QINV_c + \sum_{c \in C} PQ_c\ qdst_c$$

where

$TABS$ total nominal absorption

Ratio of Investment to Absorption

$$INVSHR.TABS = \sum_{c \in C} PQ_c\ QINV_c + \sum_{c \in C} PQ_c\ qdst_c \quad (29)$$

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