Applied Energy 235 (2019) 1254–1265

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Emissions trading systems and social equity: A CGE assessment for China

Hai Huang[a], David Roland-Holst[b], Cecilia Springer[c], Jiang Lin[b,d], Wenjia Cai[e], Can Wang[a,*]

[a] State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), School of Environment, Tsinghua University, Beijing 100084, China
[b] Department of Agriculture and Resource Economics, University of California, Berkeley, CA 94720, United States
[c] Energy and Resources Group, University of California, Berkeley, CA 94720, United States
[d] China Energy Group, Lawrence Berkeley National Lab, Berkeley, CA 94720, United States
[e] Ministry of Education Key Laboratory for Earth System Modeling, and Department of Earth System Science, Tsinghua University, Beijing, 100084, China

HIGHLIGHTS

- The impact of the ETS on social equity is assessed.
- A dynamic CGE model with disaggregated labor and household sectors is developed.
- Employment in China's coal industry will decline by 75% in 2030 in the ETS scenario.
- ETS revenue will peak at 2278 billion yuan in 2042 in our scenario.
- ETS revenue redistribution can reduce the Gini coefficient by 10% compared to BAU.

ARTICLE INFO

Keywords:
Emissions trading system (ETS)
Computable general equilibrium (CGE) model
Employment
Low carbon transition
Cap and trade

ABSTRACT

Carbon dioxide emissions trading systems (ETS) are an important market-based mitigation strategy and have been applied in many regions. This study evaluates the potential for a national ETS in China. Using a dynamic computable general equilibrium (CGE) model with detailed representations of economic activity, emissions, and income distribution, we examine alternative mitigation policies from now until 2050. Based on statistical and survey data, we disaggregate the labor and household sectors and simulate the impacts of ETS policies on the incomes of different household groups. We find that ETS has the potential to reconcile China's goals for sustained, inclusive, and low-carbon economic growth. Results show some key findings. First, the number of unemployed people in energy-intensive industries such as coal and construction will continue to increase; by 2050, employment in the coal industry will decline by 75%. Second, if the scope of the carbon market extends to all industries in China, carbon market revenues will continue to increase, reaching a maximum of 2278 billion yuan ($336 billion) in 2042 to become the world's largest carbon market. Third, the distribution of benefits from the national ETS can help achieve greater social equity. By comparing different distribution policies, we find that the combination of targeted subsidies for unemployed coal workers and direct household subsidies based on proportional per capita will reduce the social income gap to the greatest extent compared with other scenarios. By 2050, this distribution policy will reduce the Gini coefficient in China by 10% compared to the Business as Usual (BAU) scenario.

1. Introduction

China ratified the Paris Agreement and submitted its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change on September 3, 2016. The Chinese government pledged to achieve a CO_2 emissions peak by approximately 2030 and strive to peak emissions before that. China also pledged to lower CO_2 emissions per unit of GDP by 60%–65% compared with 2005 levels and increase the share of non-fossil energy in primary energy consumption to 20 [1]. To achieve these NDC targets, the Chinese government directly incorporated low-carbon development into the 13th Five-Year National Development Plan, including measures to optimize industrial and energy systems, implement energy conservation and emissions reduction projects, strengthen technical support for energy-saving and emissions reduction technologies, and establish a comprehensive market-based mitigation mechanism. In recognition of the latter measure, the national emissions trading system (ETS) is an important tool that can leverage market forces to optimize resource

* Corresponding author.
E-mail address: canwang@tsinghua.edu.cn (C. Wang).

https://doi.org/10.1016/j.apenergy.2018.11.056
Received 3 August 2018; Received in revised form 25 October 2018; Accepted 16 November 2018
Available online 26 November 2018
0306-2619/

allocation in response to the need to mitigate climate change. Since 2011, China has launched carbon pilot emissions trading programs in seven provinces and cities: Beijing, Shanghai, Guangdong, Shenzhen, Tianjin, Chongqing, and Hubei. By the end of 2017, the cumulative volume of transactions in the seven pilot carbon markets exceeded 200 million tons, and cumulative turnover exceeded 4.7 billion yuan [2]. In December 2017, the National Development and Reform Commission printed and issued the "National Carbon Emissions Trading Market Construction Program (Power Generation Industry)", marking the official launch of China's national carbon ETS. This national ETS has the potential to become the world's largest carbon trading system, covering approximately 1700 power generation companies across the country responsible for total annual greenhouse gas emissions of more than 3 billion tons.

As China's ETS programs have only been established for a few years, they have encountered some challenges in terms of legal and regulatory foundations [3,4]; stringency of the emissions cap [5,6]; and monitoring, reporting, and verification [7,8]. Some scholars have analyzed the impact of China's ETS in different regions and scenarios. Tang et al. [9] and Wang et al. [10] used a multi-agent-based model and computable general equilibrium (CGE) model, respectively, to analyze the economic impacts of China's pilot ETS markets. Some scholars focused on the national carbon market, assessing the economic impact of the national ETS on different regions [11,12] and the impact of permit distribution on the fairness of regional development [13,14]. Other researchers explored the economic impact of the allocation of emission allowances in the power [15] and construction industries [16]. Still other researchers evaluated carbon prices and noted that a certain price level can promote the development of clean technologies [17,18].

The analysis of permit allocation, especially the proportion of auctioned or traditional grandfathering of permits, is becoming a popular research topic and has been studied by many scholars. Hübler et al. [19] examined the difference between free allocation and full auctioning of permits, discovering that although the macro-economic impacts were similar, the average consumer would gain revenues from auctioning. Peng et al. [20] compared different shares of auctioned permits and free allocation using a dynamic CGE model. They found that different allocation methods exerted nearly the same impacts on GDP, but effects on different sectors were significantly different. Wu et al. [21] compared free allocation and auctioning and found that free allocation led to lower macroeconomic costs, whereas auctioning was better at adjusting the industry structure. Li et al. [22] also recommended increasing the ratio of auctions after simulating the carbon emissions trading market using a CGE model.

Studies of ETS in other regions, particularly in the EU, have generally indicated that auctioning is better than free allocation by a variety of efficiency criteria, including reducing tax distortions [23], providing greater flexibility in cost distribution [24], and offering more incentives for innovation [25] because the ETS can become more efficient and transparent with auction systems [26,27]. In the EU's ETS, although the share of auctions accounted for only 5% in the initial stage and 10% in the second phase, the ratio has increased sharply in recent years. Permits were distributed 100% through auctioning in energy industries in 2013, and the European Commission decided to increase the share to at least 50% in other sectors in the third phase [28]. At present, several ETS pilots in China have auctioned some permits, including Guangdong, Hubei, and Shenzhen. Although the total volume of trading is relatively small, it contributes to capacity-building and experience to support a national carbon market allocation mechanism in the future. The proportion of auctions in China's ETS will likely increase going forward.

Through auctioning permits, the government can obtain revenue directly from an ETS. Some countries that implemented ETS earlier have already gained substantial revenues. The Australian government estimated the revenue from the Australian ETS to be 8.52 million USD between 2011 and 2012 [29,30]. In California, a statewide cap and trade system is currently generating about 2 billion USD per year. The revenue in Canada was estimated to be 662 million USD in 2011 [30]. For the EU, member states generated nearly 5.71 billion USD from the auctioning of EU ETS allowances in 2015 [31]. As the country with the most CO_2 emissions each year, China will become the world's largest carbon market after establishing a national ETS. With an increase in the proportion of auctioned permits, the carbon market revenue is also expected to increase. Revenue growth will also depend on the cost of mitigation technologies [32]. To the extent that low-carbon investment is cheaper than buying the right to pollute, permit prices and revenues will decline.

Appropriate use of ETS revenues is becoming an important issue for sponsoring governments. The Canadian province of British Columbia uses revenue to compensate households (with 22% of the revenue allocated for lower-income household payments and 42% for reductions in personal income tax) and businesses (22% for reduction of the corporate income tax and 14% for small businesses) [30]. The revenues in the EU's ETS are distributed within affected industries, earmarked for special purposes such as low-carbon technology [33]. The Australian government distributed revenues to lower-income households and compensated with additional energy efficiency measures [34,35]. The California ETS compensates all households with a "California Climate Credit", an annual credit to each household's utility bill, and directs some ETS revenue to a Greenhouse Gas Reduction Fund for low-carbon technologies and greenhouse-gas-mitigating activities.

Several researchers have examined the distribution of ETS revenues. Burtraw and Szambelan [36,37] examined four conceptual options for use of ETS revenues, including ameliorating adverse environmental impacts, financing government expenditures, returning allowance value to households through dividends, and reducing taxes. Roland-Holst [38] used the BEAR (Berkeley Energy and Resources) CGE model to assess the potential benefits of different allocation strategies in California. The model simulated 18 scenarios, and results showed that most revenue recycling options could contribute to long-term economic growth and job creation. Liu et al. [39] used a dynamic CGE model to explore the impact of a carbon tax and different tax revenue recycling schemes on China's economy. Li et al. [40] applied a dynamic CGE model to evaluate the economic impact of ETS with a certain carbon price and proposed using carbon revenue to reduce consumption tax in the first year and then reducing production tax in the following year. However, these investigations focused on macroeconomic impacts rather than in-depth analysis of different income groups and related social equity issues. In addition, China has not explored social equity in the context of ETS revenue redistribution, which could address specific issues associated with the country's development strategy.

China also faces unique challenges in its low-carbon transition, the most prominent of which is the degree of reliance on and demographic importance of the coal industry. As the country's most important energy source, coal once comprised more than 70% of primary national energy consumption. However, with the advent of more stringent environmental policies—especially the pressure accompanying CO_2 emissions reduction policies—the coal industry's production capacity has been declining. The 13th Five-Year Plan for the coal industry, released in 2016, clearly states that coal production capacity will be capped at 3.9 billion tons by 2020. The decline of coal production is expected to reduce labor demand substantially in this sector. In 2013, the number of people employed directly in the coal industry peaked at 5.29 million but has been declining rapidly since then. By the end of 2014, coal full-time-equivalent jobs had decreased to 4.88 million and then to 4.43 million in 2015. By October 2016, employment had fallen to 3.955 million; total coal sector employment is expected to be less than 3 million by 2020 [41].

In light of these considerations, this study examines how ETS revenues can achieve social and environmental objectives, mitigating adjustment costs for those who may be adversely affected in carbon-intensive sectors. This study seeks to address the following gaps in the literature. First, our research suggests the government has important opportunities (i.e., through the emissions permit and auction system) to pursue dual objectives of improving environmental quality and social protection, which have been neglected in most relevant studies, to assess ETS policies. Second, to quantify social equity impacts, we establish a comprehensive CGE method with disaggregated household and labor sectors based on statistical data from the national demographic census and survey data from independent demographic research. This model can unveil the impacts of different groups in ETS policies and can support more relevant research. Third, our study considers the unemployment situation in the coal industry, a special challenge in China's current low-carbon transition, which will render our results more practical for actual policy applications. The remainder of this paper is organized as follows: Section 2 describes the CGE model and database used in the study; Section 3 outlines revenue distribution scenarios; Section 4 presents the main results; and Section 5 provides a detailed discussion of results and limitations of this study.

2. Methods

This study adopts the PRC Aggregate National Development Assessment (PANDA) model, a dynamic CGE model of the Chinese economy constructed at the University of California, Berkeley, which can be used to analyze China's energy and climate policies [42]. The PANDA model is calibrated to the 2012 Input–Output table of China [43] and the 2012 energy balance table [44] with 42 aggregated production sectors (Appendix A). To better analyze the impacts of low-carbon policies on different groups, households were disaggregated into 12 sub-groups by income level and region, while the labor sector was disaggregated into 28 categories by education level, gender, and region.

2.1. Core GE model

In the production block, value added is modeled with a constant elasticity of substitution (CES) function, the most common non-linear function for CGE models, to represent the different substitution possibilities across factors in each sector (see Fig. 1). The non-energy intermediate demand bundle (ND) is combined with a capital-energy-labor bundle (KEL) to generate final output, where intermediate demand follows the fixed proportion input–output relationship (Leontief function). This assumption can be considered a special form of the CES function wherein the substitution elasticity is 0 [45]. The KEL bundle is split between a capital-energy bundle (KE) and a labor demand bundle (AL). In the third level, the AL bundle is split into labor demand by skill while the KE bundle is split into energy and capital. In the fourth level, energy demands by fuel type are combined to generate energy output. More details can be found in the technical documentation by Roland-Holst [46].

In the consumption block, PANDA includes two representative consumers: households and government. Household income includes labor wages, investment income, and transfer payments, and such income is allocated to goods and savings by an exogenous rate calibrated to the social accounting matrix. Each representative household is assumed to maximize utility by consuming different goods and services as modeled by the Linear Expenditure System specification. The government receives revenues from various tax instruments (income, indirect trade, and factor taxes), net of subsidies, and transfers. Government income is allocated to goods and services, and aggregate expenditures are fixed in real terms.

For international trade, the Armington assumption allows for differentiation between domestic products and imports and exports [47]. In addition, this model simulates this differentiation as an aggregate, with one domestic Armington agent per product category using CES and CET functions to represent the import and export sides, respectively.

2.2. Emissions trading system

Based on the core GE model, this study added the ETS module to simulate the carbon market in the future. A country's CO_2 emissions come from production sectors and consumers. For production sectors, the CO_2 emissions of a sector (EF_i) equals the input of different energy sources in that sector ($xap_{i,e}$) multiplied by the emissions factor of the energy ($emit_e$). In addition, because energy inputs in certain industries (e.g., chemical industry) are not all consumed as fuel, some energy inputs are transformed into consumer products without producing direct CO_2 emissions; thus, there is a correction for these industries. The proportion of energy input that is not used as fuel ($feedstock_{i,e}$) is calculated through the energy balance table [44] (Eq. (1)). The total CO_2 emissions of a country (EFT) equal the sum of production sectors minus the feedstock adjustment (Eq. (2)).

$$EF_i = \sum_e emit_e \times xap_{i,e} \times (1 - feedstock_{i,e}) \tag{1}$$

$$\text{EFT} = \sum_i EF_i \tag{2}$$

In this model, China's total annual carbon emissions (EF_{cap}) are set exogenously (Eq. (3)); the amount of emissions restrictions (EFcap) will be introduced in Section 3. To meet annual CO_2 emissions constraints, the concept of shadow carbon price (μ), the cost to be paid for each unit of CO_2, is introduced in the model. Each unit of production that generates carbon emissions in the production process requires an additional payment ($ctax_{i,e}$) (Eq. (4)). In the model, the additional emission payment is added to the production function. This way, carbon emissions constraints are introduced into the economic system in terms of production costs and affect producers' behavior, including using cleaner energy and upgrading industrial structure. Eventually, the system will reach a new equilibrium in the ETS scenario. The carbon price is

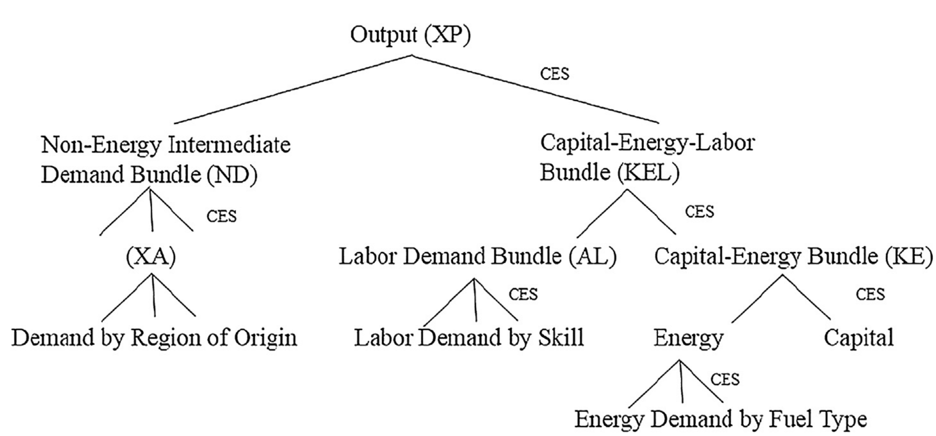

Fig. 1. Production block CES nesting.

endogenously determined by production conditions, energy use efficiency, carbon constraints, and other factors. Although China's current national carbon market only targets the power sector, the goal is for it to gradually expand its coverage in the future. Considering that this study focuses on the medium- and long-term (through 2050) development of China's carbon market, the scope of the market in the model is stipulated across all industries. The carbon market's revenue (ETSR) comes from carbon emissions permits purchased by production sectors (Eq. (5)).

$$EF_{cap} = EF_t \tag{3}$$

$$ctax_{i,e} = \mu \times emit_{i,e} \tag{4}$$

$$\text{ETSR} = \sum_i \sum_e ctax_{i,e} \times xap_{i,e} \tag{5}$$

2.3. Labor and household disaggregation

To identify heterogeneous impacts of ETS policies on different groups, this research disaggregated labor and household categories. The datasets used for disaggregation include the following: (1) the China Statistical Yearbook 2012 [48], which provides data on the household expenditure per capita and rural household income per capita; (2) the China Urban Life and Price Yearbook 2012 [49], which provides data on the urban household income per capita; (3) the 6th Chinese population census [50], which provides the quantity of employment in sectors for different labor types; (4) the 2012 Chinese Input–Output table [43], which provides the total value of labor compensation in sectors; and (5) the Chinese Household Income Project (CHIP) database [51], which was compiled by Beijing Normal University with 26,527 samples and provides the average wage for each labor type and the ratio of different labor types in household sectors. According to the division of labor and household sectors in these datasets, we disaggregated labor sectors into 28 types by gender, region, and education level (Table 1; more details appear in Appendix B). We disaggregated household sectors into 12 types by region (urban/rural) and household income level. In the China Statistical Yearbook 2012, urban and rural residents were divided into seven and five groups, respectively, according to income level; household proportions were obtained from the National Bureau of Statistics (Table 2).

Our labor sector disaggregation method followed that of Mu et al. [42]. Theoretically, labor compensation is the product of average wage and labor quantity for a specific sector and labor type. The labor quantity for a specific sector and labor type was obtained from available data. The average wage for labor type l in sector i ($LW_{l,i}$) can be calculated by Eq. (6) [52]. LAV_i^0 represents the total value of labor compensation in sector i. $LQ_{l,i}^0$ represents the employment quantity for labor type l in sector i. LAW_l^0 represents the average wage for labor type l. More details about the methodology can be found in Mu et al. The household sector disaggregation method mainly relied on Fence and Turner's research on households in the UK [53]. First, we calculated the share of total household expenditure by adding a population weight; relevant data were found in the China Statistical Yearbook 2012 and the 2012 Chinese Input–Output table. Then, we grouped the sectors in the input–output table and split household expenditure into sectors based on these proportions. Second, we calculated the share of total household operations, properties, and transfers by population weights and split these into different household types; these data were obtained from the China Statistical Yearbook 2012 and the China Urban Life and Price Yearbook 2012. Third, the model defines the income range for different household types according to Eqs. (7) and (8). Here, $wages_{i.min}$ represents the minimum wage in group i. The variable $wages_i$ denotes the average wage in group i, which can be obtained from the China Statistical Yearbook 2012 and the China Urban Life and Price Yearbook 2012. Then we used a sample of 7514 households with data on labor and household types and calculated the number of each labor type in different household types. Next, we calculated the proportions of different labor types in each household type, calculated the number of labor types in each household based on the results, and split the wages into 12 households. To address data inconsistencies across sources, survey data were only used for calculating ratios rather than absolute numbers. After this initial allocation, the RAS method was used to balance the disaggregated SAM table, as in Peters and Hertel [52].

Table 1
Components of labor disaggregation.

Gender	Region	Education
Male	Urban	Unlettered
Female	Rural	Elementary school
		Middle school
		High school
		Junior college
		Regular college
		Postgraduate

Table 2
Disaggregated Household Types.

Abbr.	Description	Proportion
HHR1	Low-income household in rural area	20%
HHR2	Lower-middle-income household in rural area	20%
HHR3	Middle-income household in rural area	20%
HHR4	Upper-middle-income household in rural area	20%
HHR5	High-income household in rural area	20%
HHU1	Lowest-income household in urban area	10%
HHU2	Low-income household in urban area	10%
HHU3	Lower-middle-income household in urban area	20%
HHU4	Middle-income household in urban area	20%
HHU5	Upper-middle-income household in urban area	20%
HHU6	High-income household in urban area	10%
HHU7	Highest-income household in urban area	10%

$$LW_{l,i} = \frac{LAW_l^0}{\sum_l \sum_i (LAW_l^0 \times LQ_{l,i}^0 / \sum_l \sum_i LQ_{l,i}^0)} \times \frac{LAV_i^0}{\sum_i LQ_{l,i}^0} \tag{6}$$

$$wages_{i.min} = wages_{i-1} + \frac{wages_i - wages_{i-1}}{2} \tag{7}$$

$$wages_{i.max} = wages_i + \frac{wages_{i+1} - wages_i}{2} \tag{8}$$

2.4. Social equity evaluation index

Gini proposed the Gini coefficient theory in 1912, which eventually became the leading indicator for measuring income inequality[54]. Our disaggregated household income and population data enabled us to calculate Gini coefficients from the PANDA model, according to Eq. (9). In this expression, AI_i represents the average income in group i. r_i represents the population ratio of group i, and AI_{max} represents the average income for the highest-income group. In this calculation, it is assumed that the income per capita within one group is uniform, although this assumption will generate a certain deviation of the Gini coefficient. Considering that this study focuses on the comparison between different distribution scenarios, rather than absolute value, this assumption did not influence our qualitative welfare conclusions. In addition to the Gini coefficient, the Oshima index [55] was calculated in this study as an indicator of social equity. This Oshima index is the ratio of the highest 10% income group in a country to the lowest 10% income group. When income is equally distributed, the indicator reaches its lowest value. The higher the value of the indicator, the greater the income inequality between the top and bottom deciles.

$$\text{Gini} = 1 - \frac{\sum_i AI_i \times r_i}{0.5 \times AI_{max}} \tag{9}$$

3. Scenarios

To evaluate the impact of the ETS policy, this research applies the Business as Usual (BAU) and ETS scenarios. In the BAU scenario, the model simulates the pathway of China's future low-carbon development without an ETS policy. Many research institutions have offered predictions and roadmaps on China's green future and low-carbon development. We referred to *Reinventing Fire China: A Roadmap For China's Revolution In Energy Consumption And Production To 2050* [56], produced jointly by China's Energy Research Institute, the Lawrence Berkeley National Laboratory, Rocky Mountain Institute, and the Energy Foundation China, published in September 2016. This report provided an innovative energy roadmap to 2050 using a bottom-up technology model in which China meets its energy needs and improves energy security and environmental quality using the maximum feasible share of cost-effective energy efficiency technologies and renewable energy sources. The BAU scenario in this model is based on the key parameters in the *Reinventing Fire China* report. First, the structure of China's power sector was adjusted from initial-year values. The proportion of fossil energy declined over time while renewable energy increased (more details appear in Appendix C). Second, the share of primary coal use for heavy industry sectors (e.g., chemistry, non-metallic mineral products, metal smelting, and refining) gradually declined while the share of primary gas use increased. Third, we specified autonomous energy efficiency improvements based on the findings of the bottom-up technology model from the *Reinventing Fire China* Roadmap.

For the ETS scenario, because some scholars are optimistic about China's CO_2 emissions peak [57,58], we specified that total CO_2 emissions would further decrease under the ETS scenario in this model compared with the BAU scenario. The ETS policy begins in 2020, matching the expected start date for the national ETS in China. For the ETS, we specified a 20% reduction in economy-wide emissions below BAU by 2030 and a 30% reduction by 2050. The carbon market revenue was added to government accounts as government revenue.

Building from the ETS scenario, to analyze redistribution of carbon market revenues, three more scenarios were specified to represent different revenue distribution strategies. Considering that China's green and low-carbon development plans will exert a large negative impact on coal output and use, the ETS with Coal labor subsidy (ETSC) scenario uses carbon market revenues for targeted subsidies to unemployed coal industry workers by offsetting the labor tax in the coal industry, with the rest collected as government revenue. In the ETS with revenue distribution by population (ETSP) and ETS with revenue distribution by income (ETSI) scenarios, drawing on lessons from the EU, Australia, and other countries' carbon markets, the model first uses part of the carbon market's revenues to protect unemployed workers in the coal industry; then, the remaining revenue is distributed to households. The household allocation is based on two alternative methods, proportional per capita (ETSP) and/or per dollar of income (ETSI), respectively. The five scenarios in the model and their descriptions are listed in Table 3.

4. Results

4.1. CO_2 emissions

In the BAU scenario, CO_2 emissions will peak in 2030 at 16.7 billion tons, which will achieve China's NDC emissions target. After that, CO_2 emissions will continue to decline, eventually dropping to 78.5% of peak emissions by 2050. This trend is essentially in line with the level of emissions in 2019. In the ETS scenario, CO_2 emissions will peak in 2025, 5 years ahead of the BAU scenario. This result is consistent with recent predictions by some scholars and research institutions that China's CO_2 emissions will peak well before 2030. The peak amount in the ETS scenario is 13.9 billion tons, only 83.7% of the BAU scenario. By 2050, emissions will drop to 65.7% of peak emissions, roughly the same as the emissions level in 2013 (see Fig. 2).

4.2. Economy and employment

In the BAU scenario, China's GDP continues to grow robustly. By 2050, GDP will reach 196.3 trillion yuan ($28.95 trillion), 3.67 times the GDP in 2012 (see Fig. 3). In the ETS scenario, although the emissions constraint is strengthened, the market will lead the economy to achieve efficient, market-directed emissions reductions. GDP actually increases because of efficiency and redistributive gains and is approximately 3% higher than BAU by 2050.

Decarbonization and demand shifting induce structural adjustment in China, and some industries may be adversely affected. Looking at employment in various industries in 2012 and 2050 in the ETS scenario, we identified five industries with the largest reduction in labor demand during China's low-carbon transition process (see Fig. 4): textiles, apparel, coal, wood production, and construction. The total employment decline in these five sectors accounts for approximately two-thirds of all reductions in labor demand relative to BAU. In these industries, the reduction ratio in the coal industry is substantially higher than other industries. By 2050, the labor demand in the coal industry will be reduced by about 75%. Through further analysis of different labor types, we see that coal workers are mainly male urban junior high and middle school graduates and male rural junior high school graduates (see Fig. 5). Findings show that under the BAU scenario, the coal industry will lose 0.89 million male urban middle school graduates, 0.59 million male rural middle school graduates, and 0.51 million male urban high school graduates from the coal industry. Under the ETS scenario, job losses in coal will total 1.06 million, 0.67 million, and 0.61 million from the same categories, respectively. On one hand, because these workers' education level is not high, they may have difficulty finding suitable new jobs within a short time. On the other hand, many adult males are the main source of family income. Thus, coal sector job losses will present substantial economic difficulties, locally and in the home communities of migrant coal workers. China's low-carbon transition is thus not simply about environmental or even technology policy but also points to relevant issues in social policy. For this reason, our scenarios explicitly include alternatives for labor market adjustment assistance, which would help workers through challenging times via subsidies and training.

4.3. Household income

Given the country's emissions inventory, our ETS results indicate that China's carbon market potential is enormous. With the constraints of total carbon emissions and economic development, carbon prices will steadily increase and stabilize at around 200 yuan ($30) per ton after 2040. Beginning with the national carbon market launch in 2020, permit revenue can be expected to grow robustly. By 2042, it will be the world's largest, reaching 2278 billion yuan ($336 billion) per year. Although the scale of the carbon market will eventually decline, market revenue will still be as high as 2026 billion yuan ($299 billion) per year by 2050, a result generally consistent with findings of other studies (see Fig. 6). How to allocate this revenue appropriately will present a growing challenge for the government. This study draws on the experiences of developed countries or states such as the EU and California, taking into account China's actual national conditions, and examines four hypothetical scenarios for revenue distribution to calculate the per capita real income impacts on different stakeholder groups. In the ETS scenario, all ETS revenues are returned to the government. In the ETSC, ETSP, and ETSI scenarios, ETS revenues are first used to subsidize unemployed workers in the coal industry. Before 2030, as the number of unemployed people in the coal industry increases

Table 3
Scenarios and Descriptions.

Scenarios	Description
Baseline (Business as Usual; BAU)	Power structure adjustment, increasing the proportion of renewable energy; Reducing coal input in heavily polluting industries; Improving energy efficiency
Emissions Trading System (ETS)	Increasing emissions limits relative to BAU; ETS revenues return to government
ETS with coal labor subsidy	Using ETS revenues to subsidize unemployed workers in the coal industry; Residual revenues return to government
ETS with revenue distribution by population	Using ETS revenues to subsidize unemployed workers in the coal industry; Residual revenues distributed to households by population
ETS with revenue distribution by income	Using ETS revenues to subsidize unemployed workers in the coal industry; Residual revenues distributed to households by income

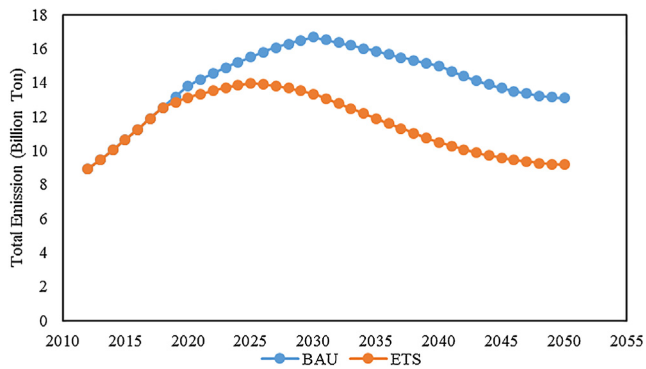

Fig. 2. CO_2 emissions trajectory.

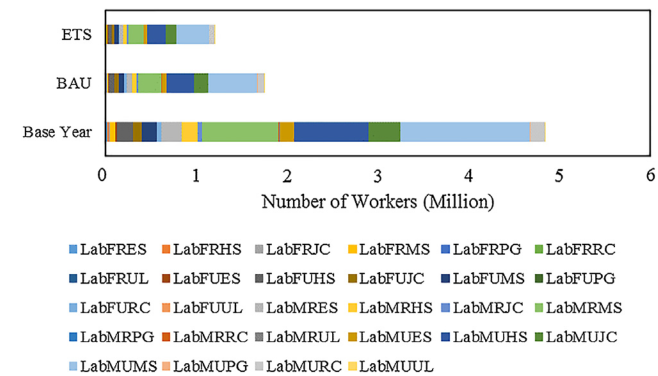

Fig. 5. Change of different types of labor in the coal sector in 2050.

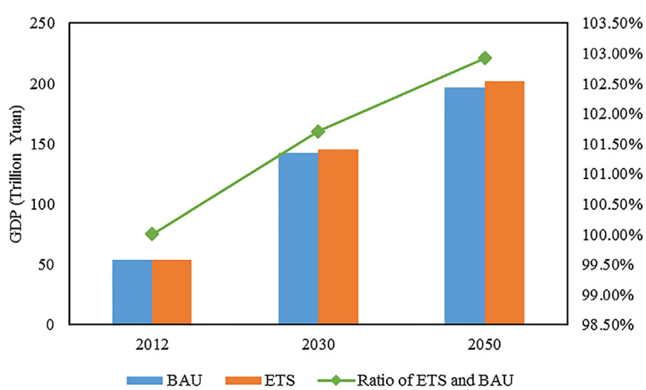

Fig. 3. GDP.

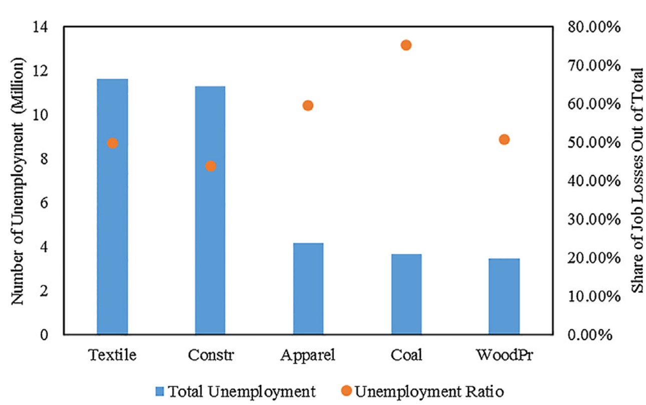

Fig. 4. Top five sectors by unemployment.

significantly, the amount used to subsidize unemployed workers in the coal industry accounts for more than 20% of total ETS revenues. However, the proportion continues to decline as the number of unemployed people slows, eventually reducing to 5% by 2050. Residual ETS revenues are allocated in different ways across three scenarios.

Compared with the BAU scenario, the impacts of different revenue allocation schemes on Chinese incomes can be identified. When all ETS revenues are returned to the government, which then balances its budget with revenue-neutral transfers, the impact on the income of residents in rural areas is positive and increases with permit revenue. ETS effects on urban households are generally in the opposite direction, declining as revenue increases but accelerating after revenue peaks. There are two drivers of these results: government fiscal transfers and adverse income effects of enterprise (carbon) taxes. For the sake of comparison to BAU, all counterfactual scenarios assume the government maintains a fiscal balance that is fixed in real terms. Thus, when new net (e.g., permit) revenue comes in, it is returned to households as a lump-sum, income-proportional transfer. In this case, the ETS will contribute positively to the incomes of all registered households whether rural or urban. Yet the ETS also imposes an implicit emissions tax on covered enterprises, escalating their costs and adversely affecting workers' wages and employment. As rural household activities are not covered by the ETS, their incomes are not directly affected and indirect effects (e.g., remittances) are smaller than fiscal transfer benefits. For urban households, however, the burden of implicit taxes is greater than the uniform fiscal benefit. The net negative effect is exacerbated when ETS revenues decline after 2042.

Even in the simple ETS framework, there may be a case for equitable redistribution. Noting that rural and urban populations are nearly equal in China, as appear to be the average net benefits and costs in Fig. 7, reducing transfers to rural households and increasing them for urbanites might restore welfare to BAU conditions for most people. Our next scenarios explore these kinds of options in more detail, targeting the most adversely affected (i.e., coal sector) workers first.

When a portion of ETS revenues are used to directly subsidize

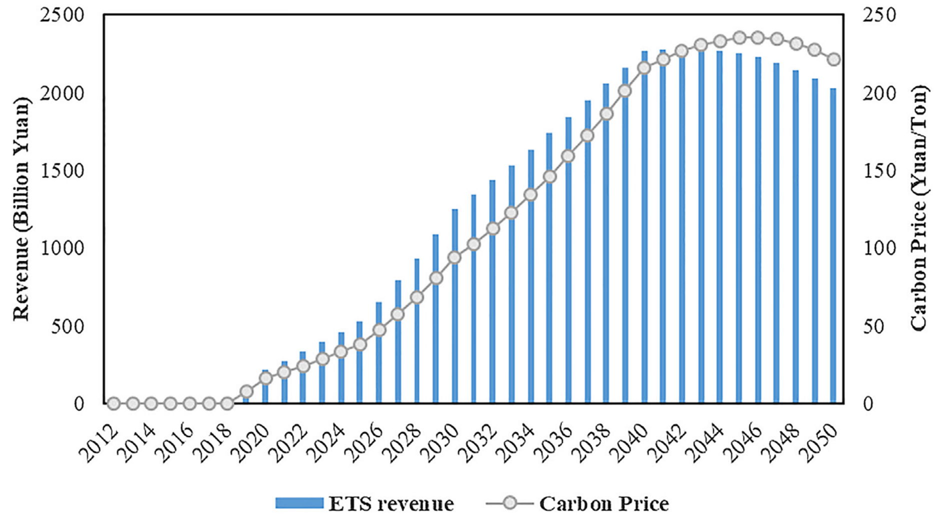

Fig. 6. ETS revenue.

unemployed coal workers (i.e., the ETSC scenario), the household income impacts change significantly (see Fig. 8). Before 2045, the impact of this policy on the income of urban residents would be positive and increasing as long as permit revenues increase. By 2040, the policy will increase the income of urban residents by 0.55%–1.19%, with the relative benefit varying inversely with BAU income because workers in the coal industry are mostly from low- or middle-income groups. The subsidy policies for coal industry workers increase their incomes directly *in addition* to their entitlement to redistributed residual permit revenue. The impact of this policy on the income of rural residents is also positive. Compared with the ETS scenario, the impact will be even greater, reaching 2.96% at most; this finding is shaped by rural workers' presence in the coal industry, as they see higher levels of rural income distribution. In addition, the positive impacts on rural and urban residents will decline from 2040, a combined result of a decline in permit revenue and the rate of coal sector job losses. By 2050, the impact of this policy on incomes of urban residents will be negative but smaller than in the ETS-only scenario, whereas the impact of this policy on rural residents will return to a level consistent with the ETS scenario.

When part of ETS revenues are used to subsidize unemployed coal workers and the remaining revenue is allocated to residents proportional to the population, the impact of the policy on the income per capita of all residents is positive (ETSP scenario). Because of initial inequality within and between rural and urban areas, this policy is highly progressive from a fiscal perspective. Lower income groups benefit most, and urban highest-income groups see a negative income effect by 2049 because per capita compensation does not offset the "emissions tax" burden they experience as a result of the ETS. It should be emphasized, however, that most annual variations from the BAU emissions policy are positive, and the cumulative effect on wealth for all income groups will be overwhelmingly positive (see Fig. 9). By 2050, the policy will increase the annual income of China's three poorest household groups by 12.9%, 9.28%, and 7.47%, respectively. The groups least affected by the policy are those with the highest income in urban areas; by 2050, this policy will reduce the income of the highest-income urban group by 0.26% and increase that of the second-highest income group and middle-high income group by 0.63% and 1.58%, respectively. However, all income changes will be more positive compared to the ETS and ETSC scenarios.

When part of ETS revenues are used to subsidize unemployed coal workers, and the remaining revenue is distributed to residents proportional to income (ETSI scenario), the impact of this policy on the per capita income of all residents is positive, and the impact on different groups is relatively uniform in percentage terms (see Fig. 10). Before 2040, the positive impact of the policy continues to increase, though it falls after 2040. However, by 2050, this positive impact can still be maintained between approximately 3.28% and 4.23% higher than BAU income. Compared with the ETSP scenario, the positive impact on rural residents will be reduced, but the positive impact on urban residents will increase. The most important takeaway from this scenario is that income-proportional compensation, while distributionally neutral, offers positive net benefits from the ETS for all income groups. While targeting sector (employment) adjustment costs for the coal sector is certainly appropriate as part of the ETS, it is not at all clear whether an emissions policy is an appropriate instrument for addressing BAU income inequality. Next, we examine this issue more directly.

In all scenarios, the contribution of ETS revenues to households will face a dramatic turning point in 2040, mainly because the total amount

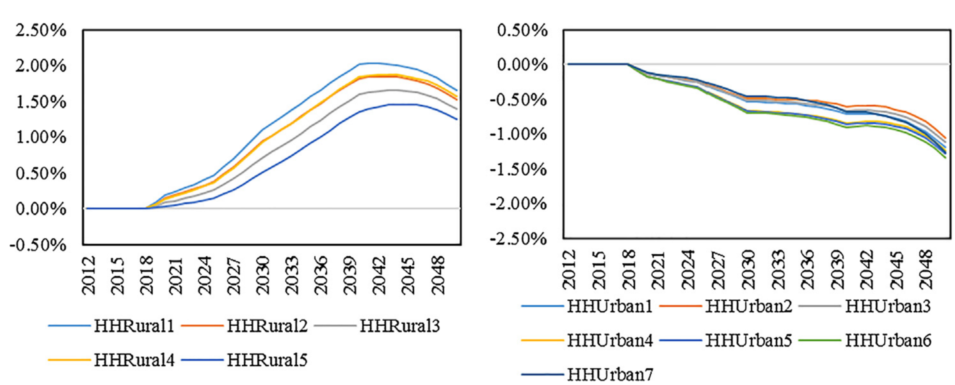

Fig. 7. ETS contribution to household income.

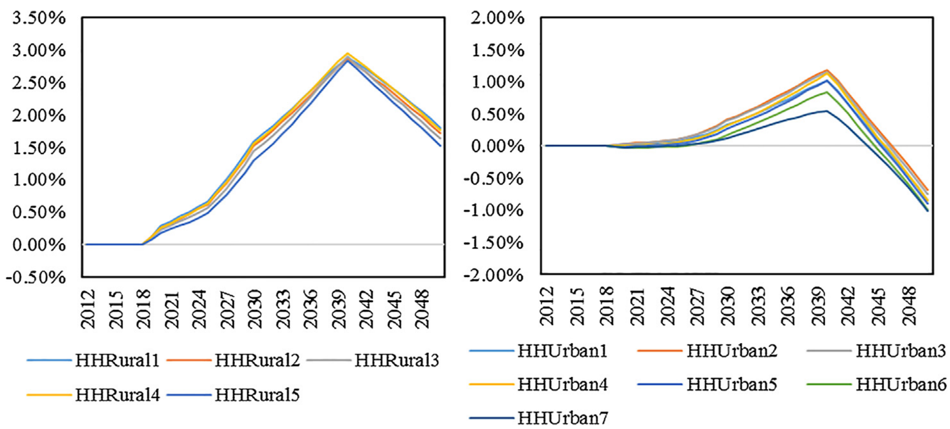

Fig. 8. ETSC contribution to household income.

of carbon emissions in these scenarios has been constrained; China's total carbon emissions will have peaked in 2025. Under this assumption, carbon market revenues will stabilize gradually after 2040, accounting for changes in carbon prices. However, in the dynamic CGE model, GDP will maintain a certain growth rate after 2040, which will further increase household income. The rate of increase in ETS revenues and household income begins to differ in 2040, at which point the contribution of ETS to household income will decline.

4.4. Social equity

Figs. 11 and 12 illustrate the estimated Gini and Oshima coefficient changes in different scenarios; corresponding coefficient values appear in Appendix D. These indicators are designed to measure income differentials across domestic households. Compared to the BAU scenario, we can infer the distributional consequences of our emissions policy experiments.

From the Gini perspective, by 2050 the ETSP allocation method will reduce Gini inequality by about 10% with respect to BAU, whereas the ETS and ETSC lead to nearly equal reductions of the Gini coefficient (−4%). The contribution of the ETSI distribution method to the reduction of the Gini coefficient is lowest, only about 1% below the BAU value. The Oshima results are qualitatively identical, with a reduction of 11% by 2050 in the ETSP scenario whereas the ETS and ETSC are again nearly equal at about −3%. The ETSI scenario has an insignificant Oshima impact, less than 0.1%.

These results suggest that, without reference to initial conditions, the ETSP allocation method exerts the strongest impact on inequality. This result is intuitive because (assuming equal household size) the relative income effect of equal per capita transfers will always be progressive. Conversely, the social equity implications of income-proportional revenue distributions such as the ETSI distribution are likely to be significant and may even have a negative impact depending on the source of fiscal revenue. Accordingly, if the government takes a property rights approach to emissions policy, such as equal entitlement per capita to air quality, progressive fiscal effects can be expected to follow. This pattern holds true even if revenues are only allocated locally (i.e., for emissions reductions *within* rural and/or urban areas). Because the poor carry a higher average health risk burden from most pollution sources, this trend may pave the way to a broader agenda for environmental justice.

5. Conclusions and discussion

5.1. Main findings and policy suggestions

This study examined opportunities for Chinese policymakers to pursue emissions reductions with market-based emissions rights trading schemes. Our general finding is that China can use mechanisms such as this to reconcile its ambitious goals for economic growth and environmental quality. By designing these policies carefully, the country may also be able to achieve other important social objectives. Green and low-carbon development will shift industrial structure, accompanied by significant adjustments in the energy sector, which has important implications for labor markets. First, our research reveals that the number of unemployed people in the country's most energy-intensive industries (e.g., coal and construction) will grow. By 2050, employment in the coal industry can be expected to decline by over

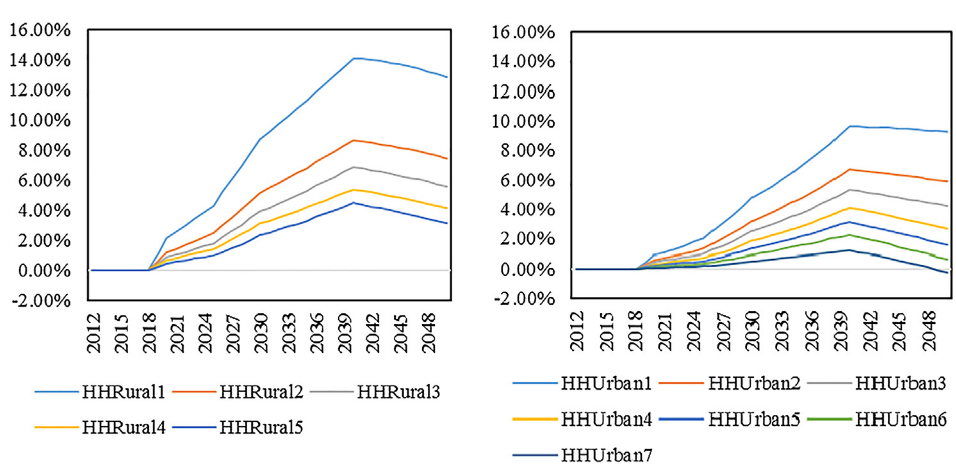

Fig. 9. ETSP contribution to household income.

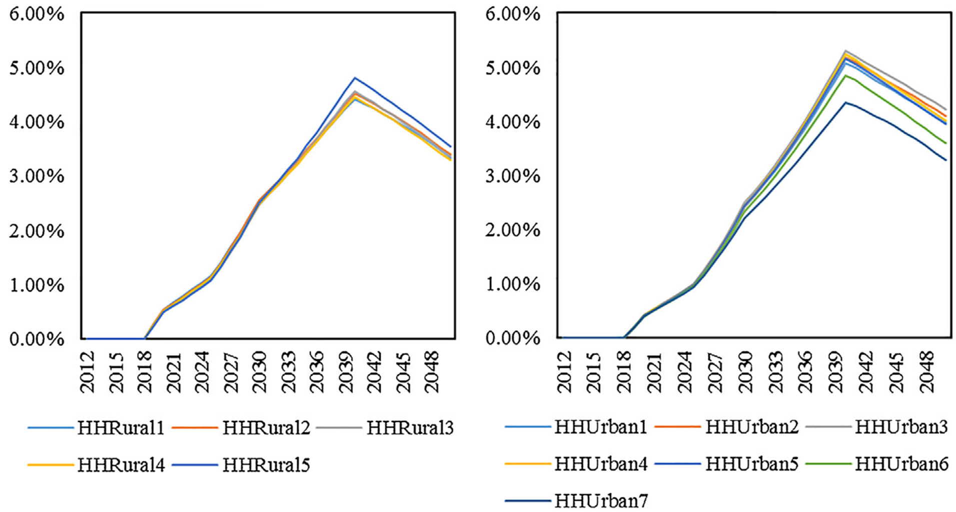

Fig. 10. ETSI contribution to household income.

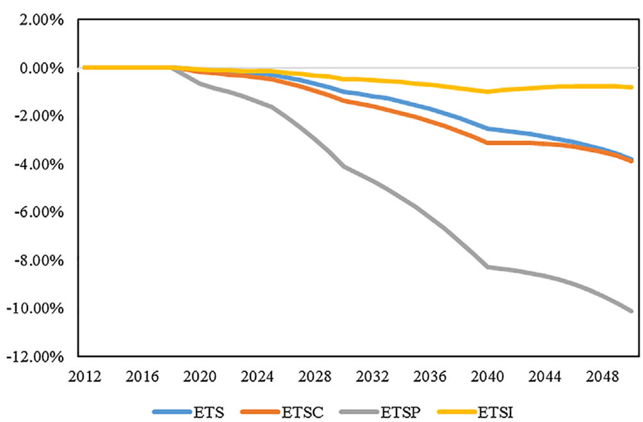

Fig. 11. Gini coefficient relative to baseline.

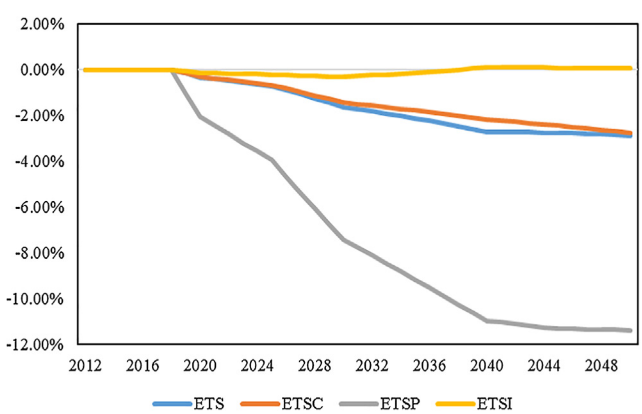

Fig. 12. Oshima coefficient relative to baseline.

75%. Using more disaggregated labor data, we also find that the proportion of men with low levels of education in these industries is high, meaning that the low-carbon transition will disproportionately affect this group. In light of this finding, we recommend that the government explicitly include adjustment assistance measures in the design and implementation of its transition policies, including transitional social insurance and relevant training measures to improve the prospects of those seeking new employment (and their families). These measures may be essential to social stability, sustained local economic growth, and the political feasibility of low-carbon policies themselves.

Second, the evidence we present indicates that the establishment of an ETS can have a positive effect on overall economic development. Indeed, our results imply that implementing a national ETS could increase GDP by 3% by 2050. This growth results from a combination of improved sectoral efficiency and income redistribution without accounting for the many other important benefits of reducing pollution (e.g., averted health problems, mortality, and lower productivity). Fiscal redistribution of carbon market revenues is equivalent to shifting income from producers to consumers, which offers more diverse and job-intensive demand and facilitates China's transition to a post-industrial economy.

Our analysis also suggests that, if the scope of the carbon market can be extended to all industries in China, carbon market revenues will continue to increase to reach a maximum of 2278 billion yuan ($336 billion), becoming the world's largest carbon market. At present, the Chinese government has taken the lead in implementing the ETS in the national electric power industry. It will gradually expand into other industries, in which case the carbon market will play an increasingly important role in China's green and low-carbon development.

Finally, the distribution of benefits from the ETS can offset adjustment costs for adversely affected groups and contribute beyond that to social equity. By analyzing the effects of different ETS revenue distribution strategies, we find that ETS will have a negative income impact on urban residents but a positive impact on rural residents, largely due to the negative indirect effect of the carbon market on energy-intensive industries where employment comprises mostly urban workers. However, if we alter the distribution of ETS revenues, the results can be quite different. If unemployed workers in the coal industry (most affected by the ETS) are subsidized appropriately, then the income of urban residents will be generally unaffected by emission policy. If other revenues are directly allocated to households, the contribution of ETS to their income will increase further. Our disaggregation of household sectors revealed that the rural poor can be the largest (relative to income) beneficiaries of ETS policies. In various scenarios, ETS policies can increase the income of this group by up to 13% by 2050. China's emissions permits are mainly distributed to producers at no charge. In some pilot regions, some emissions permits have also been auctioned, although the amount is not large. However, to make the ETS more effective in the long term, the government must continuously increase the proportion of emitting activities covered by auctions while remaining attentive to appropriate revenue distribution strategies.

In general, from a policy perspective, the modeling results provide promising evidence for the development of ETS, particularly in the following aspects. First, the establishment of ETS can promote China's economy towards green, low-carbon, and efficient energy. It plays a positive role in promoting the Chinese economy. Considering the synergies with the environment and health, the degree of such impact will be even greater. Second, China faces vast unemployment problems in the coal industry in the low-carbon transition. The Chinese government has used fiscal revenue to subsidize unemployed workers. In the future, carbon market revenue will be a possible source of funds. Therefore, this paper recommends that China gradually expand ETS to other industries based on the national carbon market in the power industry and continuously expand the proportion of auction permits to obtain revenues. Third, the ETS policy will also play an active role in promoting social equity. This research suggests that the government allocates carbon market revenues to households according to population, which can promote social equity to the greatest extent.

5.2. Limitations and future work

This study provides an empirical assessment of design alternatives for China's carbon markets. Although we consider detailed economic structures and complex linkages between policy, emissions, industrial structure, employment, and income, important limitations need to be addressed in future work. First, to support more effective policy targeting, the income distribution data should be improved and scenario analysis extended. Some scholars and government agencies have advocated for the use of carbon market revenue to subsidize clean energy industries, with a vision of accelerating development of these industries. Such scenarios require detailed information about technology and innovation potential, presenting a challenging area for future research. A second priority is to improve detail in our modeling of carbon market design and implementation. In this study, the entire industry's carbon market is centralized and otherwise simplified, and the price of emissions permits is set endogenously by the market. In most emissions markets, prices are determined endogenously by the auction mechanism. As China begins to implement a carbon market for the power industry in 2018, it is still uncertain when or how this method will be applied in other industries. In addition, emissions permits are still mainly free. Not only that, in CGE-based carbon market research, the obtained carbon price is the equilibrium price reflected under various optimal constraints, and the model can obtain the annual price change with policy disturbance. However, it cannot reflect the volatility in CO2 prices in the market, which is also a very critical issue. Therefore, to make the study more consistent with the current ETS situation, the carbon market can be calibrated more precisely to present conditions. Finally, analysis and discussion of social equity warrants much more research attention and, as needed, more data development. The conclusion of this study is that ETS policies and revenue distribution policies offer an extensive and politically attractive spectrum of opportunities to advance economic and social objectives, but their precise and optimal characteristics must be substantiated by empirical work and analysis. Future research can also address important issues of detailed sectoral abatement costs and other adjustment effects, enabling more comprehensive assessment of social equity.

Acknowledgements

We gratefully acknowledge the comments and suggestions from anonymous reviewers. This research was funded by the National Natural Science Foundation of China (No. 71773062 and No. 71525007) and the National Social Science Foundation of China (No. 17ZDA077). The first author gratefully acknowledges financial support from China Scholarship Council.

Appendix A. Sectors in PANDA model

No.	Sector	Abbr.	No.	Sector	Abbr.
1	Agriculture, forestry, farming & fishery products	AgFFF	22	Other manufacturing products	OthMfg
2	Coal mining products	Coal	23	Waste and scrap	Waste
3	Oil & natural gas products	OilGas	24	Metal products & repair	MachRep
4	Metal mining products	MetMin	25	Electricity, heat production	ElecDist
5	Non-metallic mining	NMetMin	26	Gas production and supply	GasDist
6	Food and tobacco	FoodPr	27	Water production and supply	WatDist
7	Textiles	Textile	28	Construction	Constr
8	Wearing apparel	Apparel	29	Wholesale and retail	WhRetTr
9	Wood products and furniture	WoodPr	30	Transportation	TranspSrv
10	Paper products	PaperPr	31	Accommodation and catering	HotRest
11	Petroleum, coal & nuclear	RefPet	32	Information services	ICTServ
12	Chemical products	Chemical	33	Finance	Finance
13	Non-metallic mineral	NMetPr	34	Real estate	RealEst
14	Metal smelting and refining	Metals	35	Business services	BusServe
15	Metal products	MetalPr	36	Research and technical	ResTech
16	General equipment	GenEqp	37	Environmental management	EnvServ
17	Special equipment	SpecEqp	38	Resident services, repairs	ResServ
18	Transportation equipment	TransEqp	39	Education	Education
19	Electrical equipment	ElecEqp	40	Health and social work	Health
20	Communications equipment	ICTEqp	41	Culture, sports, entertainment	RecEnt
21	Instruments and meters	PrecInst	42	Public administration	PubAdm

Appendix B. Disaggregated labor types

No.	Gender	Region	Education	Abbr.
L1	Male	Urban	Unlettered	LabMUUL
L2			Elementary school	LabMUES
L3			Middle school	LabMUMS
L4			High school	LabMUHS
L5			Junior college	LabMUJC
L6			Regular college	LabMURC
L7			Postgraduate	LabMUPG
L8		Rural	Unlettered	LabMRUL
L9			Elementary school	LabMRES

L10			Middle school	LabMRMS
L11			High school	LabMRHS
L12			Junior college	LabMRJC
L13			Regular college	LabMRRC
L14			Postgraduate	LabMRPG
L15	Female	Urban	Unlettered	LabFUUL
L16			Elementary school	LabFUES
L17			Middle school	LabFUMS
L18			High school	LabFUHS
L19			Junior college	LabFUJC
L20			Regular college	LabFURC
L21			Postgraduate	LabFUPG
L22		Rural	Unlettered	LabFRUL
L23			Elementary school	LabFRES
L24			Middle school	LabFRMS
L25			High school	LabFRHS
L26			Junior college	LabFRJC
L27			Regular college	LabFRRC
L28			Postgraduate	LabFRPG

Appendix C. Proportion of fossil energy in electric power

Year	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar	Biomass
2012	0.627	0.060	0.024	0.042	0.169	0.054	0.002	0.022
2013	0.620	0.057	0.025	0.043	0.168	0.058	0.007	0.021
2014	0.613	0.054	0.027	0.043	0.167	0.063	0.013	0.021
2015	0.606	0.051	0.028	0.043	0.166	0.068	0.018	0.020
2016	0.600	0.048	0.030	0.044	0.164	0.072	0.023	0.019
2017	0.593	0.045	0.031	0.044	0.163	0.077	0.029	0.019
2018	0.586	0.042	0.032	0.044	0.162	0.081	0.034	0.018
2019	0.579	0.039	0.034	0.045	0.161	0.086	0.039	0.017
2020	0.572	0.036	0.035	0.045	0.160	0.090	0.045	0.016
2021	0.566	0.033	0.037	0.045	0.159	0.099	0.050	0.016
2022	0.559	0.030	0.038	0.046	0.157	0.100	0.055	0.015
2023	0.552	0.027	0.040	0.046	0.156	0.104	0.061	0.014
2024	0.545	0.024	0.041	0.046	0.155	0.109	0.066	0.014
2025	0.538	0.021	0.042	0.047	0.154	0.113	0.071	0.013
2026	0.532	0.018	0.044	0.047	0.153	0.118	0.077	0.012
2027	0.525	0.015	0.045	0.047	0.151	0.122	0.082	0.011
2028	0.518	0.012	0.047	0.048	0.150	0.127	0.087	0.011
2029	0.511	0.009	0.048	0.048	0.149	0.131	0.093	0.010
2030	0.504	0.006	0.049	0.048	0.148	0.136	0.098	0.009
2031	0.495	0.006	0.050	0.050	0.147	0.138	0.105	0.009
2032	0.485	0.006	0.050	0.052	0.145	0.140	0.112	0.009
2033	0.476	0.006	0.050	0.054	0.144	0.142	0.119	0.010
2034	0.466	0.006	0.050	0.056	0.143	0.144	0.125	0.010
2035	0.457	0.006	0.050	0.058	0.142	0.146	0.132	0.010
2036	0.447	0.006	0.050	0.060	0.140	0.148	0.139	0.010
2037	0.437	0.006	0.050	0.061	0.139	0.150	0.146	0.010
2038	0.428	0.006	0.050	0.063	0.138	0.152	0.153	0.010
2039	0.418	0.005	0.050	0.065	0.137	0.155	0.159	0.010
2040	0.409	0.005	0.050	0.067	0.135	0.157	0.166	0.010
2041	0.399	0.005	0.050	0.069	0.134	0.159	0.173	0.010
2042	0.389	0.005	0.050	0.071	0.133	0.161	0.180	0.011
2043	0.380	0.005	0.050	0.073	0.132	0.163	0.187	0.011
2044	0.370	0.005	0.050	0.075	0.130	0.165	0.194	0.011
2045	0.361	0.005	0.050	0.077	0.129	0.167	0.200	0.011
2046	0.351	0.005	0.050	0.078	0.128	0.169	0.207	0.011
2047	0.342	0.005	0.051	0.080	0.127	0.171	0.214	0.011
2048	0.332	0.004	0.051	0.082	0.126	0.173	0.221	0.011
2049	0.322	0.004	0.051	0.084	0.124	0.175	0.228	0.011
2050	0.313	0.004	0.051	0.086	0.123	0.177	0.234	0.012

Appendix D. Social equality index

		2012	2030	2050
Gini	BAU	0.4185	0.3136	0.2656
	ETS	0.4185	0.3105	0.2555
	ETSC	0.4185	0.3092	0.2553
	ETSP	0.4185	0.3007	0.2387
	ETSI	0.4185	0.3122	0.2634
Oshima	BAU	15.5802	9.0236	6.9107
	ETS	15.5802	8.8761	6.7109
	ETSC	15.5802	8.8945	6.7203

ETSP	15.5802	8.3528	6.1249
ETSI	15.5802	8.9979	6.9143

References

[1] Commission NDaR. Enhanced actions on climate change: china's intended nationally determined contributions; 2015.
[2] The LuW. National Carbon Emission Allocation Scheme will be issued in the near future. Economic Information Daily; 2018.
[3] Wang Y, Wang W. Risk identification and regulatory system design for the carbon market. Chin J Popul Resour Environ 2016;14:59–67.
[4] Yi L, Li Z, Yang L, Liu J, Packianather M. Evaluation on the development degree of China's seven pilot carbon markets. Chin J Popul Resour Environ 2018;16:28–35.
[5] Wang Q, Wu S. Carbon trading thickness and market efficiency in a socialist market economy. Chin J Popul Resour Environ 2018:1–11.
[6] Wang W, Luo Y, Xie P, Luo Z, Zhao D. The key elements analysis of Guangdong & Shenzhen ETS & tips for China national ETS construction. Chin J Popul Resour Environ 2016;14:282–91.
[7] Jiang JJ, Ye B, Ma XM. The construction of Shenzhen's carbon emission trading scheme. Energy Pol 2014;75:17–21.
[8] Zhang D, Karplus VJ, Cassisa C, Zhang X. Emissions trading in China: progress and prospects. Energy Pol 2014;75:9–16.
[9] Tang L, Wu J, Yu L, Bao Q. Carbon emissions trading scheme exploration in China: a multi-agent-based model. Energy Pol 2015;81:152–69.
[10] Wang P, H-c Dai, S-y Ren, D-q Zhao, Masui T. Achieving Copenhagen target through carbon emission trading: economic impacts assessment in Guangdong Province of China. Energy 2015;79:212–27.
[11] Cui L-B, Fan Y, Zhu L, Bi Q-H. How will the emissions trading scheme save cost for achieving China's 2020 carbon intensity reduction target? Appl Energy 2014;136:1043–52.
[12] Zhou P, Zhang L, Zhou D, Xia W. Modeling economic performance of interprovincial CO_2 emission reduction quota trading in China. Appl Energy 2013;112:1518–28.
[13] Zhang Y-J, Hao J-F. The allocation of carbon emission intensity reduction target by 2020 among provinces in China. Nat Hazards 2015;79:921–37.
[14] Fan Y, Wu J, Xia Y, Liu J-Y. How will a nationwide carbon market affect regional economies and efficiency of CO_2 emission reduction in China? China Econ Rev 2016;38:151–66.
[15] Cong R-G, Wei Y-M. Potential impact of (CET) carbon emissions trading on China's power sector: a perspective from different allowance allocation options. Energy 2010;35:3921–31.
[16] Hong T, Koo C, Lee S. Benchmarks as a tool for free allocation through comparison with similar projects: focused on multi-family housing complex. Appl Energy 2014;114:663–75.
[17] Li W, Lu C. The research on setting a unified interval of carbon price benchmark in the national carbon trading market of China. Appl Energy 2015;155:728–39.
[18] Yang L, Yao Y, Zhang J, Zhang X, McAlinden KJ. A CGE analysis of carbon market impact on CO_2 emission reduction in China: a technology-led approach. Nat Hazards 2016;81:1107–28.
[19] Hübler M, Voigt S, Löschel A. Designing an emissions trading scheme for China—an up-to-date climate policy assessment. Energy Pol 2014;75:57–72.
[20] Pang T, Zhou S, Deng Z, Duan M. The influence of different allowance allocation methods on China's economic and sectoral development. Climate Pol 2018:1–18.
[21] Wu J, Fan Y, Xia Y. The economic effects of initial quota allocations on carbon emissions trading in China. Energy J 2016;37:129–51.
[22] Li W, Jia Z. The impact of emission trading scheme and the ratio of free quota: A dynamic recursive CGE model in China. Appl Energy 2016;174:1–14.
[23] Pezzey JC, Park A. Reflections on the double dividend debate. Environ Resour Econ 1998;11:539–55.
[24] Böhringer C, Lange A. On the design of optimal grandfathering schemes for emission allowances. Eur Econ Rev 2005;49:2041–55.
[25] Cramton P, Kerr S. Tradeable carbon permit auctions: how and why to auction not grandfather. Energy Pol 2002;30:333–45.
[26] Betz R, Rogge K, Schleich J. EU emissions trading: an early analysis of national allocation plans for 2008–2012. Clim Pol 2006;6:361–94.
[27] Cong R-G, Wei Y-M. Auction design for the allocation of carbon emission allowances: uniform or discriminatory price. Int J Energy Environ 2010;1:533e46.
[28] DIRECTIVE HAT. Directive 2009/139/EC of the European Parliament and of the Council; 2009.
[29] Australia Co. Carbon pollution reduction scheme green paper. Canberra: Department of Climate Change; 2008.
[30] Finance Mo. Budget and fiscal plan 2008/09–2010/11. British Columbia; 2008.
[31] Le Den Xavier, Beavor Edmund, Porteron Samy, Ilisescu Adriana. Analysis of the use of Auction Revenues by the Member States. European Commission; 2017.
[32] Hepburn C, Grubb M, Neuhoff K, Matthes F, Tse M. Auctioning of EU ETS phase II allowances: how and why? Clim Pol 2006;6:137–60.
[33] Commission E. Directorate general for environment, review of EU emissions trading scheme: survey highlights; 2005.
[34] Treasury A. Australia's low pollution future: the economics of climate change mitigation. Canberra: Commonwealth of Australia; 2008.
[35] Treasury A. Architecture of Australia's tax and transfer system. Ch 2008;8:269.
[36] Burtraw D, Szambelan SJ. A primer on the use of allowance value created under California's CO2 cap-and-trade program; 2012.
[37] Burtraw D, Szambelan SJ. For the benefit of California electricity ratepayers; 2012.
[38] Roland-Holst D. Options for cap and trade auction revenue allocation: an economic assessment for California; 2012.
[39] Liu Y, Lu Y. The Economic impact of different carbon tax revenue recycling schemes in China: a model-based scenario analysis. Appl Energy 2015;141:96–105.
[40] Li JF, Wang X, Zhang YX, Kou Q. The economic impact of carbon pricing with regulated electricity prices in China—an application of a computable general equilibrium approach. Energy Pol 2014;75:46–56.
[41] The impact of the "De-capacity" policy on the employment of the coal industry. Institute of Urban Development and Environment, Chinese Academy of Social Sciences and Global Value Chain Institute, University of International Business and Economics; 2017.
[42] Mu Y, Cai W, Evans S, Wang C, Roland-Holst D. Employment impacts of renewable energy policies in China: a decomposition analysis based on a CGE modeling framework. Appl Energy 2018;210:256–67.
[43] National Bureau of Statistics (NBS). China input–output tables 2012; 2016. Retrieved December 19, 2016, from < http://data.stats.gov.cn/ifnormal.htm?u=/files/html/quickSearch/trcc/trcc01.html&h=740 > [In Chinese].
[44] (NBS) NBoS. China energy statistical yearbook. Beijing (China): China Statistics Press; 2013.
[45] Diewert WE. An application of the Shephard duality theorem: a generalized Leontief production function. J Pol Econ 1971;79:481–507.
[46] Roland-Holst D. Berkeley Energy and Resources (BEAR) model technical documentation for a dynamic California CGE model for energy and environmental policy analysis. UC Berkeley; 2008.
[47] Armington PS. A theory of demand for products distinguished by place of production. Staff Pap 1969;16:159–78.
[48] (NBS) NBoS. China statistical yearbook 2012. Beijing (China): China Statistics Press; 2013.
[49] (NBS) NBoS. China urban life and price yearbook 2012. Beijing (China): China Statistics Press; 2013.
[50] (NBS) NBoS. Tabulation on the 2010 population census of the People's Republic of China; 2011. < http://wwwstatsgovcn/tjsj/pcsj/rkpc/6rp/indexchhtm > .
[51] Distribtuion CIfI. Chinese Household Income Project (CHIP); 2013. < http://wwwciidbnuorg/chip/indexasp > .
[52] Peters JC, Hertel TW. Matrix balancing with unknown total costs: preserving economic relationships in the electric power sector. Econ Syst Res 2016;28:1–20.
[53] Fence JD, Turner K. Disaggregating the household sector in a 2004 uk input output table and social accounting matrix by income quintiles; 2010.
[54] Gini C. Measurement of inequality of incomes. Econ J 1921;31:124–6.
[55] Oshima HT. Income inequality and economic growth postwar experience of Asian countries. Malay Econ Rev 1970;15:7–41.
[56] Reinventing Fire: China. A roadmap for China's revolution in energy consumption and production to 2050. Energy Research Institute, Lawrence Berkeley National Laboratory, Rocky Mountain Institute and Energy Foundation China; 2016.
[57] Mi Z, Wei Y-M, Wang B, Meng J, Liu Z, Shan Y, et al. Socioeconomic impact assessment of China's CO_2 emissions peak prior to 2030. J Clean Prod 2017;142:2227–36.
[58] Liu D, Xiao B. Can China achieve its carbon emission peaking? A scenario analysis based on STIRPAT and system dynamics model. Ecol Ind 2018;93:647–57.