Regional Opportunities for China to Go Low-Carbon: Results from the REEC Model

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ABSTRACT

The intention of this paper is to (i) introduce a multi-regional dynamic emissions trading model and (ii) examine the potential impact of an emissions trading scheme (ETS) on the long-term evolution of energy technologies from national and regional perspectives in China. The establishment of this model is a salutary attempt to Sinicize the global integrated assessment model that combines economy, energy, and environment systems. The simulation results indicate that: (1) for majority of regions, ETS is more effective in cutting CO_2 emissions than a harmonized carbon tax (HCT), but this might not be true for the entire country, which means that these two options have little difference in overall carbon reduction; (2) carbon tax policy is a more cost-effective option in curbing CO_2 with respect to ETS in the long run; (3) neither ETS nor pure carbon tax provide enough incentives for the breakthrough of carbon-free energy technologies, which illustrates that matching with some other support policies, such as subsidies and R&D investment, is essential to extend the niche market; and (4) In the context of ETS, the diffusion of non-fossil technologies in regions that act as sellers performs much better than this diffusion in the buyer regions.

Keywords: Integrated modeling, Emissions trading scheme, Multiple uncertainties, Energy restructuring, Technological substitution

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1. INTRODUCTION

Facing the increasingly serious climate change situation, China has stepped into a particular development phase that differs from any other historical period. On the one hand, China has been the world's second largest economy since 2010, but gross domestic product (GDP) per capita is still far from that of developed countries (only 23% of OECD's per capita GDP level, if measured in PPP), implying that there is a long way to go for China to become a developed country and take on a strict carbon reduction commitment (Carraro and Massetti, 2012). On the other hand, carbon emissions in China have been growing quickly over the years, which has positioned China as the world's largest carbon emitter since 2006, accounting for around 26.7% of the world's total carbon emissions (BP, 2013). This in turn means that China must play an essential role in future international cooperation action to mitigate global climate change.

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To cope with climate change and facilitate the reduction of carbon emissions, China has proposed three realistic medium-to-long term targets. First, China aims at reducing the amount of carbon dioxide produced per unit of GDP (carbon intensity) in 2020 by 40–45% compared to 2005 level. Second, by 2020, the share of non-fossil energy in total energy demand will be increased to 15%. Third, in the recently announced China-U.S. deal, China pledged to meet at least 20% of energy demand with non-fossil energy by 2030 (MFAC, 2014). To fulfill these tasks, China has to meet several key challenges: (1) restructuring fossil energy consumption and promoting carbon sequestration, (2) improving energy efficiency so as to reduce the energy intensity and control total energy demand, and (3) accelerating the diffusion of non-fossil energy technologies.

The Emission Trading Scheme (ETS) is a typical market-oriented tool that could be employed to address these challenges (Tietenberg, 2006; Lehmann et al., 2013).[1] Actually, the outline of China's 12th Five-Year Plan has clearly proposed launching regional emissions trading markets, with Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen as the pilots. Since the first carbon market pilot, Shenzhen, opened and started to trade on June 18, 2013, the others have followed gradually. Based on these experiences, the government has planned to establish a unified national emissions trading market by 2016. It can be expected that the emissions trading system will play a more significant role in reducing carbon intensity and controlling carbon emissions. However, there remain a number of unsolvable questions for the current emissions trading market of China.

To what extent will the ETS influence carbon reductions? How will the fossil demand change and non-fossil technological innovations be diffused? What differentiated regional impact will ETS have on the long-term evolution of carbon-free energy technologies? Are there any significant relationships between emissions trading and the development of low-carbon technologies? These questions are addressed in this paper. It addresses several tough challenges. First, the addressing of these issues asks for a specific two-dimensional integrated model that can geographically consider the interactive relationship among different regions and dynamically describe the long-term relationships between the economy, energy system, and emissions. Second, policy comparison analysis means the targeted model must incorporate and distinguish both ETS and carbon tax mechanisms. Third, multiple carbon-free technologies should be considered to fulfill the above research goals. Thus, is very difficult for the widely-used methods, such as computable general equilibrium (CGE) models and agent-based models, to fit the bill simultaneously (Yuan et al., 2013; Qi et al., 2014). We endeavored to establish a multi-regional emissions trading market model of China based on the theoretical framework of integrated assessment modeling to address the challenges.

The remainder of this paper is organized as follows. The next section reviews the related literature surrounding ETS. The subsequent section describes the Chinese multi-regional energy-economy-environmental integrated model, including the framework and some key technical details. Data processing, parameter calibration, and some exogenous trends are discussed in Section 4. Section 5 illustrates the main results and analysis. Concluding remarks and implications are presented in the final section.

1. Despite the controversy on whether we should establish a global emissions trading system, the successful practice of EU ETS proves that ETS is an effective option to stimulate carbon reduction actions and save macro abatement cost (Babiker et al., 2004; Copeland et al., 2005; Edmonds et al., 2008). Note that ETS in this paper mainly refers to carbon-trading scheme.

2. LITERATURE REVIEW

As a policy instrument for cutting down CO_2 emissions, the ETS is advantageous in at least three ways. First, it is more flexible in comparison to other market tools, such as carbon tax. It allows emitters to control their emissions by themselves or to buy allowances from other agents to achieve the given target, which gives the ETS great political appeal (Hepburn and Stern, 2008). Second, a carbon market is designed to achieve a reduction goal while allowing all enterprises to freely enter or exit the market (Koutstaal and Nentjes, 1995). Finally, ETS is a market-oriented carbon reduction option with "double dividend." ETS is cost-effective and therefore cost-saving, and revenues from auctioning permits can be used to partially offset distortions in other taxes (Burtraw et al., 2005; Tietenberg, 2006). Actually, the literature on ETS has grown to a substantial size and continues to expand; the center of interest is cost-effectiveness, equality in initial allocation of permits, impact of transaction costs, and policy comparison between ETS and the carbon tax.

2.1 Cost-effectiveness in Carbon Mitigation

Most of the studies investigate the cost-effectiveness of an emissions system for the industrial sector. Therefore, there remains a scarcity of literature that considers the cost-effectiveness of ETS from the national or regional level. Lee et al. (2008) discuss the impact of a policy portfolio of ETS and carbon tax on various industrial sectors, indicating that the mix policy is more cost-effective in comparison to a pure carbon tax policy. Cui et al. (2014) conclude that the introduction of emissions trading may help to save 23.44% of abatement cost for reaching China's carbon intensity reduction goal stipulated in the 12th Five-Year Plan. Additionally, emissions trading will affect the operation and investment decision of power enterprises to some extent, and incentivize enterprise investment to transfer to low-carbon technology (Chappin and Dijkema, 2009; Kirat and Ahamada, 2011). Lee (2011) evaluates the cost-saving effect of emissions trading on the power industry in South Korea, finding that the average abatement cost is 14.63 $/ton, and the cost-saving effect of emissions trading is significant. Additionally, there is some literature discussing the impact of the ETS on power enterprises in the European Union (EU) and the air transportation industry in the United States (US) (Mo et al., 2012; Malina et al., 2012). Actually, the National Development and Reform Commission (NDRC) announced a unified national emissions trading market would be established in 2016, and the coverage of national carbon market would be expanded from current industrial sectors to most of major emission release sources. In this context, it is of great importance to examine the effects of ETS from both national and regional perspectives.

2.2 Research on the Initial Allocation of Allowances

The specific methods of quota allocation not only affect the cost-effectiveness of the emissions trading system but also bring significant changes to the regional economy. Particularly, industrial sectors with lower energy intensity are sensitive to the ways of quota allocation (Montero, 1997; Edwards et al., 2001; Fischer et al., 2007). Fisher and Alan (2007) compare the output-based principle with the auction and grandfathering principle, arguing that output-based principle is beneficial to high-carbon emitters and is highly effective in preventing carbon leakage, but it may lead to welfare loss. Cong and Wei (2010) investigate the impact of different methods of quota allocation on China's power industry by using an agent-based model. They find that the introduction of emissions trading leads to a 12% rise in electricity prices and increases price volatility. In addition, the output-based principle performs much better than the grandfathering principle in controlling price volatility. Zhou et al. (2013) discuss the fairness of different methods of permit allocation. They conclude that an inter-provincial ETS could reduce carbon abatement costs by 40% and that grandfathering and per capita principles are two quota allocation methods with relatively high equality. Yuan et al. (2013) believe that the GDP loss of emissions trading can be minimized by auctioning all the carbon permits and returning the revenue to enterprises. Moreover, the mixed method of auction and free allocation is found to be a better choice to alleviate the unbalance influence of ETS on the regional economy.

2.3 The Impact of Transaction Cost

Transaction cost is defined as "costs of using the price mechanism" by Ronald Coase who is known as the forefather of transaction cost theory (Coase, 1937). Transaction costs are widely found in markets and include the information search, bargaining, decision-making, monitoring, and implementation costs. The existence of transaction costs may reduce the trading volume and increase the total cost of emission control (Stavins, 1995). Kerr and Maré (1998) discovered that a higher transaction cost heavily reduces the oil refinery's initiative to participate in an emission trading system. Candgadharan (2000) finds that transaction costs play an important role in the early stage of an emission-trading scheme, although this effect decreases gradually as the trading market matures. Zhang et al. (2011) explore the potential impact of transaction cost on the efficiency of the sulfur trading market in the Jiangsu Province of China. The results show that transaction costs change the equilibrium price, and place an obstacle trading volume and operational efficiency. Additionally, the empirical analysis reveals that the level of transaction cost has a close relationship with the scale of enterprise. For instance, for a large-scale firm, the ETS transaction cost is only 0.05 euro but may be as high as 2.02 euro for a small-scale firm (Jaraité et al., 2011).

2.4 ETS vs. Carbon Tax

As the two most famous policy options, ETS and carbon tax have widely been regarded as strong market tools in cutting CO_2 emissions, and they have long been the research focus of the climate change area. There is, therefore, a certain amount of literature that makes policy comparison between ETS and carbon tax, which include observations of the present situation. The effectiveness and efficiency (at both country levels and enterprise levels) of cap-and-trade and carbon tax are the focus of research (Sijm, 2005; Lee et al., 2008; He et al., 2012; He et al., 2015). Avi-Yonah and Uhlmann (2009) take a very conservative attitude toward cap-and-trade in coping with climate change, and their results show that a carbon tax adjusted over time is a better choice for achieving the carbon reduction goal, the necessary improvements in alternative energy sources, and land resource management practices. Wittneben (2009) discusses the differences between cap-and-trade and carbon tax from seven perspectives. He believes that a cap-and-trade system may not be the most cost-efficient mechanism to reduce GHGs, and an international coordinated carbon tax should be a quicker and cheaper option. MacKenzie and Ohndorf (2012) create a framework to compare the market-based policy instruments in terms of social welfare in the presence of rent seeking. They conclude that non-revenue-raising instruments are usually preferable compared to revenue-raising instruments. Shi et al. (2013) develop a multi-regional CGE model to analyze the policy effect of carbon tax, cap-and-trade, and a mix policy of both. They suggest a mixed policy combining cap-and-trade with a low carbon tax as the first option in coping with carbon mitigation.

This literature review reveals the significance of this research. Regarding the dimension of problems, there is very little literature on the potential relationships between trading-based carbon

Table 1: Regional Division Details of REEC

Regions	Provinces distribution
NORE	Heilongjiang, Jilin, Liaoning
BJTJ	Beijing, Tianjin
NORC	Hebei, Shandong
EASC	Jiangsu, Zhejiang, Shanghai
SOUC	Fujian, Guangdong, Hainan
CENC	Shanxi, Henan, Anhui, Hunan, Hubei, Jiangxi
NORW	Inner Mongolia, Shanxi, Gansu, Ningxia, Qinghai, Xinjiang
SOUW	Sichuan, Chongqing, Guangxi, Guizhou, Yunnan

Note: Tibet, Hong Kong, Macao and Taiwan are excluded in this model.

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reduction and long-term evolution of energy technologies, despite growing research on emission trading and technological evolution issues (Gerlagh and van der Zwaan, 2006; Gavard et al., 2011; Kriegler et al., 2014; Eom et al., 2015). Regarding the research object level, the majority of emissions trading research focuses on industrialized countries and only minor attention has been paid to developing countries, especially China (Fischer et al., 2007; Kirat and Ahamada, 2011; Jaraité et al., 2011). Regarding the methodology level, CGE models and agent-based models dominate the only remaining work that focuses on China's carbon market, such as Cong and Wei (2010), Gavard et al. (2011), Yuan et al. (2013) and Qi et al. (2014), and no dynamic multi-regional carbon-trading model appears, as far as we know. Actually, this type of model has a unique advantage in discussing the long-term and multi-regional policy issues of carbon mitigation. Obviously, more studies are needed to fill these gaps and pave the way for the establishment of China's national unified emissions trading market. Thus, we develop a dynamic multi-regional carbon-trading model of China, which is based on integrated system modeling theory, and we apply it to examine possible impact of trading-based carbon reduction on the long-term performance of energy technologies from both national and regional perspectives.

3. THE MODEL

Regional Energy Economy Carbon model (REEC) is an extended Ramsey model, which is theoretically based on neoclassical economics. Like integrated assessment models, REEC consists of three interdependent modules: economy, energy, and environment. It is a dynamic multi-regional model calibrated on Chinese data. We chose 2007 as a base year and cover a planning horizon of 50 years from 2007 to 2057; 2012 is the most recent year for which data is available. Based on the official habitual region division, we divide China into eight regions, as shown in Table 1.

Each region in REEC is made up of the three modules of economy, energy, and emissions, and each module is dynamically interwoven with the others. Additionally, each region is closely related with the others through common commodity flow (numéraire), energy flow, and emissions trading. REEC assumes that the society is forward-looking and has perfect foresight. Its objective is to maximize the welfare/utility of the entire society by optimizing the regional investment and consumption flows. Generally speaking, it assumes $C(rg,tp)$ and $L(rg,tp)$ represent consumption and labor, respectively. Thus, the objective utility function could be expressed as (Bosetti et al., 2006):

$$Utility = \sum_{rg} NWT(rg) \sum_{tp} \Delta(rg,tp) L(rg,tp) \log(C(rg,tp)/L(rg,tp)). \quad (1)$$

Regionally, the contribution of each region to social welfare is distinguished by Negishi weight, $NWT(rg)$, which is taken as the regional GDP share. Intertemporally, the distribution of utility among different generations is determined by the pure time preference factor $\Delta(rg,tp)$. If τ denotes the path of pure time preference, then $\Delta(rg,tp)$ can be described as (van der Zwaan et al., 2002):

$$\Delta(tp,rg) = \prod_{v=0}^{tp} (1 + \tau(v))^{-T}. \quad (2)$$

3.1 The Economy

Output is aggregated into a single commodity that is produced by employing an economy-wide nested constant elasticity of substitution (CES) production function (See Eq.3 in Appendx A). Following a putty-clay pattern, change in output Y is brought about by vintage (newly added output)YN. Similar to output, changes of key inputs, i.e., capital K, labor L, electric energy E, and non-electric energy NE, are induced by the growth of vintages of inputs KN, LN, EN, and NEN, respectively. Actually, three potential substitution relationships throughout the production process are included, i.e., the substitution of capital for labor, substitution between electric and non-electric energy, and the substitution of the capital-labor composite for energy. In Eq. 3, $\alpha(rg,tp)$ represents the economy-wide technological change that is Hicks-neutral, while exogenous energy technological change enters the production process by introducing the autonomous energy efficiency improvement (AEEI) parameter $\beta(rg,tp)$.

The current output is determined by output in the previous period and the vintage. Owing to economic inertia and the lock-in effect of technology, outputs in previous periods were not sensitive to current changes in market price, while vintages of output were usually sensitive to price changes. On this basis, output should be rationally defined so that it is price-inelastic in the short term and has relatively higher price elasticity in the long term. The output can therefore dynamically proceed as:

$$Y(rg,tp+1) = \lambda^T Y(rg,tp) + YN(rg,tp+1), \quad (3)$$

where T is the length of period, and λ is the period adjustment speed. By the same token, we could get the dynamic relationships between electric input, non-electric input, and capital stock, see Eq. 5-7 in Appendix A.

For each region, part of output is allocated to regional investment and consumption; the rest is used to pay for energy costs $TEC(rg,tp)$, including both fossil and non-fossil energy costs. In addition, the output should be allocated to balance commodity flows domestically with other regions and international trade with other countries. Denoting net outflows as and net exports as, we get:

$$Y(rg,tp) = C(rg,tp) + I(rg,tp) + TEC(rg,tp) + NEX(rg,tp) + NFO(rg,tp). \quad (4)$$

For trade, we make the common but crucial simplification that is usually adopted in partial equilibrium models (Manne and Richels, 1997), i.e., each region produces the numéraire commodity, and international trade and regional trade of this region are aggregated into a single good. This implies that trade is tackled through the Heckscher-Ohlin paradigm (international/regional uniform goods) rather than the Armington specification (region-specific heterogeneous commodities). For international trade, we assume imports and exports follow the optimal trajectories of regional GDP by setting relative upper and lower bounds, as shown by Eq. 10-11 in Appendix A.

Here, similar to Kumbaroğlu et al. (2008), GDP is defined as the difference between output Y and total energy costs TEC). Regional trade must meet with a trade-balance constraint, i.e., the sum of outflows $FO(rg,tp)$ must equal the sum of inflows $FI(rg,tp)$ for all regions, implying:

$$\sum_{rg} NFO(rg,tp) = \sum_{rg} (FO(rg,tp) - FI(rg,tp)) = 0. \quad (5)$$

3.2 The Energy Sector and Carbon Emissions

For each region, energy input in the production process consists of electric energy (fossil fuels nuclear power and renewables) and non-electric energy (coal, oil and natural gas). Electric energy available for consumption partly comes from inner production, including fossil energy $PCE(rg,tp,i)$ and non-fossil energy $PRE(rg,tp,j)$, and partly flows in from other regions $NFOE(rg,tp,i)$ and other states $NEXE(rg,tp,i)$. This relationship remains valid for the supply and demand of non-electric energy. Specifically, internal production is endogenously determined through system optimization, and energy imports and exports follow the path of GDP, while energy flows among different regions are assumed to remain constant on base year dynamics. The relationship between supply and demand can be described as Eq. 13-14 in Appendix A for electric and non-electric energy, respectively.

We assume that the lifetime of fossil plants is 30 years; after this, plants will be retired and phased out gradually while new ones take over.[2] Specifically, for electric energy technology, this process is portrayed as

$$\begin{aligned} PCE(rg,tp+1,i) &= PCE(rg,tp,i) + T \cdot PCEINC(rg,tp+1,i) \\ &\quad - (T/30) PCE0(rg,\text{‘2007’},i), \qquad \text{if } tp \leq T/30; \\ PCE(rg,tp+1,i) &= PCE(rg,tp,i) + T \cdot PCEINC(rg,tp+1,i) \\ &\quad - T \cdot PCEINC(rg,tp-(1+30/T),i), \quad \text{if } tp > T/30. \end{aligned} \quad (6)$$

Analogously, we can get the retirement relationship for non-electric technology, as given in Eq. 16 of Appendix A. Here $PCEINC(rg,tp+1,i)$ and $PNEINC(rg,tp+1,i)$ represents vintages of electric energy production and non-electric energy production. $PCE0(rg,\text{‘2007’},i)$ and

2. In fact, the ‘real world’ data from 4573 retired fossil plants show that the mean lifetimes of coal-fired, oil-fired and gas-fired generators are 38.6, 33.8 and 35.8 years, respectively (Davis et al., 2010). In this paper, we conservatively value the average lifetime to be 30 years.

$PNE0(rg,\text{'2007'},i)$ stand for the initial production of electric and non-electric energy in the base year, respectively.

The development of non-fossil technologies features two aspects: first, cost of low-carbon technologies decreases over time due to the learning-by-doing (LBD) effect, which is the main driving power behind expanding niche markets; second, most of the non-fossil technologies, particularly the renewables, are at the nascent stage of development, and the cost of these technologies is high in comparison to conventional fuels. Based on this, the evolutionary mechanism of non-fossil technology is defined as:

$$PRE(rg,tp+1,j) - MSF(rg)E(rg,tp+1) \leq (1+EXPR(rg))^T PRE(rg,tp,j) \qquad (7)$$
$$PRE(rg,tp+1,j) \geq (1-DECR(rg))^T PRE(rg,tp,j),$$

where $MSF(rg)$ is the possible maximal share of non-fossil energy in total primary energy demand. $EXPR(rg)$ and $DECR(rg)$ denote the maximum expansion and declining rates, respectively.

For conventional technology, carbon-saving technological change is exogenously modeled as reducing the ratio of CO_2 emissions to carbon-based energy inputs. The price trends of electric energy $EFC(rg,tp,i)$ and non-electric energy $NFC(rg,tp,i)$ are also exogenously assumed by giving time-invariable growth rates. As for non-fossil energy, technological change (technological advancement) takes an endogenous form through the LBD process. Knowledge (or experience) accumulated through learning will significantly decrease the technology cost as outlined by Duan et al. (2014).

The fossil energy cost $FC(rg,tp)$ is composed of two parts, one being the electric energy cost $EC(rg,tp)$ and the other the non-electric energy cost $NC(rg,tp)$. Production cost is the main part of electricity costs; the remainder covers energy net flow-outs and net exports. The detailed expressions can be referred to Eq. 22-23 in Appendix A. Note that if ETS is launched, expenditures of buying allowances for buyers and gains in selling allowances for sellers should be taken into account when calculating the total energy cost. In this case, total fossil energy cost becomes:

$$FC(rg,tp) = EC(rg,tp) + NC(rg,tp) + CRC(rg,tp), \qquad (8)$$

where $CRC(rg,tp)$ is the carbon reduction cost, either coming from an ETS or HCT mechanism. And the total energy cost $TEC(rg,tp)$ is the sum of the total fossil energy cost and the non-fossil energy cost, as described in Eq. 26 (Appendix A).

Finally, CO_2 emissions are computed annually by using technology-specific emission factors $EFA(i)$ on the production side, i.e.,

$$EMIS(rg,tp) = \sum_i (PCE(rg,tp,i) + PNE(rg,tp,i))EFA(i). \qquad (9)$$

3.3 The ETS and Carbon Tax Mechanism

The main policy instruments to cut down carbon emissions in the REEC model are ETS and HCT. Hence, if carbon emission is curbed by means of ETS, then the carbon reduction cost $CRC(rg,tp)$ in (9) is expressed as:

$$CRC(rg,tp) = (EMIS(rg,tp) - EMISPMT(rg,tp))CP(tp), \qquad (10)$$

where $EMIS(rg,tp)$ stands for CO_2 emissions in period tp, and $EMISPMT(rg,tp)$ shows the carbon quotas allocated to region rg. If $EMIS(rg,tp) \geq EMISPMT(rg,tp)$, region rg has to buy carbon permits from the carbon market. However, if $EMIS(rg,tp) \leq EMISPMT(rg,tp)$, region rg becomes a seller. Note that transaction costs are not considered here. Obviously, emission trading will bring about income transfers, which may in turn change the income distribution pattern across regions. In this situation, the choice of the quota allocation principle becomes particularly important, and revenue-neutral permit allocation is always preferred for regional fairness (Nordhaus, 1994).

In addition, $CP(tp)$ in (10) is the equilibrium price of the carbon market and determined by:

$$\sum_{rg}(EMIS(rg,tp) - EMISPMT(rg,tp)) = 0. \tag{11}$$

If a carbon tax mechanism is employed to reduce CO_2 emissions, then the carbon reduction cost $CRC(rg,tp)$ should be described as:

$$CRC(rg,tp) = EMIS(rg,tp)CT(tp). \tag{12}$$

Here, the carbon tax variable is endogenous in the REEC model, and $CT(tp)$ is the level of HCT, subject to the given national emission space constrains. Since we don't differentiate carbon caps among regions, the carbon tax is therefore unified nationally.

4. DATA, KEY PARAMETERS AND EXOGENOUS TRENDS

REEC is written in the General Algebraic Modeling System (GAMS) and optimally solved by employing the CONOPT solver. The simulation horizon of REEC ranges from 2007 to 2057, operating in five year periods. All flow variables are defined as annual flows, while the stock variables measure five-year values at the end of a period, including the knowledge stock from LBD. The optimal solution of REEC is cooperative, which means that the objective of this model is to maximize the joint welfare of all regions.

4.1 Macro Economy: Initial Data and Key Parameters

According to NBS (2012a), China's GDP was USD $3.67 trillion in 2007. In addition, the trade surplus in 2007 is significant for China; the gross import and export scale was USD $0.97 and 1.24 trillion, respectively. As one of most important drivers of China's economy, consumption reached USD $1.77 trillion in 2007, accounting for over 48% of GDP. The differentiated data for all the regional divisions are listed in Table 2.

In REEC, the capital depreciation rate for all the regions is identical, with the value assumed to be 5%. The capital depreciation rate has dynamically changed over time, making accurate measurements and forecasts difficult and complex. What we choose here is largely paralleled with the historical capital depreciation rate of state-owned firms in China's statistical yearbooks. It is a little lower than the assumption used in DICE and DEMETER (Nordhaus, 1994; van der Zwaan et al., 2002) but equals the value assumed in Kumbaroğlu et al. (2008). By using a trans-log production function model, the elasticity of substitution between capital-labor and energy is estimated to be 0.88, and it is assumed to be unchangeable for different regions. In fact, this elasticity level is slightly higher than the global level that assumed in WITCH and the domestic industry level valued in C-GEM; however, it approaches estimates in the CE3METL model (Bosetti et al., 2006; Qi et

Table 2: Initial Economic Data Details

	GDP	Capital stock	Consumption	Net exports	Net flowouts
NORE	310.75	2800.38	142.07	16.12	3.63
BJTJ	191.50	2363.10	95.02	−92.24	112.34
NORC	527.49	4575.55	228.07	36.94	28.04
EASC	753.98	7061.06	338.84	145.09	−58.56
SOUC	552.51	2870.21	267.10	131.65	−40.16
CENC	691.90	5237.98	352.67	13.67	3.94
NORW	258.66	2461.17	128.78	8.62	−20.35
SOUW	377.70	2894.87	222.01	7.17	−28.88

Note: The items in the table is measured in terms of numéraire, with billion USD to be the unit.
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Table 3: Economy-Related Key Parameter Estimations and Assumptions

	MPC	Capital share	Electric share	NWT	Capital/GDP
NORE	5.17	0.49	0.09	0.08	9.01
BJTJ	3.78	0.50	0.13	0.05	12.34
NORC	5.51	0.50	0.11	0.14	8.67
EASC	5.03	0.50	0.17	0.21	9.37
SOUC	8.97	0.52	0.18	0.15	5.19
CENC	5.63	0.65	0.11	0.19	7.57
NORW	4.00	0.63	0.12	0.07	9.52
SOUW	5.36	0.72	0.11	0.10	7.66

al., 2014; Duan et al., 2014).[3] The marginal productivity of capital (*MPC*) could be estimated by employing the double logarithmic pattern of the Cobb-Douglas production function. The other estimated and calibrated parameters, such as capital share in GDP, capital value share, electric energy share, and Negishi weight (*NWT*), are presented in Table 3. Note that *NWT* refers to regional GDP shares. The capital value share and electric share are ratios of regional capital stock and electricity consumption, respectively. Thus, these parameters could be simply calculated in terms of electric and non-electric energy data as well as GDP and capital stock data (NBS, 2012a; 2012b).

4.2 Energy-related Data and Cost Trends

It is assumed that the AEEI initiates at 0.7% and decreases gradually to 0.58% per year (Nordhaus, 1994; Manne and Richels, 1997). This is the main source of breakthrough for conven-

3. We carry out a sensitivity analysis on some key economic parameters to identify their influences on the model results, and the conclusion reveals that the key economy, energy and emission results are quite robust to the chosen parameters (Appendix C).

tional fossil technologies. Energy production and consumption in 2007, initial energy net flow-outs among different regions, and initial imported and exported energy for each region can be obtained from NBS (2012b).[4] The initial price of coal is set according to the plate price of cooking coal in Shanxi province; the price of natural gas is taken as the average price of the residential sector in 2007. The domestic oil price has largely been in line with that of international crude oil (WTI), as oil import dependence keeps rising, but price controls still exist in the oil market. Based on this observation, the world's average crude oil price is used in model calibration. Furthermore, it is assumed that the future price of coal, oil, and natural gas proceed at a constant annual growth rate, i.e., 0.5%, 1.2%, and 1%, respectively, which is based on the estimated average price volatility from 2000 to 2012.[5] Initial prices for hydropower, nuclear power, and wind power are the domestic average feed-in tariff, while the future trends endogenously lie in the learning effect.

Estimating learning rates that control the learning process is complex and controversial, which is partly because of the unavailability of realistic cost data for new innovations, and partly because the learning effect largely varies as power station scales, specific sites, and stage of technological development change. In general, for mature technologies, such as nuclear energy, the learning rate is lower (McDonald and Schrattenholzer, 2001) at only 9% in REEC. Di et al. (2012) investigate the learning rate of wind for China, estimating it to be around 12%, which is significantly higher than estimates by Kumbaroğlu et al. (2008) but lower than Jamasb (2007). The other renewables are composed of solar PV, geothermal, biomass, and tidal energy; obviously, all the components are less mature technologies. Hence, the learning rate of these technologies is assumed to be 18% in REEC, which is close to what is assumed by Criqui et al. (2000), McDonald and Schrattenholzer (2001), and Kumbaroğlu et al. (2008).

4.3 Population Trends

Population is one of the key components of economic production, and it affects energy demand and carbon emissions. In REEC, population growth is exogenous, and its projection path follows the forecast of the World Bank (World Bank, 2012). According to this, China's population will keep growing until 2032, peaking at 1.45 billion. We assume that the population share for each region remains stable over the planning horizon, and we thus get regional population trends (see Table 4).[6] Obviously, central China (CENC) is the region with the largest population, and SOUW is next, while BJTJ has the smallest population.

4.4 CO_2 EMISSIONS CAP AND ALLOCATION OF ALLOWANCES

ETS works on the cap and trade principle; thus, the first step is to find an appropriate trajectory of emission cap to fulfill the definition of the ETS scenario. Fang et al. (2009) argue that

4. Fossil Energy in NBS (2012b) is measured in ton of coal equivalent (tce), in the REEC model; we transform the unit of measure into kWh through equivalent heat transfer coefficient to facilitate comparison with non-fossil energy.

5. Generally, there are some controversies on the price volatility assumptions of fossil fuels, owing to the limitation of data availability; in fact, price controls are widely existed in China's energy market, it is therefore difficult for us to get unbiased price data; and this should be one of sources of result uncertainty. What we can do is to make great effort to keep the price projections reasonable, despite still not so precise.

6. The statistics suggest that the historical population shares for all the regions seems relatively stable (from 2000 to 2010), despite a flow trend from southwest of China and central China to eastern China and southern China, but the extent of variation is just around 1% (NBS, 2012a).

Table 4: Exogenous Trends for Gross and Regional Population (Unit: 100 Million)

	2012	2022	2032	2042	2052
NORE	1.130	1.182	1.192	1.172	1.126
BJTJ	0.337	0.352	0.355	0.349	0.335
NORC	1.732	1.811	1.826	1.795	1.725
EASC	1.612	1.685	1.700	1.671	1.605
SOUC	1.548	1.619	1.632	1.605	1.542
CENC	3.683	3.852	3.884	3.819	3.669
NORW	1.254	1.311	1.322	1.300	1.249
SOUW	2.468	2.581	2.603	2.559	2.459
TOTAL	13.764	14.393	14.514	14.269	13.711

Table 5: Exogenous Trends of Carbon Allowances for Different Regions (GtC)

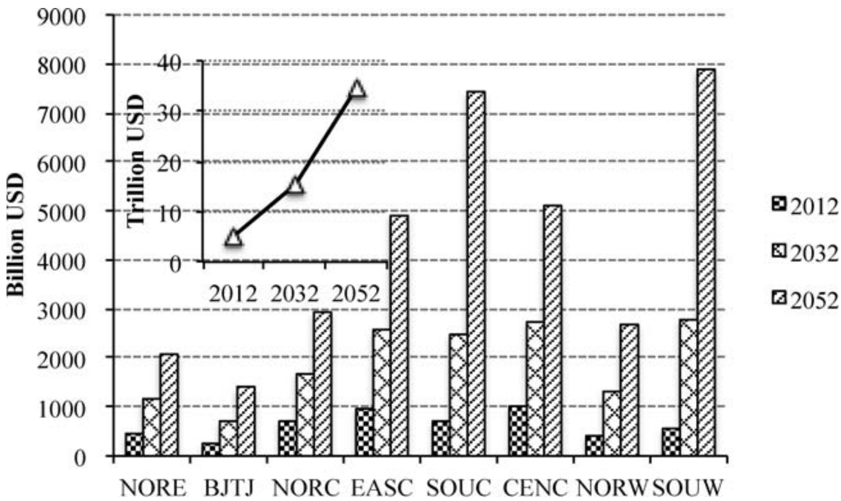
	2012	2022	2032	2042	2052
NORE	0.346	0.530	0.575	0.481	0.306
BJTJ	0.053	0.082	0.089	0.074	0.047
NORC	0.508	0.777	0.843	0.706	0.449
EASC	0.323	0.495	0.537	0.450	0.286
SOUC	0.170	0.260	0.282	0.236	0.150
CENC	0.560	0.857	0.929	0.778	0.495
NORW	0.461	0.706	0.765	0.641	0.408
SOUW	0.293	0.448	0.486	0.407	0.259
TOTAL	2.714	4.154	4.506	3.772	2.401

China's CO_2 emissions will keep growing until 2035, peaking at 4.4 GtC (gigatons of carbon). In addition, it is argued that the possible cumulative CO_2 emissions per capita from 2006 to 2050 will be between 71tC and 109tC.[7] Based on this information, a dynamic carbon emissions path is obtained, which could be viewed as the cap trajectory of the emissions trading scenario (see Table 5).

After setting the cap, allocation of carbon permits is the next step. In fact, allowance allocation heavily affects the cost-effectiveness of ETS and the equity of different regions (Edwards et al., 2001; Fischer et al., 2007). Of all the options of quota allocation, the grandfathering principle is one of most popular and is widely regarded as the closest to revenue-neutral permit allocation (Zhou et al., 2013). Hence, carbon quotas in the emissions trading scenario are allocated in terms

7. According to Fang's plan, the global CO_2 emissions in 2050 will be cut down by 50% compared to 2005 level, and the atmospheric carbon concentration will be stabilized at 450 ppmv.

Figure 1: Economic Growth under the BAU Case: National and Regional Level



of the grandfathering principle. The distributed trends of carbon allowances are portrayed in Table 5. Based on its population, CENC gets the most carbon permits, which implies that this region is the largest carbon emitter. Furthermore, northeast of China (NORE) is the region with the second most carbon allowances, while the fewest permits are allocated to Beijing and Tianjin (BJTJ) based on its lowest ratio of carbon emissions.

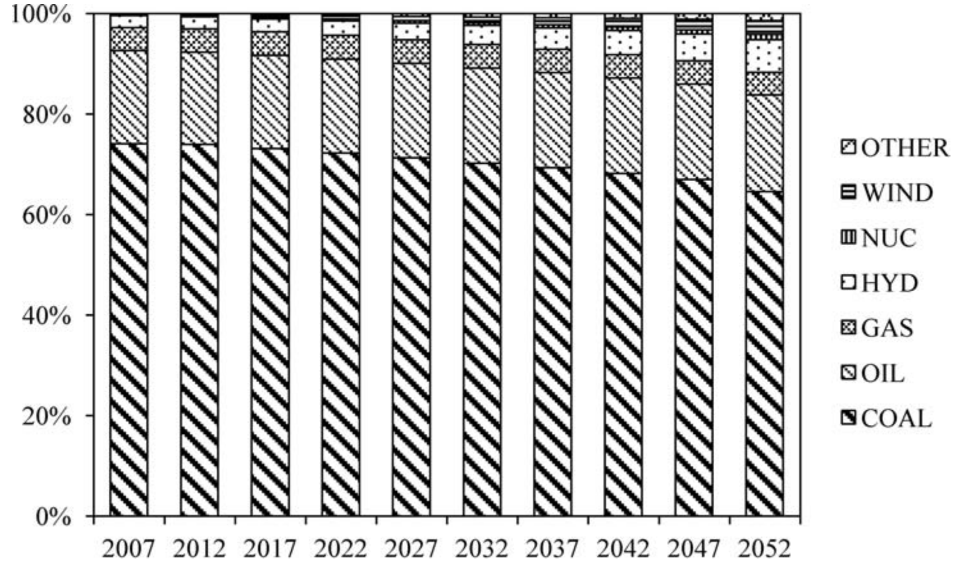
5. SIMULATION RESULTS AND ANALYSIS

To investigate the impact of emissions trading on the long-term evolution of energy technologies, three scenarios are introduced: the first one is the business-as-usual scenario (BAU), which is the scenario that does not take any carbon constraints into account; the second one is the harmonized carbon tax scenario (HCT). In this scenario, carbon tax is the only instrument that is employed to control CO_2 emissions, while differences in carbon tax are determined by the discrepant carbon cap. The last scenario is the ETS scenario, which requires achieving the same carbon reduction target by means of emissions trading. Under the ETS scenario, each region optimizes its carbon reduction amount and trading volume in terms of its marginal abatement cost and initially allocated allowances so as to minimize the total carbon mitigation cost.

5.1 Basic Results without Carbon Constraints

In the absence of carbon constraints, China's economy is projected to keep growing steadily, although the growth rate will decline over time. It can be observed from Figure 1 that China's GDP will expand from USD $3.5 trillion in the base year to USD $15.44 trillion in 2032. By 2052, the size of the economy will have achieved a more than nine fold increase, reaching USD $34.44 trillion. Meanwhile, from 2012 to 2032, the average growth rate of GDP stabilizes at 5.7%. When moving to the entire simulation horizon, this growth rate averages at 4.9%. The macroeconomic results largely conform to mainstream findings (Bosetti et al., 2006; Shi et al., 2013; Cui et al., 2014, Qi et al., 2014).

Figure 2: The Dynamic Energy Structure under the BAU Case



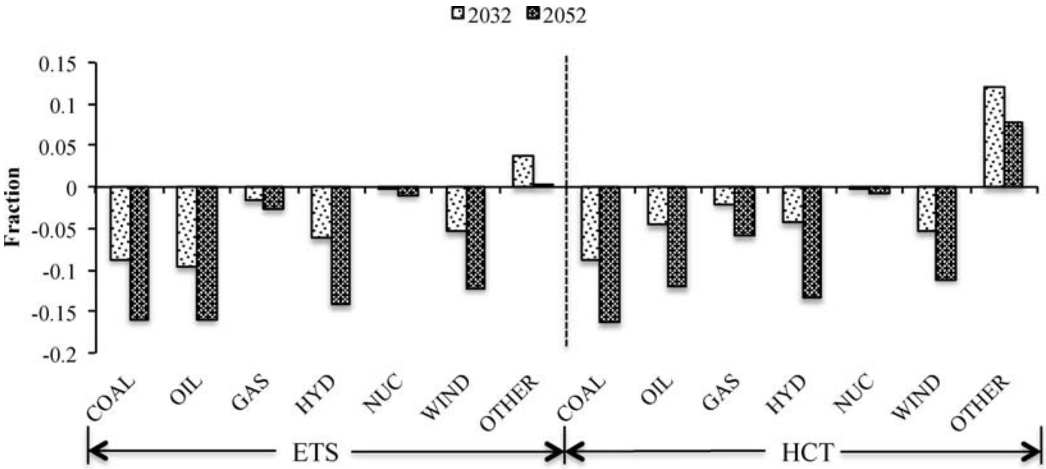
Regionally, SOUC and SOUW are the two fastest-growing economies, with a global average GDP growth rate of 6.0% and 6.8%, respectively, which is significantly higher than the national average level. By 2052, the size of economy for these two regions will account for over 44% of the economy (Figure 1). This implies that with Guangdong province at the core, southern China will be leading economic growth, and this will gradually influence surrounding areas of southwestern China. In addition, strengthening the trade and tour connections between SOUW and Southeast Asia is also of great importance to promote the development of southwest China. Subsequently, CENC and EASC will maintain a favorable position in terms of economic growth, which could be largely explained by the national strategy of promoting the economic rise of central China. NORC and NORE are the two regions with lowest economic growth; the corresponding average annual GDP growth rates in the next four decades are projected at 3.6% and 4.0%, respectively, remarkably lower than the national level.

The change of the energy consumption structure over the simulation horizon is depicted in Figure 2. In the BAU case, shares of oil and natural gas are relatively stable, while the consumption ratio of coal significantly decreases, shrinking by around 10%. Despite this situation, the energy market is still dominated by fossil energy throughout the first half of the twenty-first century. Even in 2052, the share of fossil fuels still accounts for over 80% of energy consumption. This implies that it is difficult for low-carbon technology development to breakthrough in the absence of carbon control or other supporting policies.

5.2 The Impact of ETS on Energy Production and Consumption

Overall, carbon reduction actions have a negative impact on energy production during our simulation horizon, including both fossil and non-fossil energy. For example, coal production may be reduced by at most 16.4% relative to the BAU level, which corresponds to a decrease of 14.2% for hydropower (Figure 3). The decrease of fossil energy may be directly attributed to its high carbon content, while the negative economic effect resulting from carbon reduction actions should

Figure 3: Changes in Energy Production under Both ETS and HCT Case (Relative to BAU Case)



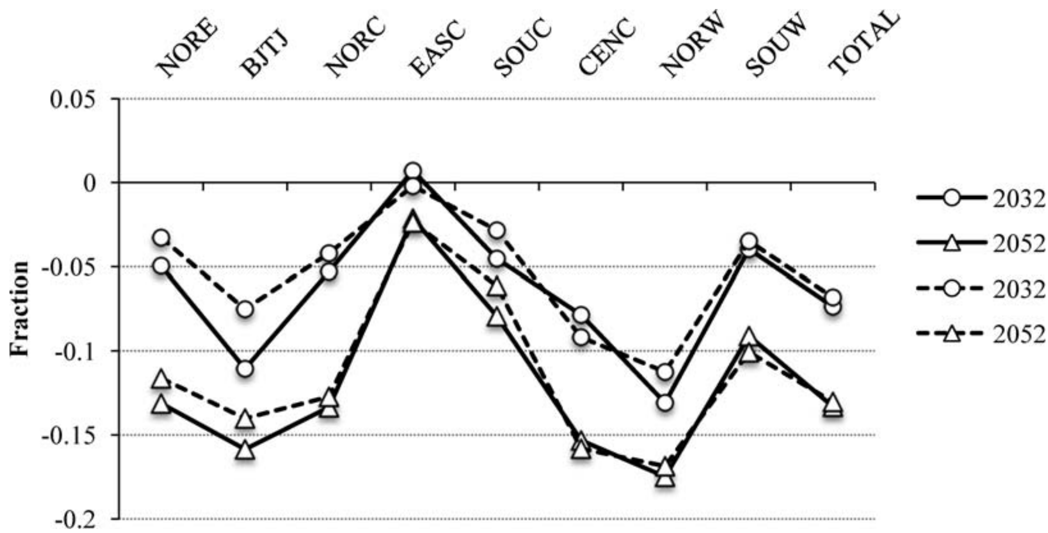
be responsible for the contemporary decrease of low-carbon energy. In addition, Figure 3 shows that the introduction of ETS and HCT has different effects on energy production. Specifically, emissions trading has less influence on fossil fuel production and more effect on non-fossil energy production, compared to the harmonized carbon tax. Actually, coal production under the ETS scenario decreases by 15.9% by 2052 versus 16.4% in the HCT scenario. When looking at the production of non-fossil energy, the incentive effect of carbon tax on the development of non-fossil technologies is significant and consistent, especially for the other renewables (in comparison to the ETS case). For example, by 2052, the production of other renewables will be around 8% higher in the HCT case compared with the ETS case.

As for energy consumption, regional level results reveal that energy consumption for the majority of regions are less influenced under the HCT scenario compared to the ETS case, and this remains true at the national level (Figure 4). In fact, the impact of ETS on energy demand is significantly different across regions. For instance, as representative regions with a high reduction of energy demand, the percentages of decrease for BJTJ and NORW reach 15.9% and 17.5% in 2052, respectively. When looking at EASC and SOUW, the percentages decline to 2.1% and 9.1%, respectively. At the national level, the differences in the effect on energy demand for ETS and HCT are lower (only about 0.285% in 2052), which implies that both ETS and HCT are non-differentiated options for curbing CO_2 emissions as long as the change in the energy consumption of the whole country is not the main concern of the policy maker.

5.3 The Impact of ETS on Carbon Abatement

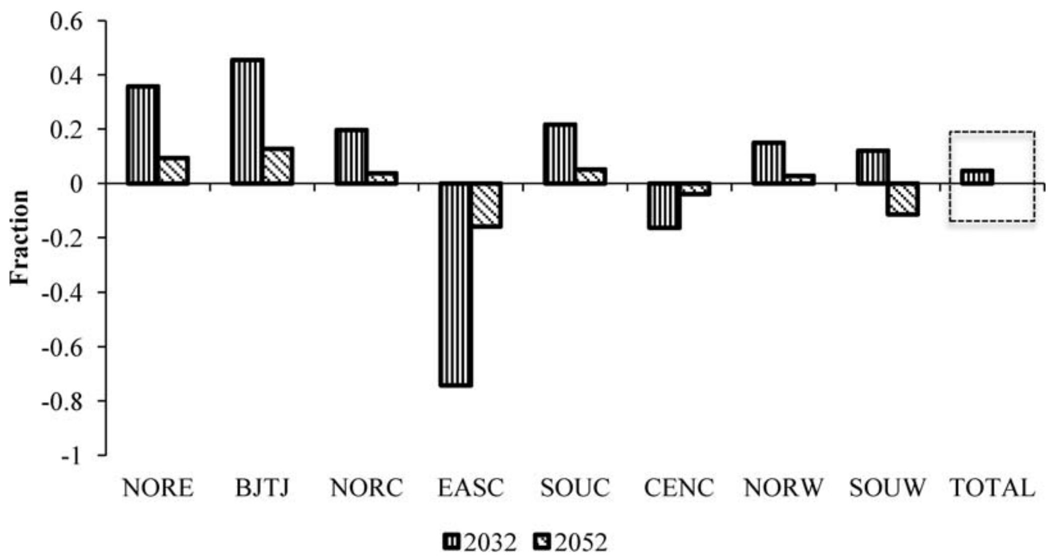
ETS and HCT bring significant and different changes to CO_2 emission reductions, as can be observed in Figure 5. From a regional perspective, except for EASC and CENC, carbon reductions for the rest of the regions in the ETS scenario are significantly higher than the HCT case, although this advantage decreases gradually over time. Specifically, in the ETS case, BJTJ gains the largest advantage of carbon abatement, and the carbon reductions will be no more than 45.5% higher than those in the HCT case. Note that HCT may be preferred in response to carbon mitigation

Figure 4: Changes in Energy Consumption under ETS and HCT Case (Relative to BAU Case)



Note: The red solid lines presents the results under the ETS case; the blue dotted lines show the corresponding results under the HCT case.

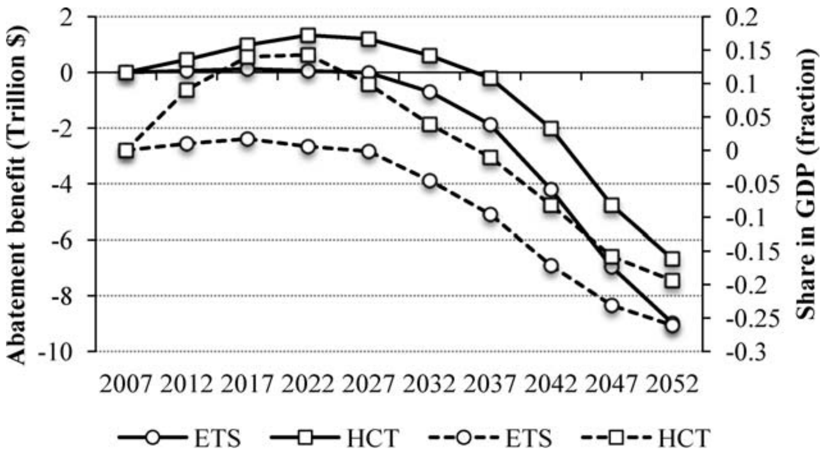
Figure 5: Changes of Carbon Reductions under the ETS Case versus the HCT Case



Note: The fraction on the y-axis means ratio of change in carbon reductions under the ETS case (relative to BAU case) to the change in the HCT case (relative to BAU case)

for EASC and CENC. For example, EASC will at most get a 74.2% reduction in carbon when moving from the HCT to the ETS scenario. It is interesting to note that the impact on carbon reductions between HCT and ETS have little difference in the national perspective. In 2032, the difference in carbon reductions is only 4.7%, and by 2052, it almost disappears (Figure 5). Thus,

Figure 6: The National Abatement Costs under Both Cases, HCT and ETS



Note: The solid lines depicts the macro carbon abatement costs associated with ETS and carbon taxes (left y-axis); the dotted lines portray the shares of macro abatement costs in GDP (right y-axis).

if the regional difference in carbon reduction is not a critical consideration for policy makers, ETS and HCT are approximately non-differentiated options for achieving the national carbon-control target, especially in the long run.

Figure 6 depicts the national abatement costs or benefits (left y-axis) and the corresponding shares in GDP (right y-axis) in both ETS and HCT. Overall, the dynamic curves of the macro abatement costs have a hump shape for both scenarios, and the peak year for abatement costs is 2022, with the GDP share of abatement cost −0.56% in the emission trading case versus −14.28% in the carbon tax case. Owing to uncertainties in the development of carbon reduction technologies, emitters hold a wait-to-see attitude towards carbon reduction and tend to delay their actions under the given carbon goal. As shown in Figure 6, curbing CO_2 is profitable in the early stage of carbon control until 2027 in the ETS case and 2037 in the HCT case. Along with the enhanced carbon reduction, the macro carbon abatement costs keep increasing until the inflexion points appear in around 2047. Meantime, the abatement cost under the ETS case is larger than under the HCT case for the whole planning horizon.

The distribution of regional abatement costs is presented in Figure 6 where the y-axis denotes the fraction of cumulative abatement cost to cumulative GDP during the planning horizon (with a 5% discount rate). As presented in Figure 7, the HCT-based carbon reduction action gains more in the early phase of carbon control, and it loses less in the late phrase, compared to the ETS-based carbon-control option (i.e., the benefit line under the HCT case lies above the corresponding line under the ETS case). This regional result reveals that emission trading is a more expensive option in curbing CO_2 with respect to a harmonized carbon tax policy. Actually, at the national level, the cumulative abatement cost will be 8.36% if carbon is cut by ETS, while carbon reduction becomes profitable when curbing CO_2 using HCT, with a cumulative abatement benefit (or negative abatement cost) around 1% (Fig. 10). Therefore, it is true that the harmonized carbon tax policy is a less costly option in curbing CO_2 emissions compared to ETS at both national and regional levels, which fits well with the conclusion drawn by Avi-Yonah and Uhlmann (2009), Wittneben (2009), and Shi et al. (2013).

Figure 7: The Distribution of Cumulative Regional Abatement Cost

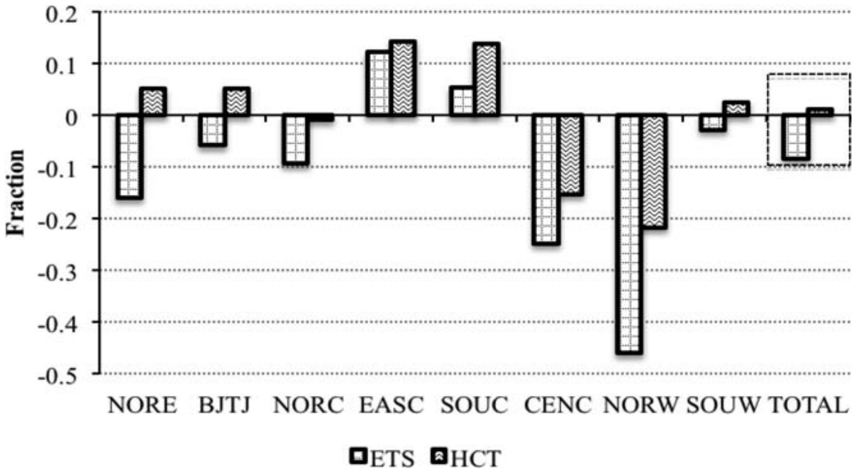
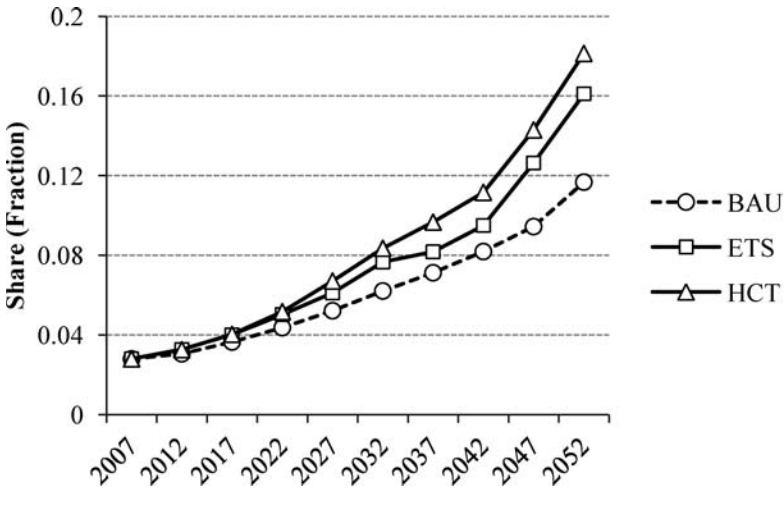


Figure 8: Evolution of Non-Fossil Technologies under Various Scenarios



5.4 Impact on Technological Evolution: Regional and National

The performance of non-fossil energy technologies under the considered scenarios is depicted in Figure 8. We find that (i) no breakthrough appears for the development of non-fossil technologies either by ETS or HCT even though carbon emissions are controlled. Throughout the planning horizon, carbon-based energy use dominates the energy market. Even in the mid-twenty-first century, the maximal share of non-fossil technologies is lower than 20%. This implies that it is rather hard for low-carbon technologies, particularly for renewables, to develop from the cradle stage to the mature stage, even in the presence of carbon control, which is in agreement with Gavard et al. (2011). To spur an accelerated diffusion of low-carbon technologies, some other supplementary policy instruments, such as direct subsidies and R&D investment, may be needed. (ii) With respect to ETS, HCT gains a weak advantage over the development of non-fossil energy. As shown in

Figure 9: Dynamic Paths of Emissions Trading for All the Regions (Trading Volume)

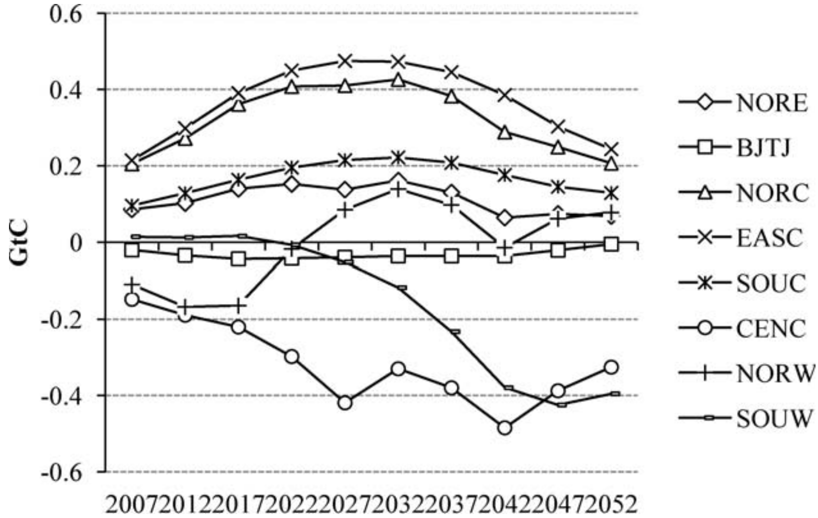


Figure 8, market share of non-fossil energy in the HCT case is no more than 2% higher than in the ETS case. In this situation, carbon reduction from technological substitution could not be dominant in curbing CO_2; reducing energy consumption, improving energy efficiency, and restructuring the energy mix would play a major role instead.

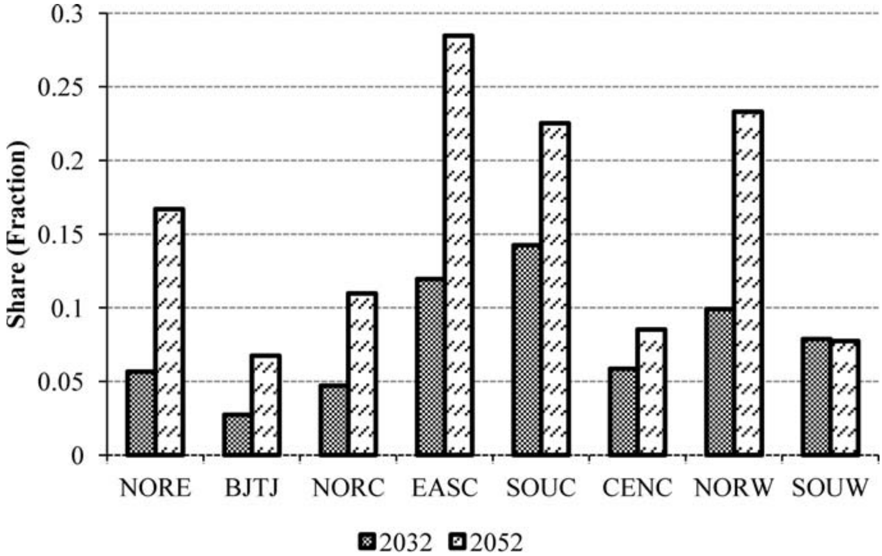
In order to explore the impact of trading-based carbon control on the performance of non-fossil technologies from a regional perspective, emissions trading flows across regions need to be analyzed. Intuitively, regions with larger carbon reductions may act as sellers in the carbon market, while regions with less CO_2 emission control should perform as buyers. Actually, the position of emitters in the trading market is partly determined by the marginal abatement cost that affects the ease of carbon control and partly determined by its allocated quotas.

In general, the developed regions are buyers due to higher marginal abatement costs, while most of the carbon reductions occur in less developed regions. However, this relationship may not be true all the time (see e.g., Mckibbin et al., 1999). As Anandarajah et al. (2010) point out, because of capital flows among different countries, some developing countries may act as buyers in the emissions trading market, while other countries become sellers in the long run. Two immediate questions arise: (i) can the market position of buyers and sellers be determined by the levels of economic development? and (ii) are there any possible relationships between emitter's carbon-control choices and diffusion of low-carbon technologies?

Figure 9 shows the emission trading trajectories for all regions. It can be seen that all agents are active in the trading market. EASC, NORC, SOUC, and NORE act as sellers, while CENC and BJTJ are the main buyers. Additionally, SOUW starts as a seller and then transforms into a buyer; NORW adopts the opposite pattern. It is worth noting that part of the developed regions, such as EASC and SOUC, act as sellers in the carbon market, while some other regions, such as SOUW and CENC, act as buyers.[8] This shows that uncertainty in the relationship between

8. SOUW mitigates at a lower initial abatement cost, which makes it perform as sellers in the early phase; after that, it transforms to a buyer, and this may largely be explained by the sharp increase of marginal abatement cost. Actually, the high unemployment rate, serious capital outflows, social instability and government corruption are the possible factors responsible for the steep increase (Sterner and Coria, 2012).

Figure 10: Regional Difference in Development of Non-Fossil Technologies



levels of economic development and positions of emitters in the emissions trading market still exists among different regions, which is consistent with the finding of Anandarajah et al. (2010).

The regional performance of non-fossil technologies shows that regions with a better development of non-fossil technologies are sellers in the emission trading market. For the buyer regions, non-fossil technologies grow much slower. For example, the market shares of non-fossil energy in EASC and SOUC will be as high as 28.4% and 22.5%, respectively, in 2052. When moving to the buyer region, such as BJTJ, the corresponding share will be lower at 6.7% (Figure 10). It follows that sellers and buyers play different roles in promoting the development of non-fossil technologies. By reducing more CO_2 emissions, sellers could sell the extra permits to get additional revenue, which partly offsets the energy cost, particularly non-fossil energy cost, and provides more incentives for the diffusion of non-fossil technologies.

6. DISCUSSION AND CONCLUDING REMARKS

Based on the integrated system modeling theory, a Chinese multi-regional dynamic carbon-trading model, REEC, is developed in this study. By exploring this model, the impact of trading-based carbon control on the restructuring of fossil energy and the long-term evolution of non-fossil technologies is examined, and the effects are explored at regional and national levels.

Production of fossil and non-fossil energy has a negative impact of carbon reduction. The high carbon content of fossil fuels largely explains the decrease of its production in the presence of carbon abatement, while the economic downturn resulting from carbon reduction lies behind the production decline of low-carbon energy. Additionally, the introduction of ETS and HCT has a different effect on energy production. In particular, ETS has less influence on fossil fuel production but more effect on non-fossil energy production, compared to the HCT. On the regional consumption side, energy consumption has less influence in the HCT scenario than in the ETS one, which is true for most regions. An interesting finding is that the difference of ETS and HCT influence on energy consumption is not significant at the national level, which implies that if regional differences in energy demand are not the main concern, a change of energy consumption at the national level should not be the deterministic factor for policy makers to make a choice between ETS and HCT.

ETS and HCT have significant and different effects on carbon reduction in achieving the same carbon-control target. Compared to HCT, ETS is more favorable for mitigating CO_2 emissions; this is true for most regions. This result is conductive to absorbing more emitters to participate in the emission trading market, and plays a supporting part in building a unified national carbon market.[9] It is important to note that the impact of ETS and HCT on carbon mitigation shows little difference from the national perspective, which reveals that if the regional difference in carbon reductions is not the critical consideration of policy makers, ETS and HCT are non-differentiated options for achieving the national carbon-control target. In addition, compared to ETS, carbon tax policy is more cost-effective for achieving the same carbon-control target in the long run from both national and regional perspectives. In fact, carbon tax may be a win-win in both carbon reduction and cost-saving carbon abatement in the long term, which confirms the findings in Avi-Yonah and Uhlmann (2009),Wittneben (2009), and Shi et al. (2013).

Although HCT performs a little better than ETS in the development of non-fossil technology, it is rather difficult for a niche market of renewables to grow from the inception phase to the mature phase, even in the presence of carbon control. This means that some other supplementary instruments, such as direct subsidies and R&D investment incentivization, might be needed to achieve more breakthroughs (Gavard et al., 2011). Therefore, the policymakers should fully understand the long-term process of transitioning energy supply from fossil fuels to non-fossil energy, and they should emphasize building a whole set of comprehensive policy systems to decarbonize fossil fuels and mature the non-fossil energy market.

The most interesting finding is that there are some potential relationships between the development of non-fossil technology and the position of emitters in the emissions trading market. In particular, it is found that sellers and buyers play different roles in promoting the diffusion of low-carbon technologies, and the regions acting as sellers in the emissions trading market encounter accelerated rates of technological diffusion. For example, the shares of non-fossil energy in 2052 for the representative sellers, such as EASC and SOUC, are 28.4% and 22.5%, respectively, versus 6.7% and 8.4% for the buyer regions BJTJ and CENC. In addition, model results reveal that some developed regions act as sellers, while some developing regions act as buyers. This implies that the uncertainty on the relationship between levels of economic development and market positions of emitters still exists at the regional level, which provides more evidence to support the argument of Mckibbin et al. (1999). Hence, at a national level, the 'one size fits all' policy must be avoided when making a non-fossil energy development plan, and a differentiation strategy should be adopted instead to balance the regional technological development. At the regional levels, governments should pay attention to coordinating the development of non-fossil technologies with carbon reduction actions, as permit buyers and sellers may need different policy portfolios to promote the technological diffusion.

Note that unlike IAMs, REEC doesn't focus on the entire world; it is a Sinicized multi-regional energy-economy-carbon integrated model. Thus, some limitations are inevitable. First, the objective of REEC is to maximize the welfare of society at large; thus, the optimal solution is actually a cooperative game solution. This handing might be appropriate for a country such as China whose general interest is achieved by the central government; however, the central government's

9. Globally, ETS is a cost-effective option to cut down CO_2 emissions (Hepburn & Stern, 2008), and our result proves that this argument is still true, when turning to the regional level.

goal is usually to maximize the welfare of all of society, and it may fail to balance regional interests. In fact, as a rational agent, each local government will aim at maximizing its own welfare, especially in the context of devolving power from the central government. To consider and model this, each region should be treated as an independent forward-looking gamer and seek the non-cooperative open-loop Nash equilibrium solution by optimizing the gamer's utility simultaneously (Bosetti, et al., 2006). Second, REEC endogenizes technological change by using the one-factor learning curve method, i.e., the LBD, while omitting the learning-by-searching (LBS) effect that has proven to be an effective option to hedge against knowledge oblivion (Duan et al., 2014). Additionally, REEC says nothing about the impact of knowledge spillovers on the performance of non-fossil technologies, which is also an important gap to fill when investigating the long-term evolution of energy technologies (Watanabe et al, 2001).

Still, there are some limitations on our model assumptions and scenario setting. For example, the REEC views output as a composite good, incorporates only representative non-fossil energy technologies, leaves out the transaction cost of carbon market, and doesn't consider different sectors as CGEs. This may cause some uncertainties in our results. Additionally, models are simplified representations of real situations. As with the classical IAMs, we try to form our assumptions by balancing the simplicity needed to achieve the research goals against the complexities of the real world (van Vuuren et al., 2011). Furthermore, carbon permits are allocated mainly based on the plan proposed in Fang et al. (2009). However, several institutions and researchers are investigating the allocation of global emission spaces, such as Garnaut (2008), UNDP (2008), and OECD (2008). A multi-scenario comparison and analysis should be an interesting expansion in the near future.

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APPENDIX A. KEY STRUCTURE OF REEC MODEL

A.1 EQUATIONS

$$Utility = \sum_{rg} NWT(rg) \sum_{tp} \Delta(rg,tp) L(rg,tp) \log(C(rg,tp) / L(rg,tp)) \quad \text{(Eq.1)}$$

$$\Delta(tp,rg) = \prod_{v=0}^{tp} (1+\rho(v))^{-T} \quad \text{(Eq.2)}$$

$$YN(rg,tp) = \Big[\alpha(rg,tp) \Big(KN(rg,tp)^{\eta} LN(rg,tp)^{(1-\eta)} \Big)^{\rho} + \beta(rg,tp) \Big(EN(rg,tp)^{\mu} NEN(rg,tp)^{(1-\mu)} \Big)^{\rho} \Big]^{1/\rho} \quad \text{(Eq.3)}$$

$$Y(rg,tp+1) = \lambda^{T} Y(rg,tp) + YN(rg,tp+1) \quad \text{(Eq.4)}$$

$$E(rg,tp+1) = \lambda^{T} E(rg,tp) + EN(rg,tp+1) \quad \text{(Eq.5)}$$

$$NE(rg,tp+1) = \lambda^{T} NE(rg,tp) + NEN(rg,tp+1) \quad \text{(Eq.6)}$$

$$K(rg,tp+1) = \lambda^{T} K(rg,tp) + KN(rg,tp+1) \quad \text{(Eq.7)}$$

$$KN(rg,tp+1) = \frac{T}{2} \Big(I(rg,tp) + I(rg,tp+1) \Big) \quad \text{(Eq.8)}$$

$$Y(rg,tp) = C(rg,tp) + I(rg,tp) + TEC(rg,tp) + NEX(rg,tp) + NFO(rg,tp) \quad \text{(Eq.9)}$$

$$IMP(rg,tp) \le \theta_{imp} GDP(rg,tp) \quad \text{(Eq.10)}$$

$$EXP(rg,tp) \ge \theta_{exp} GDP(rg,tp) \quad \text{(Eq.11)}$$

$$\sum_{rg} NFO(rg,tp) = \sum_{rg} \Big(FO(rg,tp) - FI(rg,tp) \Big) = 0 \quad \text{(Eq.12)}$$

$$\sum_{i\in I} PCE(rg,tp,i)+\sum_{j\in J} PRE(rg,tp,j) - \sum_{i\in I} NFOE(rg,tp,i)-\sum_{i\in I} NEXE(rg,tp,i)\geq E(rg,tp) \quad \text{(Eq.13)}$$

$$\sum_{i\in I} PCN(rg,tp,i)-\sum_{i\in I} NFONE(rg,tp,i) - \sum_{i\in I} NEXNE(rg,tp,i)\geq NE(rg,tp) \quad \text{(Eq.14)}$$

$$\begin{aligned} PCE(rg,tp+1,i) &= PCE(rg,tp,i)+T\cdot PCEINC(rg,tp+1,i) \\ &\quad -(T/30)PCE0(rg,\text{'2007'},i), \qquad \text{if } tp\leq T/30; \\ PCE(rg,tp+1,i) &= PCE(rg,tp,i)+T\cdot PCEINC(rg,tp+1,i) \\ &\quad -T\cdot PCEINC(rg,tp-(1+30/T),i), \qquad \text{if } tp> T/30; \end{aligned} \quad \text{(Eq.15)}$$

$$\begin{aligned} PNE(rg,tp+1,i) &= PNE(rg,tp,i)+T\cdot PNEINC(rg,tp+1,i) \\ &\quad -(T/30)PNE0(rg,\text{'2007'},i), \qquad \text{if } tp\leq T/30; \\ PNE(rg,tp+1,i) &= PNE(rg,tp,i)+T\cdot PNEINC(rg,tp+1,i) \\ &\quad -T\cdot PNEINC(rg,tp-(1+30/T),i), \qquad \text{if } tp> T/30; \end{aligned} \quad \text{(Eq.16)}$$

$$PRE(rg,tp+1,j)-MSF(rg)E(rg,tp+1)\leq \left(1+EXPR(rg)\right)^{T} PRE(rg,tp,j) \quad \text{(Eq.17)}$$

$$PRE(rg,tp+1,j)\geq \left(1-DECR(rg)\right)^{T} PRE(rg,tp,j) \quad \text{(Eq.18)}$$

$$RC(rg,tp,j)=RC(rg,\text{'2007'},j)\left(CUMK(rg,tp,j)/CUMK(rg,\text{'2007'},j)\right)^{-LI(j)} \quad \text{(Eq.19)}$$

$$LR(j)=1-2^{LI(j)} \quad \text{(Eq.20)}$$

$$CUMK(rg,tp+1,j)=\left(1-depr(rg)\right)^{T} CUMK(rg,tp,j)+PRE(rg,tp+1,j) \quad \text{(Eq.21)}$$

$$\begin{aligned} EC(rg,tp) &= \sum_i PCE(rg,tp,i)EFC(rg,tp,i)-\sum_i NFOE(rg,tp,i)EFC(rg,tp,i) \\ &\quad -\sum_i NEXE(rg,tp,i)\cdot EFC(rg,tp,i) \end{aligned} \quad \text{(Eq.22)}$$

$$\begin{aligned} NC(rg,tp) &= \sum_i PNE(rg,tp,i)NFC(rg,tp,i)-\sum_i NFONE(rg,tp,i)NFC(rg,tp,i) \\ &\quad -\sum_i NEXNE(rg,tp,i)NFC(rg,tp,i) \end{aligned} \quad \text{(Eq.23)}$$

$$FC(rg,tp)=EC(rg,tp)+NC(rg,tp)+CRC(rg,tp) \quad \text{(Eq.24)}$$

$$REC(rg,tp)=\sum_j PRE(rg,tp,j)RC(rg,tp,j) \quad \text{(Eq.25)}$$

$$TEC(rg,tp)=FC(rg,tp)+REC(rg,tp) \quad \text{(Eq.26)}$$

$$EMIS(rg,tp)=\sum_i \left(PCE(rg,tp,i)+PNE(rg,tp,i)\right)EFA(i) \quad \text{(Eq.27)}$$

$$CRC(rg,tp)=\left(EMIS(rg,tp)-EMISPMT(rg,tp)\right)CP(tp) \quad \text{(Eq.28)}$$

$$\sum_{rg}\left(EMIS(rg,tp)-EMISPMT(rg,tp)\right)=0 \quad \text{(Eq.29)}$$

$$CRC(rg,tp)=EMIS(rg,tp)CT(tp) \quad \text{(Eq.30)}$$

A.2 INDICES

rg	region
tp	time period
i	fossil energy technologies, i.e., coal, oil and natural gas
j	non-fossil fuels: hydro, wind, nuclear and the other renewables

A.3 VARIABLES

NWT	negashi weights
K	capital stock
I	investment flow
C	consumption
L	labor/population
KN	vintage of capital stock
E	electricity energy input
EN	vintage of electricity energy
NE	non-electric energy
NEN	vintage of non-electric energy
Y	output
YN	vintage of output
IMP	import
EXP	export
NEX	net exports
FI	flow-ins from the other regions
FO	flow-outs to the other regions
NFO	net flow-outs
GDP	gross domestic product
PCE	production of electric energy
PCEINC	increment of electric energy production
PNE	production of non-electric energy
PNEINC	increment of non-electric energy production
PRE	production of non-fossil/low-carbon energy
PREINC	increment of low-carbon energy production
NFOE	net flow-outs of electric energy
NFONE	net flow-outs of non-electric energy
NEXE	net exports of electric energy
NEXNE	net exports of non-electric energy
TEC	total energy cost
EC	electric energy cost
NC	non-electric energy cost
FC	fossil energy cost
REC	renewable/non-fossil energy cost

CRC	carbon reduction cost
EFC	price of electric fuels
NFC	price of non-electric energy
RC	price of non-fossil energy
CUMK	cumulative knowledge stock
EMIS	carbon emissions
EMISPMT	carbon emission permits/allowances
CT	carbon tax level
CP	equilibrium carbon price of emissions trading market

A.4 PARAMETERS

τ	pure rate of social time preference (per year)
Δ	discount factor
T	length of time period
ρ	capital share
μ	electric energy share
η	elasticity of substitution
α, β	scale parameters which includes LPF and AEEI
λ	period adjustment speed
$\theta_{imp}, \theta_{exp}$	lower bound and upper bound for imports and exports
MSF	maximal share of low-carbon energy
EXPR	maximal expansion rate of non-fossil energy
DECR	maximal declining rate of non-fossil energy
LR, LI	learning rate and learning index
depr	rates of depreciation for conventional capital and knowledge capital
EFA	carbon contents of fossil fuels (carbon emission factors)

APPENDIX B. LIST OF ABBREVIATIONS

REEC	Regional Energy Economy Carbon (model)
CGE	Computable General Equilibrium (model)
ETS	Emissions trading scheme
HCT	Harmonized carbon tax
GDP	Gross domestic product
LBD	Learning-by-doing
LBS	Learning-by-searching
NORE	Northeast (of China)
BJTJ	Beijing and Tianjin
NORC	Northern China
EASC	Eastern China
SOUC	Southern China
CENC	Central China
NORW	Northwest (of China)
SOUW	Southwest (of China)

GtC Giga tons of carbon

BAU Business-as-Usual (scenario)

AEEI Autonomous energy efficiency improvement

APPENDIX C. SENSITIVITY ANALYSIS

We carried out a sensitivity analysis on some key economic parameters, i.e., the capital depreciation rate and substitution between capital-labor and energy, to identify their influences on the model results. The lower bounds and upper bounds are obtained by cutting and adding 40% of the basic value, and GDP, energy demand, and carbon emissions are chosen to be the key indicators for analyzing sensitivity. We test the robustness of the chosen parameters from both national and regional perspectives; however, for simplicity, we present the corresponding results at the national level. It is worth mentioning that regional level results are in parallel with national ones. The sensitivity results are listed Tables 6 and 7.

The sensitivity analysis results reveal that the key economy, energy, and emission results are quite robust within the chosen parameters. Specifically, a 40% fluctuation of the depreciation rate triggers a change of indicators that is less than 8.58%. The rates of change under the upper value case are even lower than the lower value case. In terms of substitution elasticity, electric energy demand encounters a relatively significant parameter fluctuation, with the highest rate of change at 9.97%, which corresponds to the lower value case. Overall, a 40% change of substitution elasticity leads to a less than 10% variation in the chosen indicators.

Table 6: Sensitivity of the Depreciation Rate to Key Model Results (%)

		2012	2022	2032	2042	2052
GDP	Lower case	-0.78	-2.04	-5.08	-8.58	-8.35
	Upper case	0.34	3.11	7.42	5.73	4.26
Electric energy	Lower case	0.62	0.80	1.92	3.64	2.66
	Upper case	-0.61	-2.03	-4.61	-2.94	-1.65
Non-electric energy	Lower case	-0.19	-0.36	-0.59	-0.69	-0.28
	Upper case	0.13	0.46	0.82	0.19	0.09
CO_2 emissions	Lower case	0.27	0.34	0.91	1.97	3.02
	Upper case	-0.38	-0.95	-2.10	-1.08	-0.42

Table 7: Sensitivity of the Substitution between Capital-Labor Blender and Energy to Key Model Results (%)

		2012	2022	2032	2042	2052
GDP	Lower case	-0.78	-2.04	-5.08	-8.58	-8.35
	Upper case	0.34	3.11	7.42	5.73	4.26
Electric energy	Lower case	0.62	0.80	1.92	3.64	2.66
	Upper case	-0.61	-2.03	-4.61	-2.94	-1.65
Non-electric energy	Lower case	-0.19	-0.36	-0.59	-0.69	-0.28
	Upper case	0.13	0.46	0.82	0.19	0.09
CO_2 emissions	Lower case	0.27	0.34	0.91	1.97	3.02
	Upper case	-0.38	-0.95	-2.10	-1.08	-0.42